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Greening warehouses through energy efficiency and environmental impact reduction: a conceptual framework based on a Systematic Literature Review

Abstract

Purpose – The purpose of this paper is to propose a framework of green strategies as a combination of energy-efficiency measures and solutions towards environmental impact reduction for improving environmental sustainability at logistics sites. Such measures are examined by discussing the related impacts, motivations and barriers that could influence their adoption. Starting from the framework, directions for future research in this field are outlined.
Design/methodology/approach – The proposed framework was developed starting from a Systematic Literature Review (SLR) approach on 60 papers published from 2008 to 2022 in international peer-reviewed journals or conference proceedings.
Findings – The framework identifies six main areas of intervention ("green strategies") towards green warehousing, namely Building, Utilities, Lighting, Material Handling and Automation, Materials, and Operational Practices. For each strategy, specific energy-efficiency measures and solutions towards environmental impact reduction are further pinpointed. In most cases, "green-gold" measures emerge as the most appealing, entailing environmental and economic benefits at the same time. Finally, for each measure the relationship with their primary impacts is discussed.
Originality/value – From an academic viewpoint, the framework fills a major gap in the scientific literature since, for the first time, it elaborates the concept of green warehousing as a result of energy-efficiency measures and solutions towards environmental impact reduction. A classification of the main areas of intervention ("green strategies") is proposed by adopting a holistic approach. From a managerial perspective, the paper addresses a compelling need of practitioners – e.g., Logistics Service Providers (LSPs), manufacturers, and retailers – for practices and solutions towards greener warehousing processes to increase energy efficiency and decrease the environmental impact of their logistics facilities. In this sense, the proposed framework can provide valuable support for logistics managers who are about to approach the challenge of turning their warehouses into greener nodes of their supply chains.

Keywords: Green warehousing; Systematic Literature Review; environmental sustainability; Motivations; Barriers.

Paper type: Conceptual framework

1. Introduction

Traditionally, logistics activities have been mostly focused on balancing efficiency, expressed in terms of cost reduction, and effectiveness, measured through service level optimisation and improvement. Within the entire supply chain, warehouses have been acknowledged as key components (Rai et al., 2011), accounting for about 20% of logistics costs (Ross and Pregner 2011; Dhooma and Baker, 2012) and having a direct impact on the service level companies can provide to customers (Liu et al., 2010). However, in the last decade also the environmental sustainability of logistics facilities and warehousing operations has been called into question, bringing further complexity and increased challenges to the logistics industry.

Multiple factors are behind this trend. On the one hand, more demanding regulatory pressures and growing recommendations are coming from national governments, as well as international organizations. This is strictly related to the growing concerns over the limitation of resources, global warming, and greenhouse gas (GHG) emissions. If we look at logistics and transport activities, according to the World Economic Forum (2016), they account for 13% of the overall GHG emissions worldwide, out of which 11% is related to logistics sites. Besides, increasing pressures from a variety of stakeholders, such as investors, consumers, media, and the entire society, are making sustainability one of the key drivers in logistics decision-making processes (Dobers et al. 2019; Perotti et al., 2022). This is also the case of logistics sites, whose sustainability is strictly related to the efficiency of resources and materials employed. While the ISO standard 14083 released in March 2023 now provides managers with a globally aligned framework for quantifying GHG emissions of transport and hub operations, companies so far have had to rely on various standards aiming at certifying their environmental performance, and had to struggle with a rising range of measures to be embraced at their logistics facilities to improve their energy efficiency (i.e., consumption reduction and related costs) and decrease related emissions.

As such, both logistics managers and technology providers have started looking for innovative energy-efficiency measures and solutions towards environmental impact reduction to be applied to their warehousing facilities to enhance not only the economic but also their environmental performance (Wehner et al., 2020). Growing investments have recently characterised the logistics real estate industry, with particular reference to green building projects and installation of utilities – such as photovoltaic panels on the rooftop – that could reduce energy consumption while mitigating the environmental performance of the building (Perotti et al., 2023). Moreover, digital technologies and energy-efficient systems have been progressively widespread, such as LED lighting and light sensors, lithium-ion batteries for material handling equipment, and fast chargers (Rai et al., 2012; Rajput, et al., 2020). Greener operational practices, as well as packaging consumption monitoring and waste reduction, have also increased, and several related solutions have become common (Das et al., 2023).

From an academic perspective, the literature dealing with sustainability at logistics sites has recently boosted (Ries et al., 2017; Agyabeng-Mensah et al., 2020). Indeed, the focus of logistics scientific literature over the last decade has primarily been on analyzing and mitigating the impact of transport activities and related green strategies, leaving environmental sustainability in warehousing largely overlooked (Tappia et al., 2015). However, a shift in this trend seems to be emerging, and sustainable warehousing is now starting to receive growing attention from both researchers and practitioners. Still, the academic literature on this topic appears to be still underdeveloped. Although papers that qualitatively describe green warehousing solutions have started to appear, no clear view has been presented so far on how to behave to achieve higher energy-efficiency and a lower environmental impact at logistics sites, nor the impacts related to the individual measures available. Also, motivations and barriers of such solutions haven’t deserved enough attention so far. However, as highlighted by Sukjit and Vanichchinchai (2020), "adoption of green warehousing requires motivations. However, motivations for green warehouse still receive little attention" (p. 539).

This paper aims to fill this gap. Based on a Systematic Literature Review (SLR) approach (Tranfield et al., 2003), it offers a framework of energy-efficiency measures and solutions towards environmental impact reduction that can be implemented to improve environmental sustainability at logistics sites. The environmental and economic impacts of such measures are specifically investigated, as well as the main motivations and barriers that could influence their adoption. The study is also intended to pinpoint the major research gaps, thus paving the way for future directions of investigation in this field. According to the objectives of this paper, three research questions (RQs) have been introduced:

- **RQ1.** What are the energy-efficiency measures and the solutions towards environmental impact reduction that can be implemented at logistics sites?
- **RQ2.** What are the economic and environmental impacts of such measures and solutions?
- **RQ3.** What are the main motivations and barriers that influence the companies' adoption of energy-efficiency measures and solutions towards environmental impact reduction at their warehouses?

In order to address these questions and to present the discussion in a structured way, the Systematic Literature Review methodology has been applied, since it has been identified as an effective way to discuss gaps in the existing scientific literature (Tranfield et al., 2003) and to synthesize the results of previous literature in a systematic, reproducible and transparent way to support theory building (Seuring et al., 2021; Snyder, 2019). The contribution offered by this study can be viewed as theory-building. As discussed by Seuring et al. (2021) and Kovacs and Spens (2005), this approach to literature review follows a deductive-abductive approach, and it will be applied in this study to allow a comprehensive analysis of green warehousing and the development of a framework of green strategies and energy-efficiency measures for improving the environmental sustainability at logistics sites, which is currently lacking in the existing warehousing literature. According to Choi and Wacker (2011), theory building is a crucial aspect of research that facilitates the advancement of a field over time. Additionally, theory-building approaches have been found to enhance our understanding of a specific subject, aiding in redefining concepts that were previously not clearly or extensively explained in the literature (Wacker, 2008). Our research not only improves the theoretical understanding of green warehousing but also offers insights for professionals to improve the environmental sustainability of logistics sites. Thus, our study significantly contributes to the development of middle-range theory in the field of green warehousing. Middle-range theory serves as a vital link between academic research and practical applications to explain and comprehend phenomena within specific contexts (Swanson et al., 2020). In an emerging field such as green warehousing, a rising number of contributions related to energy efficiency measures and solutions towards environmental impact reduction have appeared (Agyabeng-Mensah et al., 2020), but they are scattered. Therefore, it is particularly important to provide a comprehensive literature review to explore concepts and the relationships among them, to identify the key elements that facilitate a transition towards enhanced environmental sustainability at logistics sites from both a theoretical and practical perspective.

The remainder of the paper is structured as follows. The literature background is presented in Section 2. Section 3 illustrates the methodology adopted, while Section 4 provides descriptive information about the papers examined during the SLR phase. A critical discussion of the proposed framework is then offered, and the main research gaps are highlighted. Finally, the main conclusions are pointed out, and future research directions are outlined.

2. Literature Background

Green warehousing has been defined as “a managerial concept integrating and implementing environmentally friendly operations with the objective of minimizing energy consumption, energy cost and GHG emissions of warehouses” (Bartolini et al., 2019, p. 243). Specifically, GHG emissions and energy efficiency – which in turn involves consumption and related cost reduction – are seen as key elements when approaching the challenge of improving the environmental performance at a logistics facility (Dobers et al., 2022). Other broader definitions of sustainable warehousing have also been proposed, thus incorporating also the social perspective accordingly with the Triple Bottom Line (TBL) approach (Elkington, 2013). As an example, sustainable warehousing has been defined as an approach to maximising the efficiency and effectiveness of warehouse operations in such a way that the firm’s economic objectives can be reached, without a negative impact on the surrounding environment and society (Malinowska et al., 2018; Ali and Phan, 2022). Similarly, according to Tan et al., (2010) and Ishizaka et al. (2022), sustainable warehousing is about integrating, balancing and managing the economic, environmental and social inputs and outputs of the warehouse operations.

