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Evaluation Criteria for Intelligent and Sustainable Warehouse Transformation: A Comparison of Conventional, Energy-Efficient, Smart Automated, and Net-Zero Warehouses

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Abstract: Sustainability requirements and industrial digitalization are reshaping warehouse design and operation, yet the choice between incremental efficiency measures and more advanced intelligent systems remains difficult. This study investigates how conventional, energy-efficient, smart automated, and net-zero warehouses differ in their requirements and transformation priorities. A comparative evaluation framework was developed from the literature and organized around four dimensions: economic feasibility, environmental performance, operational performance, and intelligent technological readiness. The four alternatives were qualitatively assessed in terms of investment, operating costs, energy efficiency, resource use, automation, digital integration, real-time data availability, and implementation complexity. The roles of automated storage and retrieval systems (AS/RS), autonomous mobile robots (AMRs), the Internet of Things (IoT), warehouse management systems (WMS), energy monitoring, and renewable energy technologies were also examined. An illustrative calculation was conducted under identical throughput conditions to compare energy intensity across the four alternatives. The comparison showed that the alternatives did not form a universal progression from an inferior system to a superior one. Energy-efficient warehouses offered a comparatively accessible route to lower energy use, whereas smart automated warehouses provided stronger digital integration and operational coordination but required greater technological and organizational capacity. Net-zero warehouses achieved the lowest illustrative energy intensity, although they involved the highest investment and infrastructure demands. The findings indicate that intelligent and sustainable warehouse transformation depends on the alignment of technology, operational needs, financial capacity, and environmental objectives. The proposed evaluation perspective provides a structured basis for assessing warehouse transformation pathways under different industrial and organizational conditions.

Keywords: Intelligent warehousing; Sustainable warehouse transformation; Industry 4.0; Warehouse automation; Internet of Things; Technological readiness; Energy intensity; Net-zero warehouse

1 Introduction

Warehousing plays a central role in modern supply chains, with direct consequences for logistics performance and the environmental effects of industrial and commercial activities. Decisions concerning warehouse design and development have traditionally focused on productivity, operating costs, storage capacity, and service requirements. Growing environmental concerns and increasingly stringent sustainability regulations have broadened this decision context. Warehouses are now expected to meet operational and economic requirements while contributing to energy conservation, emissions reduction, and wider sustainability targets. Green warehousing has consequently emerged as an important component of sustainable supply-chain management, and a range of measures has been proposed to reduce the environmental footprint of warehouse operations [1]. These measures extend from relatively straightforward improvements, such as light-emitting diode (LED) lighting and energy-efficient equipment, to renewable energy systems, automated material handling, and integrated sustainable building designs. At the same time, smart warehouse solutions based on the Internet of Things (IoT) and warehouse management systems (WMS) are becoming more widely used, while net-zero warehouse concepts are attracting growing attention [2]. Conventional warehouses nevertheless remain common because of their lower initial investment, simpler technological structure, and suitability for particular operating conditions.

The selection of an appropriate warehouse concept is therefore not a simple technological choice. Conventional, energy-efficient, smart automated, and net-zero warehouses differ substantially in investment requirements, energy consumption, operational performance, technological complexity, environmental effects, and long-term sustainability potential [2]. Automated and smart warehouses can improve process coordination, data visibility, inventory control, and equipment utilization, but their implementation often requires substantial capital expenditure, compatible digital infrastructure, skilled personnel, and organizational restructuring. Renewable energy-based and net-zero warehouses can substantially reduce dependence on conventional energy sources, yet their feasibility is influenced by financial capacity, building characteristics, energy demand, site conditions, and long-term strategic priorities [3]. These interdependencies make warehouse transformation a system-level decision in which economic, environmental, operational, technological, and organizational considerations cannot be assessed independently.