Focusing on the environmental side of sustainability, contributions have recently begun to emerge on the topic of green warehousing, on either the assessment of warehouse-related energy consumption and emissions (Ries et al., 2017) or on the motivations and barriers influencing the adoption of green warehousing practices (Wahab et al., 2018). The academic community has also started to perceive the need for structuring extant knowledge and setting clear directions for future works. Accordingly, a first literature review addressing this topic has been found (Bartolini et al., 2019). The authors provide a review and bibliometric analysis of the state of knowledge regarding green warehouse management, the environmental impact of warehouse buildings, sustainability indicators, environmental certification guidelines and energy-saving issues in warehousing. Although that review could be viewed as a valuable seminal work, no comprehensive framework was offered for categorising the strategies and energy-efficiency measures for reducing the environmental impact of warehouses, nor the related impacts, benefits and barriers. They offered a broad discussion on three macro-themes, namely green warehouse management, environmental impact of warehouse building, and energy saving in warehousing. However, no detailed overview was offered on the plethora of practices and green strategies that can be implemented to improve environmental sustainability at logistics sites. Specifically, we highlighted a lack of a comprehensive classification of the energy-efficiency measures that can be practically leveraged by logistics managers to support their decision-making process when it comes to greening their logistics facilities. This opens promising streams for further conceptualisation, as the industry is currently looking for guidance on how to transition towards net-zero warehouses and related operations, what roadmap to embrace, and which energy-efficient measures to define (Perotti et al., 2013). It should also be noted that, the interesting review by Bartolini et al. (2019) does not include some relevant literature published from 2020 onwards, and this prevents the study from capturing the recent evolution of the topic. Finally, it should also be acknowledged that some researchers have also begun to address specific aspects of green warehousing. As an example, Füchtenhans et al. (2021) proposed a systematic literature review to analyse the state-of-knowledge of technologies and applications for smart lighting systems. Different technical systems were discussed (e.g. ranging from LED lighting to light sensors) together with their application areas, including but not restricted to warehousing. Nevertheless, that review focused on a specific subset of energy-efficiency measures referred to the lighting domain, without offering a holistic representation of warehousing environments. As a result, opportunities for new research efforts in this direction are still open and the need for an updated conceptual contribution based on a thorough academic literature review clearly emerges. As mentioned, the contribution offered by this study can be viewed as theory-building. Following the inductive approach discussed by Seuring et al. (2021), we contribute to theory building by synthesizing and organising existing contributions to generate new insights and understanding about green warehousing. This is particularly important in emerging fields or areas of study where there is a lack of established theory, as it happens in the case of green warehousing. As explained in the methodology section, the inductive approach followed for this literature review starts with a broad overview of the literature to identify patterns and emerging themes. By synthesizing and organising existing contributions based on these patterns and themes, our literature review proposes a comprehensive framework of green strategies and energy-efficiency measures for green logistics, along with key elements (i.e. motivations, barriers, performance assessment and monitoring, and impact) that can support the understanding of this topic and contribute to the advancement of knowledge and practice for improving the environmental sustainability at logistics sites.

3. Methodology

The framework was developed starting from the results of a Systematic Literature Review (SLR). Literature reviews aim at synthesizing research results, capturing trends in the scientific literature and detecting promising research directions for future investigation. Among the different methodologies, the SLR has been recognised as appropriate to achieve the objective of this study, because it is the most effective method to logically explore the state-of-the-art and advance the existing scientific knowledge around a topic (Tranfield et al., 2003). SLR can be defined as a process of "a systematic, explicit, and reproducible design for identifying, evaluating, and interpreting the existing body of completed and recorded work produced by researchers, scholars and practitioners" (Fink, 2019, p. 6). It is, therefore, a valuable methodology for developing propositions and discussing future research implications (Carter and Rogers, 2008). Furthermore, this methodology has been increasingly recommended to identify, collect and classify related studies in a more structured, nuanced and reproducible way (Rhoades, 2011). All these elements acquire even more importance with reference to warehouse environmental sustainability, as it is a fairly new branch of research and the need for summarizing the available studies and promoting replicable knowledge is fundamental to facilitate further investigation in this arena. As highlighted by Lagorio et al. (2016), the SLR method has already been widely used to consolidate emerging topics in other areas in the field of sustainability and supply chain management.

To reduce bias during research and ensure replicability, this study followed the guidelines set out by Denyer and Tranfield (2009). The SLR has been carried out following a five-step methodology, as illustrated in Figure 1, by adapting the steps proposed by Denyer and Tranfield (2009). These phases are described in detail in the following sub-sections.

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Scope of the analysis

In this paper, "green warehousing" is studied. The increasing attention from media, governments, and customers to green and sustainable paradigms pushes companies to invest in energy-efficient solutions to improve their green performance and customer satisfaction while reducing their operating costs. Warehouses have often been neglected in the past, but nowadays, managers have become more aware of the importance of this critical area. Hence green-related projects have been intensified. In line with the research questions presented in the Introduction, it is essential to understand the strategies and energy-efficiency measures that can be used by company managers to enhance the environmental performance of their warehouses, and related characteristics, benefits, and hurdles. Since the budget dedicated to the green warehousing project is often limited, it is important to design the most suitable combination of strategies and energy-efficiency measures to achieve the highest performance while balancing the constraints.

Locating papers

At this stage, the purpose was to search through relevant papers to create a comprehensive list of core contributions pertinent to the review questions (Denyer and Tranfield, 2009). The Scopus database was chosen to identify research papers, as it has some of the largest and most reliable business research repositories (Crossan et al., 2010) and it is often used in SLRs (Seuring et al., 2021). A set of keywords have been defined and used in the search engine.

The set of keywords, summarized in Table 1, was generated relying on readings of past literature and the authors' experience in the field of logistics. In order to identify articles related to energy efficiency measures and solutions towards environmental impact reduction adopted in green warehousing, the keywords have been grouped into three clusters, combining warehousing, environmental sustainability, and decision-making perspectives. This stage led to 1,390 results. While the search string of keywords may appear too broad and result in irrelevant findings, we deliberately chose to maintain a broad scope. In the literature on green warehousing, articles often refer to various related fields (such as energy), but valuable insights can still be gleaned. To reduce the risk of missing relevant articles, we decided to employ a broad search string of keywords and then carry out a thorough process of paper selection and evaluation, as explained in the following subsection.

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Paper selection and evaluation

This phase aimed to ensure a thorough selection of the papers as the basis of the subsequent critical analysis. Three stages have been considered, namely screening, eligibility based on inclusion and exclusion criteria, and final inclusion based on a careful reading of each document.

In the screening phase, two criteria were considered. First, papers had to be written in English, as it is the main adopted and formally approved international language for publications in the supply chain management and logistics fields (Colicchia et al., 2019). Second, to ensure high quality works had to be published in peer-reviewed international journals or conference proceedings indexed in Scopus. For these reasons, contributions from grey literature such as technical reports and secondary sources were excluded. After the screening phase, 1,060 potential papers remained in the list. During the eligibility phase, a set of inclusion and exclusion criteria, related to the content of the papers has been identified (Table I) to select only relevant publications:

- The included papers had to be focused on energy efficiency measures and solutions towards environmental impact reduction adopted in warehouses. The papers investigating these topics from a different perspective (for example, adopting a supply chain perspective), or that are related to other types of buildings, have been excluded.
- From a sustainability perspective, the papers had to address the theme of environmental sustainability and energy efficiency.
- Older papers were included only if considered as milestones and in case the measures discussed were not obsolete.

Such criteria have been checked through a careful examination of the abstracts and, in case of ambiguity, the decision has been taken after an examination of the full text. To avoid any kind of subjectivity or bias, this step was executed by two researchers independently. The result was a total database of 54 academic papers published either in peer-reviewed journals or conference proceedings. Finally, as suggested by Marchet et al. (2014) and remarked by Hohenstein et al. (2015), we also went back to other papers by cross-referencing in order to include potential papers that were not picked in the above-mentioned databases. This results in a final sample of 60 papers.

4. Descriptive analysis

Each selected publication has been classified according to:

- General characteristics: author(s), year of publication, source title, and first author's affiliation.
- Methodology adopted: as per Seuring and Muller (2008), five research methodology have been distinguished, namely "Conceptual framework", "Analytical model", "Case study", "Literature review" and "Survey".
- Themes addressed: in performing the paper evaluation and analysis, we aimed at rationalising and systematising the existing contributions on the topic under investigation. The papers were classified through thematic analysis (Vaismoradi, Turunen, and Bondas (2013), according to a deductive-abductive approach (Seuring and Muller, 2008). The first step was to carefully read the papers. Consistently with the review questions, and according to a deductive approach, we particularly focused on the thematic categories defined in the previous pages, i.e., energy-efficiency measures and solutions towards environmental impact reduction for green warehousing, their economic and environmental impacts, the main motivations, and barriers that influence their adoption. The specific elements for each of these categories were identified according to an abductive approach. For this qualitative data analysis, we followed the steps proposed by Gioia et al. (2013). Initially, we conducted the primary data coding, emphasizing the key elements presented in the papers. During this phase, our aim was to faithfully adhere to the terminology used in the selected papers. As the evaluation process progressed, we looked for commonalities and patterns among the terms employed in the papers. These findings served as the foundation for organizing the terms into categories and constructing a "data structure," which forms the final framework for our study. Both authors actively participated in this process, engaging in discussions to address any discrepancies or differences in opinions. We iteratively analysed and interpreted the papers until reaching a consensus. In instances where there was disagreement in data coding, we revisited the data, engaged in mutual discussions, and developed shared understandings to arrive at consensual interpretations. This research process employed abductive reasoning because we were not completely unaware of previous work while analysing papers; instead we had preconceived notions and theoretical knowledge about the field under investigation. In line with this approach, we intentionally chose to be ignorant of previous theories in the field of interest, rather than simply lacking awareness, to find the right balance between our existing knowledge and areas where we lacked knowledge (Gioia et al., 2013). This balance was crucial in facilitating discovery without unnecessarily reinventing established concepts (Kovacs and Spens, 2005).

Table II summarises the content and features of each paper. According to Melacini et al. (2018) the papers are listed in chronological order to show the evolution of the topic over time.

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The examined papers were published between 2008 and 2022 in 41 different international journals and 11 conference proceedings. The main focus is on industrial management or energy area. It is interesting to remark that very few journals are supply chain management- or logistics- based. Instead, many contributions have been found in energy-related journals, as well as conference proceedings, thus indicating that green warehousing is still an emerging topic that sector-specific journals have not adequately addressed.

Looking the distribution of the examined paper over time, a mounting interest in the topic of green warehousing has been detected, with 27 papers published from 2019 onwards (i.e., 45% of the examined sample). This further corroborates the need for systematizing and conceptualising the available knowledge to guide future studies in the field.

As far as the first author's affiliations, 34 papers refer to European countries – e.g., Italy (12), Germany (4), UK (4), Turkey (4) – that overall constitute more than half of the sample (57%). Asia accounts for 18 contributions – being China (4) and Malaysia (3) with the highest number of contributions – and USA for 4. Regarding the method (Figure 2), the selected papers are based on empirical studies – either case studies/interviews (21) or surveys (7) – but also analytical models (20), conceptual contributions (5) and literature review (5) are quite common. Looking at the evolution of the topic over time, as per Melacini et al. (2018), strategies and energy-efficiency measures to improve warehouse environmental sustainability (RQ1) and related economic and environmental impacts (RQ2) have been found since 2008, and mostly from 2011 onwards. If earlier papers tend to be conceptual in nature or provide some initial case studies on green warehousing measures and related impact computation, recent contributions, i.e., from 2020 onwards, seem to have evolved to include a greater emphasis on practical solutions for reducing energy consumption (e.g., smart energy charging, material handling energy consumption optimisation). Motivations and barriers influencing companies' adoption (RQ3) seem to be a more recent area of investigation, and contributions addressing these issues have been found mostly after 2015. It is interesting to note that early papers were conceptual in nature, whereas after 2019, all the examined papers are either case study/interview- or survey-based, with one analytical model being found. This highlights the rising interest in empirical research on the topic.

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5. Results and framework development

A critical analysis of the selected papers is hereinafter presented by structuring the findings according to the three RQs previously defined.

RQ1: What are the strategies and energy-efficiency measures to improve warehouse environmental sustainability?

Table III reports 23 warehouse energy-efficiency measures that have been identified and classified into six green strategies: Green Building, Utilities, Lighting, Material Handling and Automation, Materials, and Operational Practices. The majority of studies focused on Green Building, Utilities, and Lighting, with particular attention to energy-efficiency measures such as photovoltaic panels, thermal insulation, use of natural lighting and white walls, packaging reuse and recycling. It should be noted that other promising technologies that have started receiving growing attention from the industry, such as high-frequency battery charging and sensors for consumption reduction – within Material Handling strategies – or solar tubes – within Lighting – have not been found in the examined sample.

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Green building

Rai et al. (2011) highlighted that warehouse building is one factor that mostly contributes to the consumption of energy and natural resources. A number of key energy-efficiency measures have been identified in the examined literature to improve the environmental performance of a logistics building. First, the design and construction of a facility with materials and shapes allow for wise use of energy and minimise heat dispersion through walls and roof thanks to proper thermal insulation (Rai et al., 2011; Mostafaeipour, 2014). Great importance is given to the type of roof used – with solutions such as cool roofs and green roofs – as it is the surface most subject to heat sources (Sailor and Vuppuluri, 2013). Besides, the use of loading docks with insulated doors (Sarabia Escriva et al., 2020) can minimise dispersions and energy losses, especially in logistics facilities handling chilled or frozen goods.

Second, the exploitation of natural daylight and lighting controls reduces the use of artificial lights and related electrical energy required (Cook et al., 2011). Third, the joint use of selective glazing minimises heat transfer, maximises daylight and decreases the amount of energy needed for cooling (Cook et al., 2011), thanks to the higher thermal resistance of glazing materials and their ability to mitigate solar heat gains while allowing diffuse daylight to penetrate. Finally, a combination of passive design strategies can be helpful during the design and construction phases to achieve controlled environmental conditions with zero energy consumption. To obtain such conditions, the design of the constructive elements should be functional to control factors such as air stratification, ventilation, and thermal inertia of the floor and walls (Osorio et al., 2022). Depending on the specific building requirements, a fundamental element for successfully achieving high environmental performance seems to be the integration and harmonisation of such solutions within a comprehensive plan to impact the building's overall energy demand from different perspectives. Hence, creativity in the logistics building design is a key step in achieving sustainable buildings with less energy consumption (Mostafaeipour et al., 2014).

Utilities

Reducing warehousing demand for electrical energy and fuels involves the adoption of utilities that can help make the company's business more economically and environmentally sustainable. In the examined literature, four systems have explicitly been called into question, namely photovoltaic panels for self-production (Meneghetti et al., 2018; Pamungkas et al., 2019), intelligent HVAC systems (Pratt et al., 2017), liquid air energy storage (Foster et al., 2018), and thermosiphon based seasonal cold storage (Li et al., 2020). As heating, ventilation, and air-cooling operations are among the most energy-consuming in a warehouse (Bartolini et al., 2019), most of the aforementioned energy-efficiency measures can be used to mitigate this impact. It should be noted that today these solutions have become mature and able to overcome the barriers that prevented their adoption in the past (Molleti et al., 2021). Besides, their efficiency is rapidly increasing and can provide even more opportunities for greening warehouses. For instance, today the surplus of liquid air or liquid hydrogen contained in liquid air energy storage systems could be used to charge automobiles or *ad hoc* engine propulsion (Foster et al., 2018). Another example is provided by smart HVAC systems, which are no more merely reactive, but predictive and adaptive. Hence, they can reduce operating costs, CO2e emissions and energy consumption in every moment and with a higher proficiency if compared to the conventional ones (Oswiecinska et al., 2015).

Lighting

As lighting is considered one of the main drivers for energy consumption in warehouses (Ries et al., 2017), managers often consider taking initiatives in this area first (Bartolini et al., 2019), also because such initiatives are usually among the cheapest and most effortless when compared to other methods to increase energy efficiency (Perdhaci et al., 2018). Many contributions have been found in the examined literature, and this subject appears to be quite consolidated. The attention has been mainly paid to LED lighting and sensors for reducing lighting consumption (Füchtenhans et al. 2021), together with the use of natural lighting and white walls (Lapisa et al., 2020). Such solutions not only significantly concur to a steady reduction in terms of energy consumption at the site, but also lead to a decrease in lighting-related emissions.

Material handling and automation

Looking at forklifts, considerations on both fuels used and batteries have emerged in this arena. Specifically, three main solutions have been discussed: Lithium-Ion Battery (LIB) forklifts, hydrogen-powered fuel cell forklifts, and fuel cell/battery hybrid forklifts. Although Lead Acid Batteries (LAB) are still the most common in material handling applications, research indicates that lithium-ion technology could bring significant benefits, also in terms of energy efficiency (AlShaebi et al., 2017) and related emissions generated. Besides, hydrogen fuel cells have been acknowledged as a promising choice due to their cleanliness, safety, sustainability, and high efficiency (Martin et al., 2013). Finally, fuel cell/battery hybrid forklifts are relatively new, and the aim is to achieve superior performances by combining the best characteristics of hydrogen fuel cells and pure fuel cell. However, being still in its infancy, and requiring a dedicated energy management strategy to be configured *ad hoc* on the forklift, further research is still encouraged in this field (You et al., 2018).

Another key element being discussed is related to electric vehicles and the trade-off between battery autonomy and charging time. For instance, a possibility that has recently been explored is the adoption of a contactless electrical energy transmission system based on the magnetic coupling between coils installed under the ground level and a coil mounted under the vehicle floor (Faveto et al., 2022). As far as Automated Storage and Retrieval Systems (AS/RS) are concerned, the relationship between warehouse automation and its environmental implications has started to be examined. Multiple interesting elements have been investigated, such as the investigation of the trade-off between the environmental and economic dimensions when selecting warehousing technologies (Tappia et al., 2015) or the energy usage related to crane movements considering different rack shapes (Meneghetti and Monti, 2015). The energy-efficiency performance of different automated systems has been considered, such as mini-load AS/RS (Lerher et al., 2014) or Autonomous Vehicle Storage and Retrieval System (AVS/RS) with totes as the handling unit (Tappia et al., 2015). At any rate, it should be noted that operating conditions, working requirements, and warehousing environment are crucial elements to be carefully taken into account for successfully selecting the most appropriate solution for material handling, since a specific technology can be impossible to be adopted in some conditions, while favourable in others (You et al., 2018).

Materials

Packaging reduction and packaging reuse and recycling have been detected as the main practices concerning materials management (Karia et al., 2013). According to Agyabeng-Mensah et al. (2020), green packaging involves the use of green materials, cooperation with sellers to ensure standardisation, reduction of both material usage and unpacking time, adoption of returnable packaging methods, and promotion of recycling and reuse programs. All these alternatives are viable and equally important since useless packaging increases waste disposal, unnecessary production, transport costs, and increases pollution (Karia et al., 2013). Viable solutions could involve reshaping the existing packaging by eliminating unnecessary elements or avoiding materials that negatively influence the environment, or present criticalities during their disposal.

Operational practices

Operational practices – i.e., supporting material handling, storage, picking processes, and other value-added services performed within the warehouse – can be viewed as a valuable way to minimising energy consumption and related emissions. Since it is estimated that 55% of the total energy for warehousing activities comes from order-picking activities (Boenzi et al., 2016), many practices found are in this sense. The two main categories of measures identified are travel distance optimisation (Burinskiene et al., 2018) and optimal scheduling of material handling activities and battery charging (Carli et al., 2020a).

As for the first (i.e., travel distance optimisation), Ene et al. (2016) developed a genetic algorithm designed to provide effective order batching and routing in warehouses considering the minimization of energy consumption. Burinskiene et al. (2018) proposed a similar method, but using the Djikstra algorithm, while Boenzi et al. (2016) integrated into a single non-linear integer programming model simulation both the engine type of the forklift and the possible paths.

Regarding the second (i.e., optimal scheduling of material handling activities and battery charging), various models have been found. Two of them (Carli et al., 2020a; Carli et al., 2020b). identified an optimal schedule of material handling activities of a fleet of electric forklifts to minimize the total electricity cost for charging their batteries, while ensuring that jobs are executed in accordance with priority queuing and that the completion time of battery recharging is minimised. Another paper related to the optimization of the forklifts schedule was the one proposed by Stankovic et al. (2022). The authors studied a truck-to-gate assignment problem during warehousing docking door operations, where the objective was to minimize energy consumption. The problem was managed as a resource allocation problem, and solved using a linear programming model. A different approach, based on both the optimization of the travel distance and the battery charging time was adopted by Lee et al. (2022), who formulated a dynamic control algorithm for the electric forklift routing problem with battery charging. In this research, both the operational performance of the electric forklift (i.e., total travel distance and idle time for battery replacement) and the energy performance (i.e., energy cost) were considered. Finally, Yang et al. (2022) developed a multi-objective optimization model aimed at simultaneously minimizing the travel time and the energy consumption of a multi-shuttle AS/RS by finding an efficient storage/retrieval location assignment and scheduling solution to perform the requests.

RQ2: What is their economic and environmental impact?