A suitable evaluation framework must therefore account for several dimensions of warehouse performance. Initial investment, operating expenses, maintenance requirements, and possible energy savings need to be considered together with energy efficiency, resource use, operational capability, automation, digital integration, and technological readiness. An assessment based on a single criterion may favor a financially accessible alternative with limited environmental performance or a technologically advanced solution that exceeds the operational and organizational capacity of the company [4, 5]. Although sustainable logistics and green warehousing have received considerable research attention, the available warehouse concepts are often discussed separately or from a predominantly environmental, operational, or technological perspective. This separation makes it difficult to determine how the alternatives differ when they are examined under a common set of criteria. A structured comparison is consequently needed to clarify the trade-offs among warehouse concepts and to identify the conditions under which each transformation pathway may be appropriate.

Industry 4.0 has added a further layer of complexity to sustainable warehouse development. IoT devices, WMS platforms, automated storage and retrieval systems (AS/RS), autonomous mobile robots (AMRs), and real-time monitoring systems allow operational and energy data to be collected, integrated, and used in warehouse decision-making [5, 6]. These technologies can support more accurate inventory control, closer coordination of material flows, better equipment utilization, and more systematic monitoring of resource consumption. Their presence alone, however, does not guarantee improved environmental or operational performance. The outcome depends on the compatibility of the technologies with existing infrastructure, the quality of system integration, the availability of reliable data, and the capacity of the organization to operate and maintain the resulting system. IoT, WMS, automation, and real-time monitoring therefore connect technological readiness with operational performance and sustainability objectives rather than serving merely as isolated technical additions [7]. Warehouse transformation should accordingly be understood as the coordinated development of interacting physical, digital, energy, and organizational subsystems.

This study investigates 4 representative warehouse alternatives: conventional, energy-efficient, smart automated, and net-zero warehouses. It compares them through 4 dimensions—economic feasibility, environmental performance, operational performance, and intelligent technological readiness—and examines how the importance of these dimensions changes across different transformation pathways. Particular attention is paid to investment and operating requirements, energy and resource efficiency, automation, digital integration, real-time data availability, and implementation complexity. An illustrative calculation under identical throughput conditions is also used to show how energy intensity can support comparison across the four alternatives. The study does not assume that the most automated or environmentally ambitious warehouse is universally preferable. Instead, it considers how the suitability of each alternative depends on operational requirements, available resources, existing infrastructure, technological capacity, and long-term sustainability objectives. By placing the four warehouse concepts within a common evaluation structure, the study provides a system-oriented basis for examining the progression from conventional facilities to intelligent and net-zero warehouse systems.

2 Green Warehousing: Concept and Development

Warehouses play a crucial role in supply chains, as their operations directly impact the efficiency of storage, inventory management, order fulfillment, distribution processes, and customer satisfaction. Traditionally, the design and management of warehouses have prioritized operational performance, cost reduction, and optimal space utilization. Accordingly, storage capacity, throughput, labor productivity, and inventory accuracy have been standard indicators for assessing warehouse effectiveness. However, shifts in the business landscape, such as rising energy costs and heightened awareness of the environmental impacts of logistics, have transformed how warehouses are planned and managed. Today, there is an expectation that warehouses deliver not only high operational performance but also minimize negative environmental impacts while supporting the sustainability goals of supply chains [1].

The growing emphasis on sustainable development has highlighted warehouses as key areas for significant improvement. Warehouse operations are energy-intensive due to requirements for lighting, heating, cooling, ventilation, information technologies, and material handling equipment. Additionally, the expanding in e-commerce and the increasing demand for faster, more flexible delivery services have added complexity to warehouse operations, intensifying the need for efficient resource utilization [2, 3]. Consequently, companies are increasingly seeking solutions that enhance energy efficiency, reduce emissions, and maintain the necessary operational standards [1, 4].

Another significant factor driving the development of sustainable warehouses is the rise in environmental regulations volume and corporate sustainability mandates. In particular, European Union policies concerning climate neutrality, energy efficiency, and the use of renewable energy impose additional responsibilities on companies to improve the environmental performance of their facilities [6]. While these regulations support the shift toward greener logistics, they also pose challenges, especially for organizations operating older warehouse infrastructures that may require substantial modifications to meet new standards [7].