Table IV summarises the main economic and environmental impacts related to the strategies and energy-efficiency measures for improving warehouse environmental sustainability that emerged from the SLR. While the decrease in GHG emissions seems to emerge as the main environmental benefit, economic implications have also been highlighted. These latter have been split into four different types, related to: reduction of energy consumption (Sarabia Escriva et al., 2020; Li et al., 2020; Lapisa et al., 2020), reduction of heating load (Rai et al., 2011; Foster et al., 2018), reduction of electrical peak demand (Molleti et al., 2021) and increase in profitability (Mostafaeipour et al., 2014). The quantification of such impacts needs to be assessed with reference to a specific context, as they strictly depend not only on the features of the individual solution implemented but also on the warehouse characteristics (Rai et al., 2011). For instance, the impact deriving from the implementation of photovoltaic panels can differ considerably according to numerous factors such as site location (e.g., daylight, weather conditions) (Saikovski 2017; Meneghetti 2018; Pamungkas et al., 2019)

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Looking at Green Building, it was the only green strategy where all the above-mentioned impacts were highlighted. In particular, thermal insulation in warehouses reduces energy consumption (Agyabeng-Mensah et al., 2020) and increases profitability. This happens because insulation improves the building's thermal transmittance and decreases the heating load considerably (Rai et al., 2011). A reduction in operational load is directly linked to lower energy consumption and a lower carbon footprint (Cook et al., 2011). Similarly, loading docks with insulated doors are the cheapest and most effective way to solve the issue of air leakage during loading/unloading activities, thus they reduce the heating load of the warehouse, mitigate consumption and CO2 emissions (Sarabia Escriva et al., 2020). Cool roof, green roof and wind catchers have been demonstrated to be useful in reducing the cool energy demand, as well as the carbon emissions (Sailor and Vuppuluri, 2013; Mostafaeipour et al., 2014; Seihshemi et al., 2018). Selective glazing can interfere with the incoming daylight with different power, allowing its ingress in a room, but mitigating its heating (Cook et al., 2011).

As far as Utilities are concerned, they have been demonstrated as particularly useful in addressing warehouse energy consumption and heating. For instance, this is the case of intelligent HVAC systems that can reduce operating costs, CO2e emissions, and energy consumption (Oswiecinska et al., 2015). Looking at liquid air energy storage, it helps reduce carbon footprint by decreasing and shifting energy peak loads. Moreover, Dearman (2015) underlined that a surplus of liquid air or liquid hydrogen could be used to charge vehicles or *ad hoc* engine propulsion. Finally, completely passive thermosiphon-based seasonal cold storage can substitute a traditional refrigerate warehouse, thus allowing huge power and operational cost savings, and potentially eliminating a significant amount of greenhouse gas emissions that in conventional storage are caused by electricity consumption (Li et al., 2020).

Impacts related to Lighting strategies are chiefly focused on electric energy consumption reduction by means of both exploiting natural daylight (Pratt et al., 2017; Lapisa et al., 2020) and optimising artificial lighting (Cook et al., 2011; Perdhaci et al., 2018). Regarding the first aspect (natural daylight), several authors agreed that a key element is the correct sizing of the roof light ratio, as excess will bring thermal and temperature discomfort for workers (Rai et al., 2011). As far as the second aspect (artificial lighting) is concerned, the efficiency of LED lamps has been widely acknowledged (Perdhaci et al., 2018), together with sensors for reducing lighting consumption (Cook et al., 2011; Pratt et al., 2017). Indeed, sensors may allow to automatically turn on/off or dim the level of light according to the presence of workers in a room or a section of the warehouse.

Impacts related to Material Handling and Automation mostly refer to forklifts in terms of batteries or fuels, or else AS/RS. In the case of forklifts, papers usually compare different technologies with the base case of conventional LAB. A significant reduction in energy consumption and/or lower GHG emissions has been commonly highlighted (Martin et al., 2013; Al-Shaebi et al., 2017). Among the technologies under study, LIB forklifts have been attested as particularly promising due to multiple reasons. Indeed, LIB has the characteristic of being charged while being in the truck, so no battery replacement processes are needed, differently compared to LAB (Al-Shaebi et al., 2017). Second, the usable energy from LIB is higher, hence higher productivity is reached. Finally, the heat generated by LIB is only half compared to the one generated by a LAB. The reason comes from the internal resistance of lithium-ion, which is lower than the

LAB one (Al-Shaebi et al., 2017). Also, hydrogen-powered fuel cell forklifts have been highlighted as promising. It has been proved that GHG emissions are comparable to one of the battery-electric vehicles but with another potential further reduction of 10% depending on the expected lifetime of the battery (Martin et al., 2013).

Looking at Materials, no specific contributions have been found discussing economic or environmental benefits. However, it is undeniable that reducing or reusing packaging leads to increased warehouse sustainability (Agyabeng-Mensah et al., 2020). The simple reduction of paper is fundamental for a better environment (Minashkina and Happonen, 2020).

Finally, among Operational Strategies, innovative algorithms are emerging leading to economic and environmental performance improvement. For example, according to Boenzi et al. (2016), conventional travel distance optimisation practices can be further improved by means of a joint evaluation of the features and power source of the forklifts being adopted, together with other energetic aspects related to material handling activities (e.g., daily profile and peaks or other organisational patterns). Besides economic savings, even NOx and CO2 produced can be calculated and minimised (Burinskiene et al., 2018). Another interesting algorithm is the one developed by Carli et al. (2020b), intending to optimize the scheduling for electric forklifts by minimising the total electricity cost for charging batteries, while ensuring that jobs are executed following priority queuing and that the completion time of the battery recharging is minimized. The economic advantage is obtained using the minimisation of the electricity cost and can be further amplified by adopting on-line control systems for smart energy consumption.

RQ3: What are the main motivations and barriers that influence the companies' adoption of green strategies and energy-efficiency measures in their warehouses?

Only a few examined contributions explicitly investigated the decision-making process behind the adoption of green strategies and energy-efficiency measures for improving warehouse environmental sustainability. For instance, some interesting surveys were found targeting logistics managers to understand motivations and barriers in their specific companies. However, these studies were geographically limited – such as the one by Salhieh and Abushaikha (2016) that investigated the United Arab Emirates' logistics service industry, or the one by Goh (2019), focused on Asia, or else the one by Sukjit and Vanichchinchai (2020) in Thailand – or limited to few specific companies (e.g., Xin et al., 2019; Wahab et al., 2018).

Looking at motivating factors that can push a company to undertake green warehousing processes, six main elements have been identified, namely pressure from government and regulations, pressures from customers and suppliers, industry competition, top management commitment, and employee involvement.

In particular, as far as *government pressure and regulations* are concerned, new stricter regulations may oblige companies to adapt to new greener scenarios (Salhieh and Abushaikha, 2016; Kaur et al., 2018; Wahab et al., 2018; Goh, 2019; Minashkina and Happonen, 2020; Sujkit et al., 2020).

Second, customers' awareness (*customers' pressure*) and expectations about sustainability are increasing at a rapid pace; hence companies are forced to adapt (Salhieh and Abushaikha, 2016; Kaur et al., 2018; Wahab et al., 2018; Goh, 2019; Minashkina and Happonen, 2020; Sujkit et al., 2020). Besides, suppliers with a high bargaining power may force their customers to adapt to new sustainable processes that they have implemented in their company, asking them to replicate their model (*suppliers' pressure*). If the supplier is key and cannot be lost, companies usually accept the new condition (Wahab et al., 2018). *Industry competition* is another motivating factor, as key when healthy competition is present in a sector, firms can pursue to gain competitive advantage through sustainability (Wahab et al., 2018; Kaur et al., 2018; Sujkit et al., 2020).

Finally, *top management commitment* emerges as fundamental: positive attitudes, clear visions, authoritative leaderships, precise strategic intents, and profound commitment are mandatory for top managerial personnel to implement green warehousing practices (Wahab et al., 2018; Sujkit et al., 2020). However, a strong commitment among managers is not sufficient to effectively implement energy-efficient changes within warehouses, and *employee involvement* is also a key component. Indeed, if not adequately involved, workers can represent the phenomenon of resistance (Wahab et al., 2018; Goh et al., 2019; Sujkit et al., 2020; Gruchmann et al., 2021).

Focusing on the main barriers to the adoption, 9 different elements have emerged. They include cost, complexity, communication, knowledge and capabilities, government pressure and regulations, pressures from suppliers and customers, technological hurdles, and lack of a strategic approach to sustainability or scarce internal commitment. A detailed discussion is hereinafter provided for each factor identified:

- *Costs:* although several authors agree that embracing greener warehouse operations helps protect the environment ethically and comply with the reduction of operational costs in the long run (Salhieh and Abushaikha, 2016; Minashkina and Happonen, 2020), there is still a mental bias that brings logistics operators thinking that environmental sustainability is just a source of additional costs rather than a strategic opportunity for differentiating their businesses (Goh, 2019). According to the survey by Kaur et al. (2018), besides investment costs, managers are scared by the potential costs of environmentally friendly packaging, hazardous waste disposal, and the expenses of switching to new systems.
- *Complexity:* the literature suggests that the introduction of sustainability initiatives may add levels of complexity in organisations (Goh, 2019; Gruchmann et al., 2021). Implementation can be challenging, and sustainable practices need time and effort to be diffused within a company and among all supply chain players that have to adapt to sustainable standards or performance criteria.
- *Communication:* insufficient or missing communication is a typical barrier (Kaur et al., 2018; Goh, 2019; Gruchmann et al., 2021). In this sense, meetings and consultations among employees seem to be critical drivers for receiving feedback and preventing whatever form of resistance (Seuring and Muller, 2008).
- *Knowledge and capabilities:* when insufficient knowledge about sustainability or related fields is widespread among company managers, no green project can be proposed (Kaur et al., 2018; Goh, 2019; Gruchmann et al., 2021). The way out entails a robust programme of education, experience, or training, to eliminate any possible form of negative prejudice (Goh et al., 2019).
- *Government pressure and regulations:* although this can also be a motivation to increase energy efficiency and environmental sustainability projects in warehousing, several authors agree that "governments through regulation can both encourage and discourage the adoption of green practices" (Salhieh and Abushaikha, 2016, p. 60). Indeed, the problem arises when there is no harmonized regulation on how to deal with non-compliance with rules (Goh, 2019). Moreover, if regulations are uncertain, companies are unwilling to take risks by adopting more sustainable practices (Goh, 2019).
- *Suppliers' pressures:* the need for facing suppliers' reluctance to collaborate in warehouse sustainability programmes may discourage companies from implementing their ideas (Minashkina and Happonen, 2020; Kaur et al., 2018). The problem is particularly relevant when the sustainable project requires sharing confidential

information or technology related to sustainable practices that are a source of competitive advantage (Goh, 2019; Kaur et al., 2018).

- *Customers' pressures:* as in the case of government pressures, also customers' pressure on the adoption of green logistics practices is significant as a motivation (Salhieh and Abushaikha, 2016). However, a lack of awareness or no clear expectations might inhibit the adoption of energy-efficient solutions (Kaur et al., 2018; Minashkina and Happonen, 2020 Goh et al., 2019; Sukjit and Vanichchinchai, 2020).
- *Technology:* companies can lack access to innovative technologies to improve their processes even if they are already available. This can make companies unable to start their green projects (Kaur et al., 2018; Goh, 2019).
- *Lack of a strategic approach to sustainability or scarce internal commitment:* sometimes companies find difficulties in transforming positive environmental attitudes into actions simply because they have no concrete plan of action to rely on (Kaur et al., 2018).

Framework development

Based on the outcome of the SLR, a framework is proposed (Figure 3) linking six main areas of intervention towards green warehousing ("green strategies") with the related impacts, motivations and barriers that could influence their adoption. The above-mentioned green strategies include a combination of:

- energy efficiency measures, i.e., chiefly aiming at consumption reduction (as well as a decrease of related costs and emissions generated);
- solutions that can be leveraged towards environmental impact reduction, i.e., mostly oriented to cut emissions generated from the warehouse and related activities.

Some of those measures and solutions can meet both aims simultaneously.

On the left-hand side of the proposed framework, the complete list of factors that have emerged from the literature review as potential motivations or barriers to adoption has been provided. Interestingly, some of those could act as either a barrier or motivation, depending on the specific case (e.g., Top management commitment). Each individual green strategy at logistics sites is then connected to the economic and/or environmental impact that have been highlighted in the examined literature. Finally, in order to properly quantify the impacts, the framework also emphasizes the need for a system for performance measuring and monitoring.

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6. Discussion and research agenda

Although green warehousing has been traditionally under-examined compared to other green supply chain management issues (Bartolini et al., 2019), to date, institutional and social pressures have concurred to highlight the urgency of focusing on such a subject. Being a fairly new branch of research – while being one of the major areas that could reduce the environmental impact of business activities (Salhieh and Abushaikha, 2016) – the related literature is still scarce although increasing and deserves adequate attention. The objective of the paper is to build upon earlier seminal studies on the topic (Bartolini et al., 2019) and further address three key areas of investigation in order to: (i) create a clear and complete classification of the strategies and energy-efficiency measures that logistics and warehouse managers can embrace to improve warehouse environmental sustainability; (ii) discuss the related main environmental impacts, as well as their economic implications; and (iii) analyse the main motivations and hurdles behind the adoption of such practices.

This study has made significant contributions to theory-building in the field of green warehousing through a deductive-abductive approach to the literature review, as recommended by Seuring et al. (2021). Given the fragmented nature of research on energy efficiency measures and solutions towards environmental impact reduction in green warehousing, a comprehensive literature review becomes essential for exploring concepts, their relationships, and identifying key elements that can facilitate a transition towards improved environmental sustainability from both theoretical and practical perspectives.

By conducting a comprehensive analysis of green warehousing, this study has developed a framework of six main areas of intervention ("green strategies") towards environmental sustainability at logistics sites. Such a framework combines energy-efficiency measures (i.e., focus on consumption – and related costs – reduction) and solutions towards environmental impact reduction (i.e., focus on emission decrease). The proposed framework can serve as a valuable resource for future research and decision-making aimed at enhancing energy efficiency and environmental sustainability at logistics sites. The proposed conceptual framework provides insights into areas of intervention, individual measures, their impacts, motivations, and critical factors, offering a solid foundation for practitioners when making informed decisions regarding environmental strategies and performance measurement in their warehouses, in alignment with the findings of Silva et al. (2022).

Through this contribution, our study not only enhances the theoretical understanding of green warehousing but also provides practical implications for practitioners in effectively managing and improving the energy efficiency and environmental sustainability of logistics sites. In this sense, our study makes a valuable contribution to middle-range theory building within the field of green warehousing. Middle-range theory, in fact, bridges the gap between academia and practice, providing a conceptual foundation to explain and understand phenomena within a well-defined context (Swanson et al., 2020).

In addition to offering a deeper understanding of the specific phenomenon under investigation, our work also provides a basis for further theoretical development and future research directions. The proposed framework has also revealed the gaps and limitations of the revised literature, therefore highlighting streams for future investigation. In the following, five main Research Recommendations (RRs) for future investigation are offered and discussed.

RR1. Validate and, potentially, extend the proposed framework of green strategies and energy-efficiency measures for improving warehouse environmental sustainability

Building upon previous investigations in the arena of sustainable warehousing (e.g., Bartolini et al., 2019), the present review offers a strong conceptualisation based on the available academic literature on the topic and opens streams for future investigation. From this viewpoint, further validation of the proposed framework also based on a practitioners' perspective could be a promising research direction. Indeed, besides the academic literature review, a thorough analysis of secondary sources (e.g., company sustainability reports, data from solution providers), as well as direct interviews with companies could be particularly beneficial to corroborate the proposed classification and list of energy-efficiency measures, or else include potential elements that have been neglected by academia so far. This recommendation seems specifically relevant also in light of the progressive technology enhancement and the advent of new solutions that can be added to the framework (Perotti et al., 2023). An updated and complete classification of green strategies and energy-efficiency measures can represent useful support to logistics managers when making decisions to improve the environmental impact of their logistics sites. As an example, recent technologies such as mobile robots (Bogue, 2016;

Varma et al., 2021) or warehousing 4.0 solutions might be further investigated also with reference to their impact on warehouse energy efficiency and, in a broader sense, on warehouse sustainability performance.

RR2. Foster empirical investigation on the adoption of green strategies and energy-efficiency measures for improving warehouse environmental sustainability

No papers were found that specifically address the level of adoption of such strategies. Instead, most contributions were focused on one or a very limited spectrum of energy-efficiency measures, without offering a holistic perspective. Promising future research directions may involve the evolution of their adoption over time to build a benchmark, In line with Perotti et al. (2023). To this extent, it could also be interesting to study the companies' prospective interest in terms of future interventions on green warehousing processes.

RR3. Encourage the development of a shared set of indicators and methodologies to compute the GHG emissions generated in warehouses and impacted by green warehousing strategies

Based on the examined sample, only a few studies provided methodologies for computing the carbon footprint produced by logistics and warehousing activities (e.g., Perotti et al., 2023), and no shared view was offered. Overall, there is a need for more reliable data to demonstrate how sustainable actions can decrease the carbon footprint and improve warehouse energy efficiency, as per Dobers et al. (2022). This could also encourage a higher awareness of these issues and – potentially – higher future investments in the sector.

RR4. Develop analytical research to investigate logistics and supply chain-wide practices, their enablers and the related environmental effects

The study of green strategies and related energy-efficiency measures within logistics sites as offered within the present paper needs to be further expanded to a supply chain level. This should involve the examination of how changes in logistics network design might impact the overall company's (or supply chain) environmental performance. Indeed, the strategic location of warehouses and the related allocation of resources to the various stages of a supply chain is of paramount importance, and brings along the threefold objective of cost minimisation, service level improvement, and CO2 emission reduction (Doolun et al., 2018). Furthermore, the sharing economy for storage services ("warehouse capacity sharing") is also emerging as a new opportunity for improving the economic and environmental impact of warehouses thanks to a better saturation of the warehouse and better assets utilisation (Feng et al., 2017; Tornese et al., 2020). Further research is needed to explore how sharing warehouse concepts and principles can be leveraged to this aim. This new paradigm requires a further investigation of the enabling technologies and specific platforms to enable companies to match supply and demand of warehouse capacity and to acquire real-time information on the requirements of companies utilising the service to quickly and efficiently meet them (Unnu and Pazour, 2019).

RR5. Promote further investigation on the relationship between the adoption of green warehousing strategies and energy-efficiency measures for improving warehouse environmental sustainability and the related social or organisational aspects

Few studies have hinted at the positive relationship between employees' productivity and the adoption of energy-efficient solutions such as natural lighting, LED lighting and light sensors (Füchtenhans et al., 2021), or green roof technologies. Still, much must be done for other solutions to clarify their social/organisational implications for warehousing and guide changes in current organisational patterns to improve warehouse sustainability by decreasing carbon emissions and promoting energy efficiency, in line with Prataviera et al. (2022).

7. Conclusions and implications

This paper aims at offering a framework of strategies and energy-efficiency measures for improving warehouse environmental sustainability based on an SLR approach (Denyer and Tranfield, 2009) of 60 scientific publications dealing with this subject. Related economic and environmental impacts have been carefully examined, and the main motivations and barriers that could influence the adoption of these green warehousing strategies have been discussed. Finally, five major RRs have been identified for further investigation in this promising research arena.

Although interesting findings emerged from this study, limitations do exist. In particular, the main limitation lies in the potential omission of relevant contributions from the review. Although the keyword structure was trialed repeatedly during its design to achieve a highly effective and feasible research space, we cannot exclude the possibility that other papers dealing with this subject do exist, but under different labels. Nevertheless, precisely because of the methodology adopted, we believe that this analysis provides an adequate representation of the state-of-the-art of literature relating to energy-efficient solutions for warehouses.