Implementing sustainable warehouse solutions is regarded as having its own set of challenges. A primary obstacle is the substantial initial investment needed for advanced technologies, renewable energy systems, and automation solutions. Although these investments can yield long-term benefits, many companies struggle to justify significant capital expenditures, particularly when the economic returns are uncertain or take time to materialize. Furthermore, technological integration poses another challenge, as new digital systems and automated solutions must often be aligned with existing warehouse infrastructures. Organizational factors, such as employee training, changes in operational procedures, and the capacity to manage new technologies, also play a critical role in the successful implementation of sustainable warehouse strategies [4, 8].

Given these complexities, sustainable warehousing should be viewed as a gradual transformation process rather than the adoption of a single solution. Companies may pursue various approaches based on their operational needs, financial resources, technological readiness, and sustainability aspirations. Some supply chains may prioritize energy efficiency through relatively straightforward measures, while others might invest in automated, digitally connected, or energy-independent warehouse concepts. Each approach offers distinct advantages but also comes with specific limitations related to investment costs, implementation complexity, and anticipated performance gains [1].

To illustrate these differences, this study examines four representative warehouse alternatives that embody various stages of sustainable warehouse development: conventional warehouses, energy-efficient warehouses, smart automated warehouses, and net-zero warehouses. These alternatives were chosen for their relevance in discussions about enhancing warehouse sustainability, spanning from basic operational improvements to advanced concepts that integrate automation, digital technologies, and renewable energy solutions. The following section discusses their main characteristics, benefits, and potential limitations.

3 Description of Green Warehouse Alternatives

Expanding sustainability requirements in logistics are changing the way warehouses are designed and operated. In addition to their traditional role in storage and material handling, warehouses are increasingly expected to contribute to lower energy consumption, reduced environmental impacts, and better use of resources within the supply chain [2, 8].

At the same time, the development of automation, digital systems, and renewable energy solutions has created a wider range of possibilities for improving warehouse performance.

The way in which companies respond to these requirements depends on their individual circumstances. For some of them, improving existing facilities through more efficient lighting, equipment, and energy monitoring may be the most practical alternative.

Other companies may have the resources and infrastructure needed to introduce automated systems, digital monitoring, and more advanced warehouse management solutions. At a higher level of sustainability ambition, renewable energy generation and advanced energy management can be combined with energy-efficient building and operational solutions [5].

The alternatives therefore differ in several important respects. Initial investment, operating requirements, energy efficiency, level of automation, digital integration, and the complexity of implementation may vary considerably between warehouse concepts.

These differences are particularly important when a company has to decide whether to improve an existing warehouse gradually or invest in a more comprehensive transformation. Previous research also suggests that warehouse sustainability should be considered together with operational and economic aspects, since environmental improvements cannot be separated from the practical conditions under which warehouses operate [1, 4].

Against these circumstances, four warehouse alternatives are considered in this study: conventional warehouse, energy-efficient warehouse, smart automated warehouse, and net-zero warehouse. They represent different approaches to warehouse transformation, from maintaining a traditional operating model to combining energy efficiency, digital technologies, automation, and renewable energy. The main characteristics and limitations of each alternative are presented in the following sections.

3.1 Conventional Warehouse

The conventional warehouse represents the traditional approach to warehouse structure and operation, with the main focus on storage, material handling, inventory management, and order fulfillment. Such facilities generally rely on standard storage systems, conventional material handling equipment, traditional lighting, and limited digital support [1–3]. Sustainability measures may be present, but they are not usually integrated into the overall warehouse concept.

Conventional warehouses remain common because they require relatively low initial investment and involve less technological and organizational complexity than more advanced alternatives. Their simpler structure can also make day-to-day operations easier to manage and allows companies to modify processes without relying heavily on complex technological systems. These characteristics can be particularly relevant for companies that have limited investment capacity or operate with relatively stable warehouse processes [8].