This research aims to fill a gap in a field that is receiving growing interest and has the necessity to organize the related knowledge more systematically. Results might constitute an important theoretical contribution to the topic of environmental sustainability in the green warehousing scientific literature. To the best of the Authors' knowledge, this is the first attempt at building a comprehensive framework specifically categorising green strategies and energy-efficiency measures for improving environmental sustainability at logistics sites. Researchers can use it as a starting point to focus on one or more strategies to investigate their adoption level within a business context, analysing the related benefits and critical issues associated with their implementation, or else quantitatively assessing the warehouse's environmental performance over time in terms of consumption figures – and related costs – and associated GHG emissions, as per Dobers et al. (2022). This could also be extended by means of addressing other energy-efficiency measures currently neglected by the literature. A promising area for future investigation may involve the social side of sustainability connected to the adoption of green strategies within logistics facilities, as well as its related implication. Another promising area of research, with relevant potential for practical applications, can be related to the development of models to assess alternatives of investment in (sets of) energy-efficiency measures for green warehousing, evaluate the most cost-effective option, and identify the aspects that act as hurdles or drivers that determine the convenience of an option. This particular development could represent a value for companies that are considering making investments in this area but have no clear idea of the roadmap that can be embraced to reach higher energy-efficiency and environmental performance at their logistics sites, in line with Perotti et al. (2023).

Under the managerial aspect, this study constitutes valid support for warehouse managers and logistics service providers who are about to approach the challenge of turning their warehouses into greener nodes of their supply chains. Indeed, the proposed framework can be seen as a reference by managers willing to invest in green warehousing and are eager to understand the levers they should consider. Particularly, the identification of the possible areas of intervention, along with the expected related impacts (economic and/or environmental), can be a valuable starting point for the development of a strategic plan regarding the roadmap to be embraced in terms of energy-efficiency measure implementation at a logistics site. Moreover, although some specific features that influence the design and functioning of warehouses are sector-specific (i.e., refrigerated versus ambient-temperature warehouses), many commonalities would permit the application of this conceptual framework to different contexts. Wise environmental management of logistics sites can also help obtain building certifications (e.g., LEED, BREEAM, HQE, DGNB) that help achieve higher sustainable performances and might increase corporate reputation.

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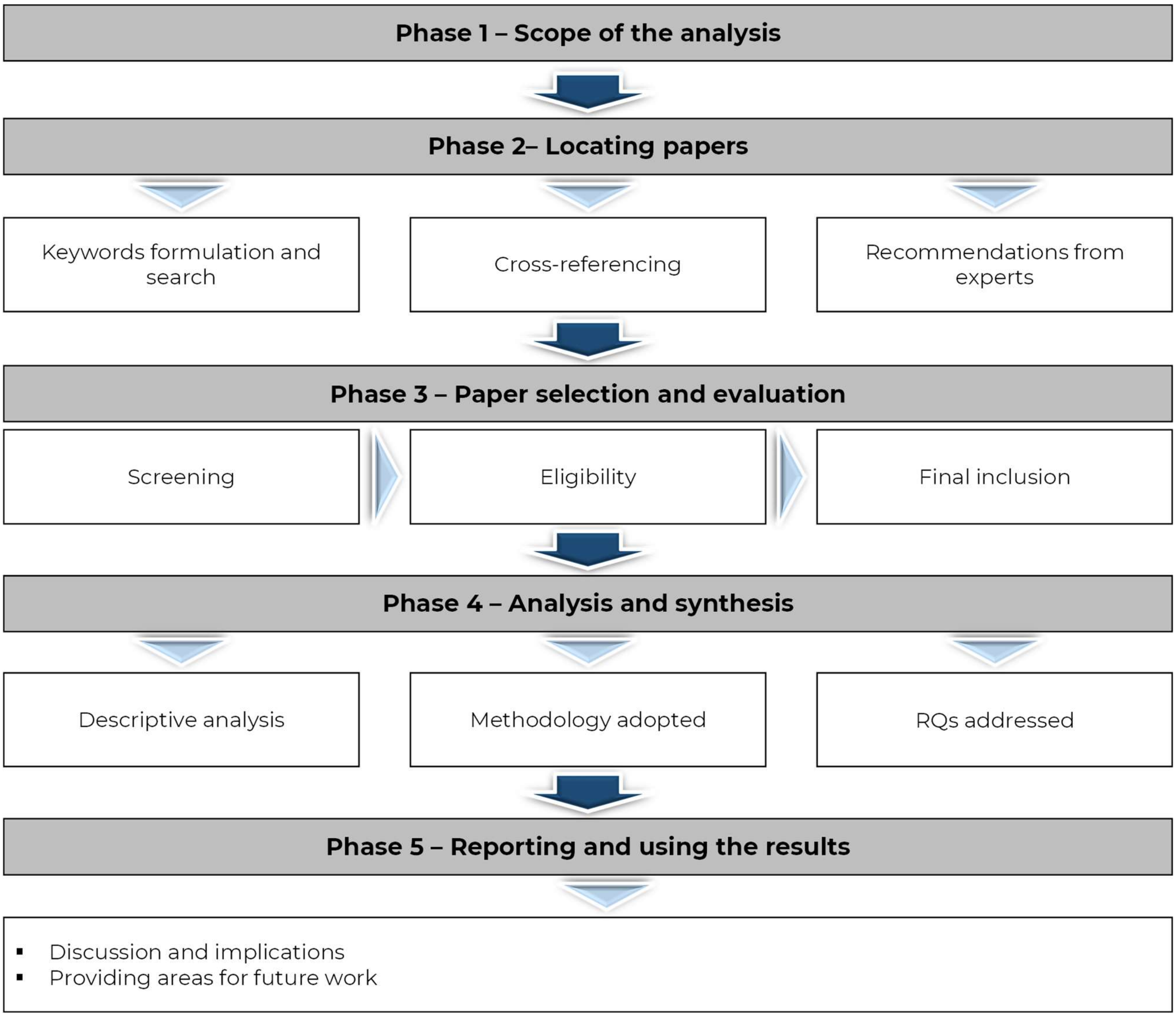
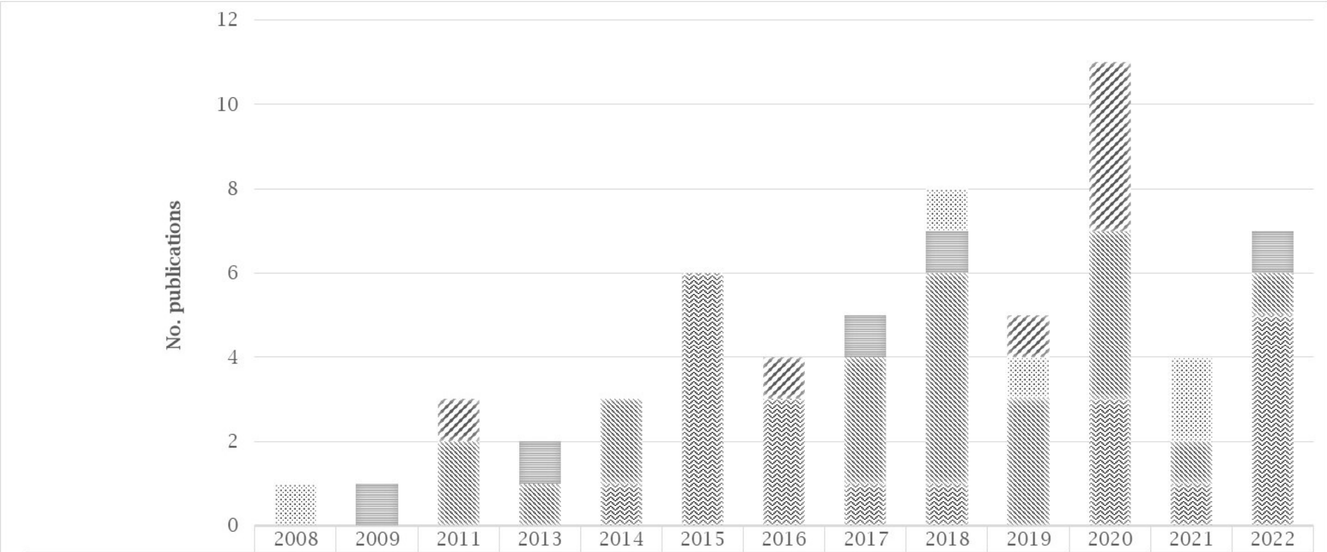


Figure 1 – SLR method (adapted from Denyer and Tranfield, 2009)

Keywords	Screening phase		Eligibility phase	
	Language	Publication type	Inclusion criteria	Exclusion criteria
TITLE-ABS-KEY (("warehous*" OR "logistic* site" OR "logistic* facility" OR "logistic* hub" OR "logistic* building") AND ("environment*" OR "sustainab*" OR "energy efficien*" OR "GHG" OR "CO2" OR "decarbon*" OR "green") AND ("light*" OR "HVAC" OR "forklift" OR "waste" OR "rainwater" OR "sensor" OR "roof" OR "glass" OR "wall" OR "pallet" OR "material handling" OR "automat*" OR "wind" OR "solar" OR "building") AND ("solution" OR "practice" OR "adopt*" OR "implement*" OR "barrier" OR "motivation" OR "driver" OR "obstacle"))	English	Journal papers and conference proceedings	Energy efficiency and environmental sustainability in warehouses	Energy efficiency and environmental sustainability in general or at supply chain level or logistics level or applied in other types of buildings
			Sustainability includes energy efficiency or environmental sustainability	Sustainability in general
			Non-commercial buildings include warehouses	Commercial and non-commercial buildings in general
			Dated but milestone documents	Dated and obsolete documents

Table I – Keywords and criteria used for paper selection (Source: Authors' own work)



	2008	2009	2011	2013	2014	2015	2016	2017	2018	2019	2020	2021	2022
Survey			1				1			1	4		
Literature Review	1								1	1		2	
Conceptual framework		1		1				1	1				1
Case study			2	1	2			3	5	3	4	1	1
Analytical model					1	6	3	1	1		3	1	5

Figure 2 – Distribution of the examined papers over time with respect to the research methodology adopted. Note that in case of multiple-methods papers were classified according to the primary methodology used (Source: Authors' own work)