The main limitation of this warehouse concept is its restricted potential for improving energy and environmental performance. Limited digitalization and monitoring make it more difficult to identify inefficient processes, track resource consumption, and use operational data for improvement. Nevertheless, the conventional warehouse should not be viewed only as an outdated model. It can serve as a starting point for gradual transformation through measures such as energy-efficient equipment, improved lighting, energy monitoring, and the introduction of digital warehouse management solutions [1].

In this study, as in common practice, the conventional warehouse is usually used as the reference alternative. Its relatively low investment requirements and simple operation provide a useful baseline for discussing the additional costs, technological requirements, and potential sustainability benefits associated with the other warehouse concepts.

3.2 Energy-Efficient Warehouse

The energy-efficient warehouse focuses on reducing energy consumption through improvements to existing facilities and equipment, without requiring a complete redesign of warehouse operations. Typical measures include LED lighting, energy-efficient material handling equipment, improved heating, ventilation, and air-conditioning (HVAC) systems, better building insulation, and energy monitoring [5, 9]. These measures can improve the energy performance of a warehouse while maintaining its existing operational structure.

One of the main advantages of this approach is that improvements can be introduced gradually. Companies can select measures according to their financial resources, warehouse conditions, and operational priorities. Energy monitoring, for example, can help identify major sources of consumption and provide a basis for targeted improvements. Such measures can reduce electricity consumption and operating costs while also contributing to lower greenhouse gas emissions [1, 4]. The integration of renewable energy can provide an additional improvement in environmental performance, particularly when combined with measures that reduce overall energy demand [5].

The main limitation is energy-efficiency measures generally improve existing operations rather than fundamentally changing the way warehouse processes are organized. Their impact may therefore be limited when compared with solutions that combine energy improvements with automation, digital monitoring, or intelligent control systems. Nevertheless, this concept applies to a wide range of existing warehouses and can provide a relatively low-risk approach to improving sustainability.

In this study, the energy-efficient warehouse represents a practical alternative for institutions aiming to reduce energy consumption and environmental impacts while maintaining their current warehouse processes. It can also serve as a suitable starting point for further integration of digital, automated, and renewable energy solutions.

3.3 Smart Automated Warehouse

The smart automated warehouse combines warehouse automation with digital technologies to improve process control, operational visibility, and resource utilization. Unlike the energy-efficient warehouse, which mainly focuses on reducing energy consumption, this concept involves a broader transformation of warehouse operations through technologies such as AS/RS, AMRs, robotics, IoT devices, real-time monitoring, and WMS.

A key characteristic of the smart automated warehouse is the ability to use operational data to support warehouse management. Information on inventory, equipment utilization, material flows, and energy consumption can be collected and monitored in real time, allowing processes to be adjusted and inefficiencies to be identified more quickly. Automation can also reduce unnecessary movements, improve inventory accuracy, and increase the consistency of material handling processes [8, 9]. These characteristics place the smart automated warehouse within the broader context of Industry 4.0 and the increasing digitalization of logistics operations.

However, the implementation of such systems requires largely higher investment and technological readiness than conventional or energy-efficient solutions. Integration of different technologies, adaptation of existing infrastructure, employee training, and management of technological change can represent significant challenges. Moreover, automation does not automatically result in lower energy consumption. The actual benefits rely on system design, utilization levels, and the way automated processes are managed.

In this study, the smart automated warehouse therefore represents an alternative characterized by a high level of digital and technological integration. It offers greater potential for process optimization and operational visibility, but also involves higher implementation complexity and financial requirements than the previous alternatives.

3.4 Net-Zero Warehouses

The net-zero warehouse represents the most ambitious sustainability concept considered in this investigation. Its main objective is to minimize energy demand and meet the remaining energy requirements through renewable energy generation, so that the overall energy balance is brought as close as possible to net-zero conditions. This approach considers the warehouse as an integrated energy system rather than focusing on individual energy-saving measures.

Achieving this level of performance requires a combination of energy-efficient building design, efficient equipment, renewable energy generation, and appropriate energy management [10]. Typical solutions include photovoltaic systems, improved building envelopes, electrified material handling equipment, energy storage, and monitoring systems. The feasibility and effectiveness of these measures depend on the characteristics of the warehouse and its location, including available roof area, local climate conditions, energy demand, and existing infrastructure [5, 11].

In this study, the net-zero warehouse represents the highest level of environmental initiative among the investigated alternatives. At the same time, it requires the most significant degree of long-term planning and the most favorable combination of financial, technical, and location conditions. The comparison in Table 1 indicates that the four alternatives do not represent a simple hierarchy in which each subsequent concept is universally better than the previous one. Instead, they reflect different directions of warehouse transformation.

Table 1. Comparative perspective on warehouse transformation alternatives

Dimension	Conventional Warehouse	Energy-Efficient Warehouse	Smart Automated Warehouse	Net-Zero Warehouse
Primary focus	Stable and simple operations	Reduction of energy consumption	Automation and data-driven operations	Minimization of energy-related environmental impact
Main transformation	No major transformation	Improvement of existing systems	Digital and operational transformation	Integrated energy transformation
Key solutions	Conventional storage and handling	LED, efficient equipment, HVAC, energy monitoring	AS/RS, AMRs, IoT, WMS, real-time monitoring	PV systems, energy-efficient design, storage, energy management
Investment requirement	Low	Low–medium	High	Very high
Digital integration	Low	Low–medium	Very high	Medium–high
Potential for energy reduction	Low	Medium–high	High	Very high
Operational change	Minimal	Limited	Significant	Moderate-significant
Implementation complexity	Low	Medium	High	Very high
Main limitation	Limited sustainability potential	Limited process transformation	High cost and technological complexity	High investment and site dependency
Most suitable for	Cost-sensitive and stable operations	Gradual warehouse improvement	Data-intensive and highly dynamic operations	Long-term sustainability-oriented strategies

Note: AS/RS = automated storage and retrieval systems; AMRs = autonomous mobile robots; IoT = Internet of Things; WMS = warehouse management systems; HVAC = heating, ventilation and air-conditioning; LED = light-emitting diode; PV = photovoltaic.

The main advantage of the net-zero concept is its potential to substantially reduce dependence on conventional energy sources and the environmental impact of warehouse operations. However, this potential is accompanied by high initial investment requirements and greater technical and planning demands. Existing buildings may also impose limitations on the installation of renewable energy systems or the introduction of new energy technologies. For this reason, the feasibility of a net-zero solution varies considerably between warehouse facilities.

The four warehouse concepts differ not only in the technologies they use, but also in the type of improvement they are intended to achieve. The energy-efficient warehouse is mainly concerned with reducing energy use and improving the efficiency of existing facilities, which makes it a practical option for companies that want to introduce changes gradually [9, 11].

The smart automated warehouse goes further by combining automation and digital systems with day-to-day warehouse operations. This can improve process coordination, visibility, and resource utilization, although the benefits depend on the company's technological capabilities and the quality of system integration [4, 8]. The net-zero warehouse has a different focus, with greater emphasis on renewable energy, energy efficiency, and reducing dependence on conventional energy sources. Its application, however, is more demanding because the feasibility of such solutions depends on investment capacity, infrastructure, energy demand, and site conditions [11]. The conventional warehouse is included as a reference point because it represents the conditions from which many companies start when considering warehouse improvements.

The comparison therefore does not suggest that one alternative is always better than the others. A solution that is appropriate for a large, highly automated facility may not be realistic for a smaller warehouse with limited investment capacity. The choice should instead reflect the company's operational requirements, financial possibilities, technological readiness, and sustainability objectives [4, 10].

4 Critical Evaluation Criteria for Intelligent and Sustainable Warehouse Transformation

The implementation of sustainable warehouse concepts depends on the availability of green technologies and a combination of economic, environmental, technological, and organizational factors. Although advanced warehouse solutions can significantly improve energy performance and operational efficiency, their practical application is influenced by investment requirements, existing infrastructure, technological readiness, and the specific needs of an organization.