No.	Author	Year	First Author's Affiliation	Title	Source	Methodology	Research Question Addressed		
							RQ1	RQ2	RQ3
1	Ciliberti et al.	2008	Italy	Logistics social responsibility: Standard adoption and practices in Italian companies	International Journal of Production Economics	Literature review	x		
2	Tan et al.	2009	New Zealand	Sustainable warehouse management	Proceedings of the International Workshop on Enterprise and Organizational Modeling and Simulation (EOMAS)	Conceptual framework		x	
3	Sellitto et al.	2011	Brazil	Environmental performance assessment in transportation and warehousing operations by means of categorical indicators and multicriteria preference	Chemical Engineering Transactions	Survey		x	
4	Rai et al.	2011	Netherlands	Assessment of CO2 emissions reduction in a distribution warehouse	Energy	Case study / interviews	x	x	
5	Cook et al.	2011	Australia	Towards low-energy retail warehouse building	Architectural Science Review	Case study / interviews	x	x	
6	Karia et al.	2013	Malaysia	Green innovations in the logistics industry: Sustainability and competitive advantage	Proceedings of the 20th International Business Information Management Association Conference (IBIMA)	Conceptual framework	x		

7	Sailor and Vuppuluri	2013	USA	Energy performance of sustainable roofing systems	Proceedings of the Heat Transfer Summer Conference (ASME)	Case study / interviews	x	x
8	Mostafaeipour et al.	2014	Iran	Economic evaluation for cooling and ventilation of medicine storage warehouses utilizing wind catchers	Renewable and Sustainable Energy Reviews	Case study / interviews	x	x
9	Lerher et al.	2014	Slovenia	Energy efficiency model for the mini-load automated storage and retrieval systems	International Journal of Advanced Manufacturing Technology	Analytical model	x	x
10	Martin et al.	2014	Austria	Hydrogen-powered fuel cell forklifts - Demonstration of green warehouse logistics	Proceedings of the World Electric Vehicle Symposium and Exhibition	Case study / interviews	x	x
11	Tappia et al.	2015	Italy	Incorporating the environmental dimension in the assessment of automated warehouses	Production Planning and Control	Analytical model	x	x
12	Oswiecinska et al.	2015	UK	Towards energy-efficient operation of Heating, Ventilation, and Air Conditioning systems via advanced supervisory control design	Journal of Physics: Conference Series	Analytical model	x	x
13	Fichtinger et al.	2015	Austria	Assessing the environmental impact of integrated inventory and warehouse management	International Journal of Production Economics	Analytical model	x	x
14	Meneghetti and Monti	2015	Italy	Greening the food supply chain: An optimisation model for sustainable design of refrigerated automated warehouses	International Journal of Production Research	Analytical model	x	
15	Meneghetti et al.	2015	Italy	Decision support optimisation models for design of sustainable automated warehouses	International Journal of Shipping and Transport Logistics	Analytical model	x	

16	Boenzi et al.	2016	Italy	Greening activities in warehouses: A model for identifying sustainable strategies in material handling	Annals of DAAAM and Proceedings of the International DAAAM Symposium	Analytical model	x	x	
17	Facchini et al.	2016	Italy	Minimizing the carbon footprint of material handling equipment: Comparison of electric and LPG forklifts	Journal of Industrial Engineering and Management	Analytical model		x	
18	Rüdiger et al.	2016	Germany	Managing Greenhouse Gas Emissions from Warehousing and Transhipment with Environmental Performance Indicators	Transportation Research Procedia	Analytical model		x	
19	Ene et al.	2016	Turkey	A genetic algorithm for minimizing energy consumption in warehouses	Energy	Analytical model	x	x	
20	Salhieh and Abushaikha	2016	Jordan	Assessing the driving forces for greening business practices: Empirical evidence from the United Arab Emirates' logistics service industry	South African Journal of Business Management	Survey	x		x
21	Alshaebi et al.	2017	USA	Evaluation of different forklift battery systems using statistical analysis and discrete event simulation	Proceedings of the 67th Annual Conference and Expo of the Institute of Industrial Engineers	Case study / interviews	x	x	
22	Roozbeh N. et al.	2017	Iran	Dual command cycle dynamic sequencing method to consider GHG efficiency in unit-load multiple-rack automated storage and retrieval systems	Computers and Industrial Engineering	Analytical model	x		
23	Pratt et al.	2017	USA	Warehouse transformation	ASHRAE Journal	Case study / interviews	x		
24	Ries et al.	2017	UK	Environmental impact of warehousing: a scenario analysis for the United States	International Journal of Production Research	Conceptual framework		x	

25	Saikovski et al.	2017	Estonia	Problems in the operating and calculation of payback of photovoltaic systems in buildings	Proceedings of the 58th Annual International Scientific Conference on Power and Electrical Engineering	Case study / interviews	x	x	
26	Kaur et al.	2018	India	A systematic literature review on barriers in green supply chain management	International Journal of Logistics Systems and Management	Literature review			x
27	Meneghetti et al.	2018	Italy	Fostering renewables into the cold chain: How photovoltaics affect the design and performance of refrigerated automated warehouses	Energies	Case study / interviews	x	x	
28	Foster et al.	2018	UK	Financial viability of liquid air energy storage applied to cold storage warehouses	Refrigeration Science and Technology	Case study / interviews	x	x	
29	Seifhashem et al.	2018	UK	The potential for cool roofs to improve the energy efficiency of single-story warehouse-type retail buildings in Australia: A simulation case study	Energy and Buildings	Case study / interviews	x	x	
30	Perdahci et al.	2018	Turkey	A comparative study of fluorescent and LED lighting in industrial facilities	IOP Conference Series: Earth and Environmental Science	Case study / interviews	x	x	
31	Burinskiene et al.	2018	Lithuania	A simulation study for the sustainability and reduction of waste in warehouse logistics	International Journal of Simulation Modelling	Analytical model	x	x	
32	Wahab et al.	2018	Malaysia	Antecedents of green warehousing: A theoretical framework and future direction	International Journal of Supply Chain Management	Conceptual framework			x
33	You et al.	2018	China	System design and energy management for a fuel cell/battery hybrid forklift	Energies	Case study / interviews	x	x	

34	Pamungkas et al.	2019	Indonesia	Impacts of Solar PV, Battery Storage and HVAC Set Point Adjustments on Energy Savings and Peak Demand Reduction Potentials in Buildings	Proceedings of the Conference on the Industrial and Commercial Use of Energy (ICUE)	Case study / interviews	x	x	
35	Bartolini et al.	2019	Italy	Green warehousing: Systematic literature review and bibliometric analysis	Journal of Cleaner Production	Literature review	x		
36	Goh et al.	2019	Singapore	Barriers to low-carbon warehousing and the link to carbon abatement: A case from emerging Asia	International Journal of Physical Distribution and Logistics Management	Case study			x
37	Ozturk et al.	2019	Turkey	Life-Cycle Cost, Cooling Degree Day, and Carbon Dioxide Emission Assessments of Insulation of Refrigerated Warehouses Industry in Turkey	Journal of Environmental Engineering	Case study / interviews	x	x	
38	Xin et al.	2019	Malaysia	A Study on the Factors Influencing Green Warehouse Practice	Proceedings of the International Conference on Building Energy Conservation, Thermal Safety and Environmental Pollution Control (ICBTE)	Survey			x
39	Carli et al.	2020a	Italy	A control strategy for smart energy charging of warehouse material handling equipment	Procedia Manufacturing	Analytical model	x	x	
40	Ali et al.	2020	Pakistan	Integration of green supply chain management practices in the construction supply chain of CPEC	Management of Environmental Quality: An International Journal	Survey	x		
41	Li et al.	2020	China	Quantitative analysis of passive seasonal cold storage with a two-phase closed thermosyphon	Applied Energy	Case study / interviews	x	x	
42	Sarabia Escriva et al.	2020	Spain	Comparison of annual cooling energy demand between conventional and inflatable dock door shelters for refrigerated and frozen food warehouses	Thermal Science and Engineering Progress	Case study / interviews	x	x	

43	Minashkina and Happonen	2020	Finland	Decarbonizing warehousing activities through digitalization and automatization with WMS integration for sustainability supporting operations	Proceedings of the 7th International Conference on Environment Pollution and Prevention (ICEPP)	Case study / interviews	x	x	x
44	Sukjit and Vanichchinchai	2020	Thailand	An Assessment of Motivations on Green Warehousing in Thailand	Proceedings of the 7th International Conference on Industrial Engineering and Applications (ICIEA)	Survey			x
45	Carli et al.	2020b	Italy	Sustainable scheduling of material handling activities in labor-intensive warehouses: A decision and control model	Sustainability	Analytical model	x		
46	Lapisa et al.	2020	Indonesia	Effect of skylight–roof ratio on warehouse building energy balance and thermal–visual comfort in the hot-humid climate area	Asian Journal of Civil Engineering	Analytical model	x	x	
47	Agyabeng-Mensah et al.	2020	China	Green warehousing, logistics optimization, social values and ethics and economic performance: the role of supply chain sustainability	International Journal of Logistics Management	Survey	x		
48	Molleti et al.	2021	Canada	Smart energy harvesting performance of photovoltaic roof assemblies in the Canadian climate	Intelligent Buildings International	Case study / interviews	x		
49	Gruchmann et al.	2021	Germany	Tensions in sustainable warehousing: including the blue-collar perspective on automation and ergonomic workplace design	Journal of Business Economics	Survey			x
50	Füchtenhans et al.	2021a	Germany	Using smart lighting systems to reduce energy costs in warehouses: A simulation study	International Journal of Logistics Research and Applications	Literature review	x	x	

51	Nantee and Sureeyatanapas	2021	Thailand	The impact of Logistics 4.0 on corporate sustainability: a performance assessment of automated warehouse operations	Benchmarking: An International Journal	Case study / interviews		x	
52	Füchtenhans et al.	2021b	Germany	Smart lighting systems: state-of-the-art and potential applications in warehouse order picking	International Journal of Production Research	Literature review	x	x	
53	Modica et al.	2021	Italy	Green Warehousing: Exploration of Organisational Variables Fostering the Adoption of Energy-Efficient Material Handling Equipment	Sustainability	Analytical model	x	x	x
54	Ishizaka et al.	2022	France	Sustainable warehouse evaluation with AHPS or traffic light visualisation and post-optimal analysis method	Journal of the Operational Research Society	Conceptual framework	x	x	
55	Stankovic et al.	2022	Croatia	Saving energy by optimizing warehouse dock door allocation	Energies	Analytical model	x		
56	Yang et al.	2022	China	Bi-objective operation optimization in multi-shuttle automated storage and retrieval systems to reduce travel time and energy consumption	Engineering optimization	Analytical model	x		