Different warehouse alternatives require different levels of financial commitment. While energy-efficient solutions can often be introduced through gradual improvements of existing facilities, smart automated and net-zero warehouses usually require more complex investments and long-term strategic planning [11].

Therefore, companies must evaluate not only the potential environmental benefits but also the economic feasibility and operational implications of each transformation pathway [1, 12]. Based on the characteristics of the analyzed alternatives, the following sections discuss the main factors influencing green warehouse implementation, including economic feasibility, environmental performance, operational requirements, and technological readiness.

4.1 Economic Criteria

Economic criteria are among the primary considerations when selecting a warehouse concept because they directly influence investment decisions and long-term financial sustainability. Although advanced warehouse technologies can improve operational performance and reduce environmental impacts, they often require considerably higher initial investments than conventional warehouse systems. Consequently, organizations need to evaluate not only implementation costs but also expected operational savings and long-term economic benefits. Relevant economic considerations include initial investment, operating costs, maintenance requirements, potential energy cost savings, and payback period [5, 12].

Energy-efficient warehouses generally represent the most economically accessible sustainable alternative because they can reduce electricity consumption through relatively moderate investments. In contrast, smart automated and net-zero warehouses require substantially greater financial resources but may provide higher long-term benefits through improved productivity, lower energy consumption, and reduced operating expenses [4, 11].

4.2 Environmental Criteria

Environmental criteria evaluate the contribution of warehouse concepts to reducing environmental impacts and improving resource efficiency. The literature identifies energy consumption, greenhouse gas emissions, renewable energy utilization, and resource efficiency as the most important environmental indicators [12–14]. Among these, energy intensity symbolizes one of the most useful logistics indicators because it relates warehouse energy consumption to operational output:

$$\text{energy intensity} = \frac{\text{annual energy consumption}}{\text{warehouse throughput}} \tag{1}$$

Energy intensity is a useful indicator of warehouse energy performance, as it relates energy consumption to operational output. Previous studies have used it to assess energy requirements for handling and storage operations [15, 16]. In pallet-based warehouses, it can also be expressed per pallet handled, enabling comparison among warehouse configurations. Lower values indicate greater energy efficiency. Net-zero warehouses generally achieve better environmental performance through renewable energy and intelligent energy management, whereas conventional warehouses tend to have higher energy intensity and carbon footprints [5, 8].

To facilitate comparison among the analyzed warehouse alternatives, the reduction in energy intensity relative to the conventional warehouse can also be calculated as follows:

$$R_i = \frac{EI_{\text{conv}} - EI_i}{EI_{\text{conv}}} \times 100\% \tag{2}$$

where, R_i is the reduction in energy intensity compared with the conventional warehouse (%), EI_{conv} is the energy intensity of the conventional warehouse, and EI_i is the energy intensity of the analyzed warehouse alternative.

4.3 Operational Performance Criteria

Operational criteria describe how effectively a warehouse can perform its main logistics activities while maintaining the required level of service. Relevant indicators include throughput, inventory accuracy, space utilization, process flexibility, order fulfillment performance, and material handling efficiency [4, 8].

Smart automated warehouses can provide significant advantages in these areas through AS/RS, robotics, and integrated WMS. Automation can improve process consistency, reduce manual handling, and support more efficient use of warehouse space and equipment [14, 17]. However, these benefits depend on the characteristics of the operation and the successful integration of the technologies into existing processes. For this reason, operational performance should be considered together with the investment and technological requirements associated with each warehouse alternative.

4.4 Intelligent Technological Readiness Criteria

Technological readiness is therefore an important criterion when evaluating warehouse transformation alternatives, particularly in relation to automation, digital integration, IoT connectivity, WMS integration, and real-time data availability. Table 2 provides a comparative overview of the four warehouse alternatives based on the main criteria discussed in the previous section.

Table 2. Comparative assessment of intelligent and sustainable warehouse alternatives based on critical evaluation criteria

Evaluation Criteria	Conventional Warehouse	Energy-Efficient Warehouse	Smart Automated Warehouse	Net-Zero Warehouse
Initial investment	Low	Medium	High	Very high
Operating cost reduction potential	Low	Medium	High	High
Energy efficiency	Low	High	High	Very high
Renewable energy integration	None	Limited	Medium	Extensive
Automation level	Low	Low	High	High
Digital integration (IoT, WMS)	Very low	Low–medium	Very high	High
Real-time data availability	Limited	Moderate	High	High
Operational flexibility	Medium	Medium	High	High
Environmental performance	Low	Medium	High	Very high
Implementation complexity	Low	Medium	High	Very high
Intelligent technological readiness	Low	Medium	Very high	High

Note: IoT = Internet of Things; WMS = warehouse management systems.

The comparison considers economic, environmental, operational, and technological aspects in order to highlight the main differences between the alternatives [18]. The assessment is qualitative and is intended to summarize the characteristics identified from the literature and the description of each warehouse concept. It does not represent a quantitative ranking of the alternatives, but provides a basis for discussing their relative advantages, limitations, and implementation requirements.

Smart automated warehouses demonstrate the highest level of technological readiness through the integration of AS systems, robotics, WMS, and digital monitoring solutions. These technologies can improve process coordination, inventory accuracy, and resource utilization. However, their implementation requires appropriate infrastructure, investment, and organizational capabilities. Consequently, technological readiness should reflect not only the technologies available to an organization but also its ability to integrate and effectively use them [17, 18].

Consequently, technological readiness should not be evaluated only according to the level of automation but also according to the ability of an organization to effectively adopt and manage intelligent warehouse solutions. This criterion represents an important connection between warehouse digitalization, operational improvement, and sustainability objectives.

5 Discussion

The findings of this study point to the fact that the transition toward sustainable warehousing cannot be reduced to the introduction of a single advanced technology. The four alternatives considered in this study follow different transformation paths and differ in terms of investment requirements, environmental benefits, operational changes, and technological complexity. The appropriate choice therefore depends on the characteristics of the warehouse, the resources available to the company, and its long-term sustainability objectives.

Table 1 summarizes the main differences between the four warehouse concepts. The comparison shows that the alternatives address sustainability in different ways. The energy-efficient warehouse focuses mainly on reducing energy consumption through improvements to existing facilities, while the smart automated warehouse combines automation and digital technologies with operational optimization. The net-zero warehouse places greater emphasis on energy efficiency and renewable energy integration. The conventional warehouse, although offering the lowest level of technological and environmental improvement, remains relevant as a reference alternative because of its lower investment requirements and simpler operation.

The qualitative comparison in Table 2 provides an overview of these differences, but it does not show how they may translate into energy performance.

To illustrate this aspect, Table 3 presents a hypothetical comparison under identical operating conditions. The same annual throughput is assumed for all four alternatives so that differences in energy performance are not affected by differences in warehouse activity. Energy intensity is used as the main indicator, since it relates energy consumption to the amount of warehouse output and therefore provides a more useful basis for comparison than total annual energy consumption alone [11, 13].

Table 3. Illustrative comparison of energy efficiency performance of intelligent and sustainable warehouse alternatives

Warehouse Alternative	Annual Energy Consumption (kWh)	Annual Throughput (Pallets/Year)	Energy Intensity[1] (kWh/Pallet)	Reduction Compared With Conventional Warehouse[2]
Conventional warehouse	1,000,000	500,000	2.00	–
Energy-efficient warehouse	750,000	500,000	1.50	25%
Smart automated warehouse	650,000	500,000	1.30	35%
Net-zero warehouse	200,000	500,000	0.40	80%

Note: [1] calculated using Eq. (1); [2] calculated using Eq. (2); "–" indicates not applicable.

The values presented in Table 3 are hypothetical and are not intended to represent measured performance from a specific warehouse. Their purpose is to illustrate the possible differences between the alternatives under the same throughput conditions. For the net-zero warehouse, the noted value represents the remaining energy demand after accounting for the contribution of renewable energy.