57	Lee et al.	2022	USA	An electric forklift routing problem with battery charging and energy penalty constraints	Journal of Intelligent Manufacturing	Analytical model	x
58	Osorio et al.	2022	Spain	Industrial Buildings with Zero Energy Consumption: Cathedral Warehouse for Sherry Wines	Sustainability	Case study / interviews	x
59	Faveto et al.	2022	Italy	Efficient management of industrial electric vehicles by means of static and dynamic wireless power transfer systems	The International Journal of Advanced Manufacturing Technology	Analytical model	x
60	Kheoi et al.	2022	Turkey	Energy minimizing order picker forklift routing problem	European Journal of Operational Research	Analytical model	x

Table II – Papers included in the SLR (Source: Authors' own work)

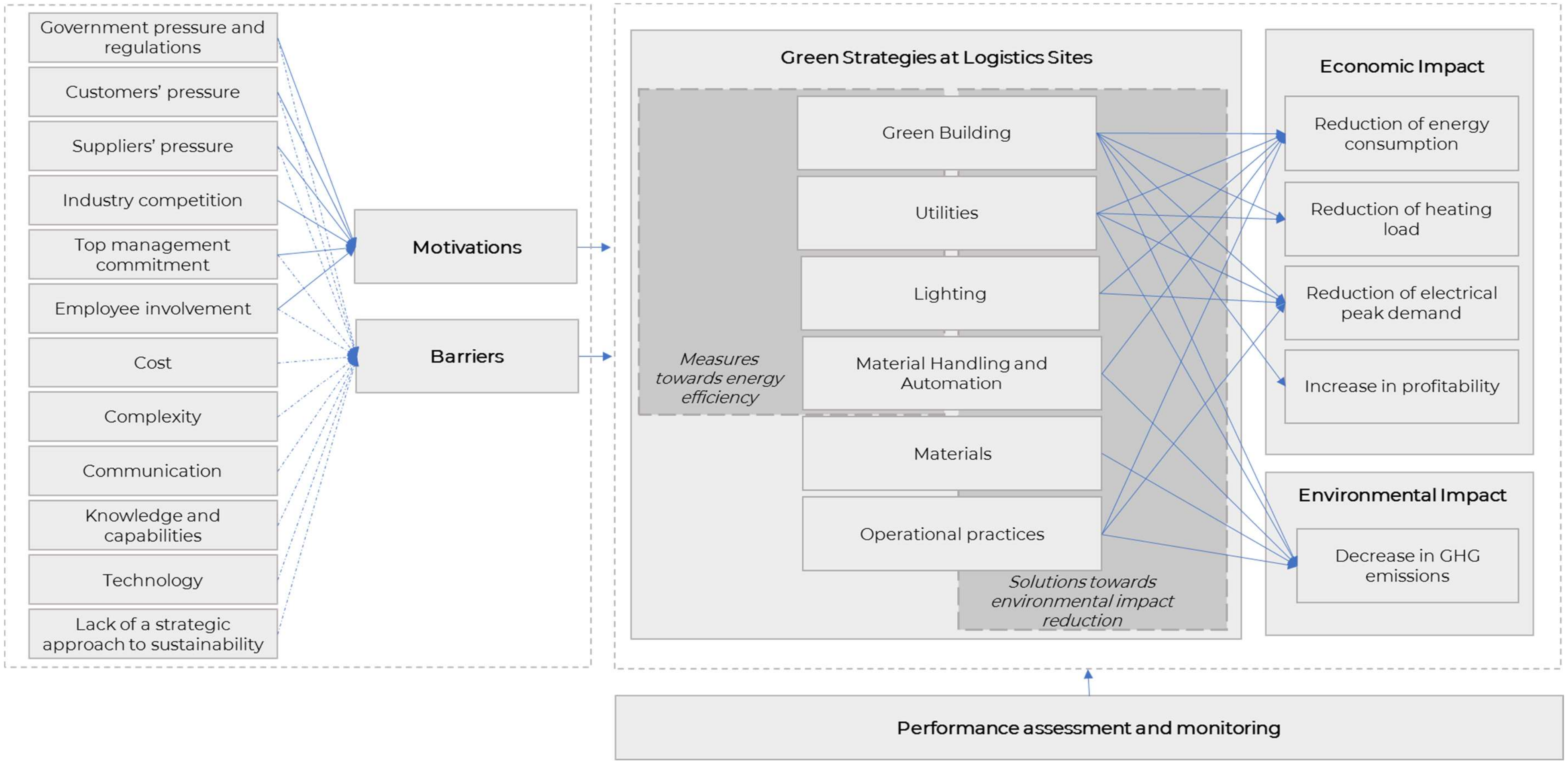


Figure 3 – Framework with six main areas of intervention ("green strategies") for improving energy efficiency and environmental sustainability at logistics sites (Source: Authors' own work)

Green strategy	Energy-efficiency (EE) measures and solutions towards environmental impact (EI) reduction	Main references
Green building	Thermal insulation (EE, EI)	Rai et al., 2011; Cook et al., 2011; Pratt et al., 2017; Ozturk et al., 2019; Agyabeng-Mensah et al., 2020
	Loading docks with insulated doors (EE, EI)	Sarabia Escriva et al., 2020
	Cool roof (EE, EI)	Sailor and Vuppuluri, 2013; Seifhashem et al., 2018
	Green roof (EI)	Sailor and Vuppuluri, 2013
	Selective glazing (EE, EI)	Cook et al., 2011
	Passive design and construction strategies (EE, EI)	Osorio et al., 2022
	Wind catcher (EE)	Mostafaeipour et al., 2014
Utilities	Photovoltaic panels for self-production (EE, EI)	Karia et al., 2013; Sailor and Vuppuluri, 2013; Salhieh and Abushaikha, 2016; Saikovski et al., 2017; Meneghetti et al., 2018; Pamungkas et al., 2019; Molleti et al., 2021
	Intelligent HVAC systems (EE, EI)	Ciliberti et al., 2008; Karia et al., 2013; Oswiecinska et al., 2015; Pratt et al., 2017
Lighting	LED lighting (EE)	Cook et al., 2011; Pratt et al., 2017; Perdahci et al., 2018; Bartolini et al., 2019; Füchtenhans et al., 2021a; Füchtenhans et al., 2021b
	Natural lighting and white walls (EE)	Rai et al., 2011; Cook et al., 2011; Karia et al., 2013; Pratt et al., 2017; Lapisa et al., 2020
	Sensors for reducing lighting consumption (EE)	Cook et al., 2011; Salhieh and Abushaikha, 2016; Pratt et al., 2017 ; Füchtenhans et al., 2021a; Füchtenhans et al., 2021b
Material Handling and Automation	Lithium-ion battery forklifts (EE, EI)	Alshaebi et al., 2017; Pamungkas et al., 2019
	Hydrogen-Powered Fuel Cell Forklifts (EE, EI)	Martin et al., 2013
	Fuel cell/battery hybrid forklift (EE, EI)	You et al., 2018
	Electric forklifts with wireless energy charging (EI)	Faveto et al., 2022
	Energy-efficient AS/RS (EE, EI)	Meneghetti and Monti, 2015; Tappia et al, 2015; Meneghetti et al., 2015; Roozbeh Nia et al., 2017; Nantee and Sureeyatanapas, 2021
Materials	Packaging reduction (EI)	Karia et al., 2013; Ali et al., 2020; Agyabeng-Mensah et al., 2020
	Packaging reuse and recycle (EI)	Ciliberti et al., 2008; Karia et al., 2013; Ali et al., 2020; Minashkina and Happonen, 2020; Agyabeng-Mensah et al., 2020
Operational practices	Travel distance optimization (EI)	Boenzi et al., 2016; Fichtinger et al., 2015; Ene et al., 2016; Burinskiene et al., 2018; Lee at el., 2022; Yang et al., 2022; Khoei et al., 2022;
	Optimal scheduling of material handling activities and battery charging (EI)	Carli et al., 2020a; Carli et al., 2020b; Lee at el., 2022; Yang et al., 2022; Stankovic et al. 2022

Table III – Framework of energy-efficient measures and solutions towards environmental impact reduction for logistics facilities as emerged from the SLR. Please note that each measure/solution is classified according to its main impact, i.e., as related to energy-efficiency improvement (EE) or environmental impact reduction (EI) (Source: Authors' own work)

Perspective	Type of impact	(A)	(B)	(C)	(D)	(E)	(F)	Main references
Economic	Reduction of energy consumption	x	x	x	x		x	Rai et al., 2011; Cook et al., 2011; Sailor and Vuppuluri, 2013; Mostafaeipour et al., 2014; Oswiecinska et al., 2015; Boenzi et al., 2016; Alshaebi et al., 2017; Seifhashemi et al., 2018; Burinskiene et al., 2018; Foster et al., 2018; Perdhaci et al., 2018; Pamungkas et al., 2019; Agyabeng-Mensah et al., 2020; Sarabia Escriva et al., 2020; Li et al., 2020; Lapisa et al., 2020; Füchtenhans et al., 2021a; Nantee and Sureeyatanapas, 2021; Füchtenhans et al., 2021b
	Reduction of heating load	x	x					Rai et al., 2011; Cook et al., 2011; Mostafaeipour et al., 2014; Foster et al., 2018; Sarabia Escriva et al., 2020
	Reduction of electrical peak demand	x	x	x			x	Pratt et al., 2017; Foster et al., 2018; Perdhaci et al., 2018; Molleti et al., 2021; Carli et al., 2020a; Carli et al., 2020b
	Increase in profitability	x						Mostafaeipour et al., 2014; Agyabeng-Mensah et al., 2020 ; Nantee and Sureeyatanapas, 2021
Environmental	Decrease in GHG emissions	x	x		x	x	x	Cook et al., 2011; Martin et al., 2013; Seifhashemi et al., 2018; Foster et al., 2018; Burinskiene et al., 2018; Minashkina and Happonen, 2020; Li et al., 2020; Carli et al., 2020a; Carli et al., 2020b; Nantee and Sureeyatanapas, 2021

Table IV – Economic and environmental impacts related to the green strategies under analysis. Note that: (A) Green Building, (B) Utilities, (C) Lighting, (D) Material Handling and Automation, (E) Materials, and (F) Operational Practices (Source: Authors' own work)