The calculation presented in Table 3 shows clear differences in energy intensity among the four alternatives. Compared with the conventional warehouse, the energy-efficient alternative reduces energy intensity from 2.00 to 1.50 kWh per pallet, corresponding to a 25% reduction. The smart automated warehouse reaches 1.30 kWh per pallet, or approximately 35% below the conventional case, while the net-zero alternative reaches 0.40 kWh per pallet, representing an 80% reduction. These values illustrate that even relatively moderate improvements in warehouse facilities can result in measurable changes in energy performance.

The difference between the energy-efficient and smart automated alternatives is also relevant. The additional reduction in the smart automated case is not attributed to automation alone, but to the combined effect of process coordination, better information availability, and more efficient use of equipment and resources. This is important because the introduction of advanced technologies does not necessarily result in proportional energy savings. Their actual contribution depends on how well the systems are integrated into warehouse operations and how intensively they are used.

The net-zero alternative shows the largest reduction in the presented scenario. This result reflects the combined effect of lower energy demand and renewable energy generation rather than a single technological intervention. At the same time, the example points to an important limitation: achieving such performance requires suitable infrastructure, considerable investment, and long-term planning. The results should therefore not be interpreted as evidence that the net-zero concept is the preferred solution for every company. Rather, they illustrate the trade-off between the expected environmental improvement and the requirements associated with implementation.

From a practical perspective, the comparison suggests that warehouse transformation can follow different paths. Companies with limited investment capacity may first focus on energy-efficiency measures, while organizations with greater technological and financial capabilities may consider automation or integrated renewable-energy solutions. The appropriate choice ultimately depends on the existing warehouse conditions, operational requirements, available resources, and sustainability objectives of the company.

6 Conclusions

This study examined four warehouse alternatives that represent different approaches to sustainable warehouse development: conventional, energy-efficient, smart automated, and net-zero warehouses. The alternatives were considered from four main perspectives: economic, environmental, operational, and technological. The comparison shows that warehouse transformation can take different forms and that the choice of a particular solution depends largely on the conditions under which a warehouse operates.

The results indicate clear differences between the alternatives. The energy-efficient warehouse offers a relatively simple way to reduce energy consumption without major changes to existing operations. The smart automated warehouse provides wider opportunities for improving warehouse processes through automation, digital systems, and better use of operational data. The net-zero warehouse has the greatest environmental ambition, but it also requires considerably higher investment and more favorable infrastructure and site conditions. The conventional warehouse remains relevant as a reference alternative, particularly for companies where investment capacity or technological readiness is limited.

One of the main findings is that the most advanced warehouse concept is not necessarily the most suitable one for every company. Warehouse size, existing infrastructure, type of products, operational requirements, available financial resources, and the level of technological readiness can all influence the feasibility of a particular solution. For this reason, sustainable warehouse transformation should be considered as a gradual process in which companies can move from relatively simple improvements toward more advanced solutions as their capabilities and requirements change.

The illustrative energy calculation provides an additional perspective on these differences. When the same annual throughput is assumed, the energy-efficient, smart automated, and net-zero alternatives show lower energy intensity than the conventional warehouse. The calculation is based on hypothetical values and therefore should not be interpreted as an empirical comparison. Its purpose is to demonstrate how energy intensity can be used to compare warehouse concepts under comparable operating conditions.

The practical value of the study is in bringing these different transformation paths together in a form that can be used for comparison across different warehouse settings. The proposed evaluation perspective does not require a company to adopt a particular technology or to follow a fixed transformation path. Instead, it can be adapted to the current situation and development objectives of the organization. This makes the approach relevant both for companies considering their first sustainability improvements and for those already moving toward more automated and energy-independent warehouse systems.

Future research should test the identified criteria using data from real warehouse facilities. More detailed analysis of investment costs, energy consumption, payback periods, and the actual effects of automation and renewable energy systems would provide a stronger basis for comparing the alternatives. Further studies could also examine how the relative importance of the criteria changes according to warehouse type, operational characteristics, and the level of technological development.

Data Availability

The data used to support the research findings are available from the corresponding author upon request.

Conflicts of Interest

The author declares no conflicts of interest.

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