Accelerating the Adoption of Energy Efficiency and Renewables in Warehouses and Distribution Centers

Carlo Bianchi,[1] M. Rois Langner,[1] Vedyun Mishra,[1,2] and Paul Torcellini[1]

1 National Renewable Energy Laboratory
2 Syracuse University

NREL is a national laboratory of the U.S. Department of Energy
Office of Energy Efficiency & Renewable Energy
Operated by the Alliance for Sustainable Energy, LLC

This report is available at no cost from the National Renewable Energy Laboratory (NREL) at www.nrel.gov/publications.

Contract No. DE-AC36-08GO28308

Technical Report
NREL/TP-5500-83583
January 2023

Accelerating the Adoption of Energy Efficiency and Renewables in Warehouses and Distribution Centers

Carlo Bianchi,[1] M. Rois Langner,[1] Vedyun Mishra,[1,2] and Paul Torcellini[1]

1 National Renewable Energy Laboratory
2 Syracuse University

Suggested Citation
Bianchi, Carlo, M. Rois Langner, Vedyun Mishra, and Paul Torcellini. 2023 *Accelerating Energy Efficiency and Renewables in Warehouses and Distribution Centers.* Golden, CO: National Renewable Energy Laboratory. NREL/TP-5500-83583. https://www.nrel.gov/docs/fy23osti/83583.pdf.

NREL is a national laboratory of the U.S. Department of Energy
Office of Energy Efficiency & Renewable Energy
Operated by the Alliance for Sustainable Energy, LLC

This report is available at no cost from the National Renewable Energy Laboratory (NREL) at www.nrel.gov/publications.

Contract No. DE-AC36-08GO28308

Technical Report
NREL/TP-5500-83583
January 2023

National Renewable Energy Laboratory
15013 Denver West Parkway
Golden, CO 80401
303-275-3000 • www.nrel.gov

NOTICE

This work was authored by the National Renewable Energy Laboratory, operated by Alliance for Sustainable Energy, LLC, for the U.S. Department of Energy (DOE) under Contract No. DE-AC36-08GO28308. Funding provided by the U.S. Department of Energy Office of Energy Efficiency and Renewable Energy Building Technologies Office. The views expressed herein do not necessarily represent the views of the DOE or the U.S. Government.

This report is available at no cost from the National Renewable Energy Laboratory (NREL) at www.nrel.gov/publications.

U.S. Department of Energy (DOE) reports produced after 1991 and a growing number of pre-1991 documents are available free via www.OSTI.gov.

Cover Photos by Dennis Schroeder: (clockwise, left to right) NREL 51934, NREL 45897, NREL 42160, NREL 45891, NREL 48097, NREL 46526.

NREL prints on paper that contains recycled content.

Acknowledgments

The authors would like to thank Sarah Zaleski, Hannah Debelius, and the U.S. Department of Energy (DOE) Building Technologies Office for supporting this research.

The authors would also like to thank members of the warehouse and distribution center sector who provided insight into building design and operational approaches that reduce energy consumption and integrate distributed energy resources, as well as barriers that impede zero-energy goals. In particular, the authors would like to thank Matt Sterritt (River Valley), Charles Bertuch (Bergmann Associates), Sam Stockdale (Link Logistics), Alex McKallor and Anna Lee Deal (Lynden Transport), Sara Berman and Adrian Avino (IKEA), and Tim Flood (QVC, Qurate Retail Group) for providing the material included in this work. Furthermore, we would like to acknowledge the NREL communications team for editing and reviewing the document.

Executive Summary

Commercial warehouses and storage facilities represent a large portion of commercial buildings in the United States, and their share increases every year. American warehouses are currently 15.5% of the national commercial sector floorspace using 0.43 quads of energy every year. Being the second most common commercial building type according to the latest EIA energy outlook, warehouses sustainability is a key component to decarbonize US commercial buildings. Companies are taking multiple steps in reducing the CO_2 emissions in the logistics sector, and specifically improving the energy efficiency of warehouse facilities.

The National Renewable Energy Laboratory worked with the U.S. Department of Energy to

- Portray the current landscape of efficiency measures and sustainability actions taken in the warehouse sector.
- Provide guidance to overcome barriers, meet sector needs, and identify opportunities to enhance sustainability and substantially reduce the carbon footprint of the warehouse sector through ultra-high-efficient, zero-energy design, electrification considerations in buildings and vehicles, and grid-friendly operation.

More than 60 pieces of literature and internet blogs about sustainability in warehouses and logistics have been consulted, to analyze the current state-of-the art research and practices in the warehouse sector. We also performed one-on-one interviews with warehouse managers and stakeholders. Data collected through literature and interviews provided the status of warehousing in the context of sustainability including energy efficiency, renewables, and carbon emissions. The key findings are listed here:

- Sustainability, decarbonization, and energy efficiency are already a concern for most interviewed companies (4 out of 6). The main areas of focus are renewable energy deployment, waste reduction, electrification, transportation emission reduction.
- All the interviewed companies reported barriers and needs that prevent them from reducing their carbon footprint further. The collected needs are summarized in Table 1.
- Economic factors, such as relatively low cost of natural gas and high electric demand charges, can inhibit companies from adopting more renewable energy and electrification. In fact, Zero Energy Buildings are often perceived as too costly.
- Multiple research areas have been proposed by the warehouse stakeholders, such as: impact of thermal mass on thermal load; quantification of lighting motion sensor impact; CFD analysis for modeling air circulation in warehouses; impact of a carbon tax to boost energy efficiency.
- Lack of metering in warehouses seemed to be the main source of inefficiencies in warehouses. Many facilities would also benefit from a training of warehouse managers on energy efficiency.

- Real-world case studies, warehouse efficiency newsletters, the implementation of a repository of third-party technology evaluations, are some of the resources needs expressed by the interviewed companies.

The collected needs and barriers have been organized in Table 2. They have been prioritized to highlight research and resource areas more appropriate for federal funding. The results are intended to inform areas for new research and deployment activities to achieve **zero-energy and zero-carbon goals.**

Table of Contents

1 Introduction

Buildings play a major role in American energy consumption and carbon emissions. In 2021, the U.S. building stock consumed approximately 40% of primary energy, 75% of electricity, and is responsible for more than 35% of U.S. greenhouse gas emissions [1]. According to the 2022 Energy Information Agency (EIA) Annual Energy Outlook, warehouses represented 15.5% of 2021 U.S. commercial buildings (by area)—the second most common commercial building type with 14.63 billion ft^2 (Figure 1). The warehouse sector is rapidly growing in the United States. In 2018, over 183 million ft^2 of new warehouse space was constructed, compared to 100 million ft^2 annually in the preceding decade [2]. EIA projects the warehouse sector will grow by 6 billion ft^2 in the next 30 years. Between 2012 and 2017, the size of a new warehouse increased by 143%, equivalent to an additional 108,665 ft^2 [3]. In this paper, we define warehouses as "buildings used to store goods, manufactured products, merchandise, raw materials" [1].

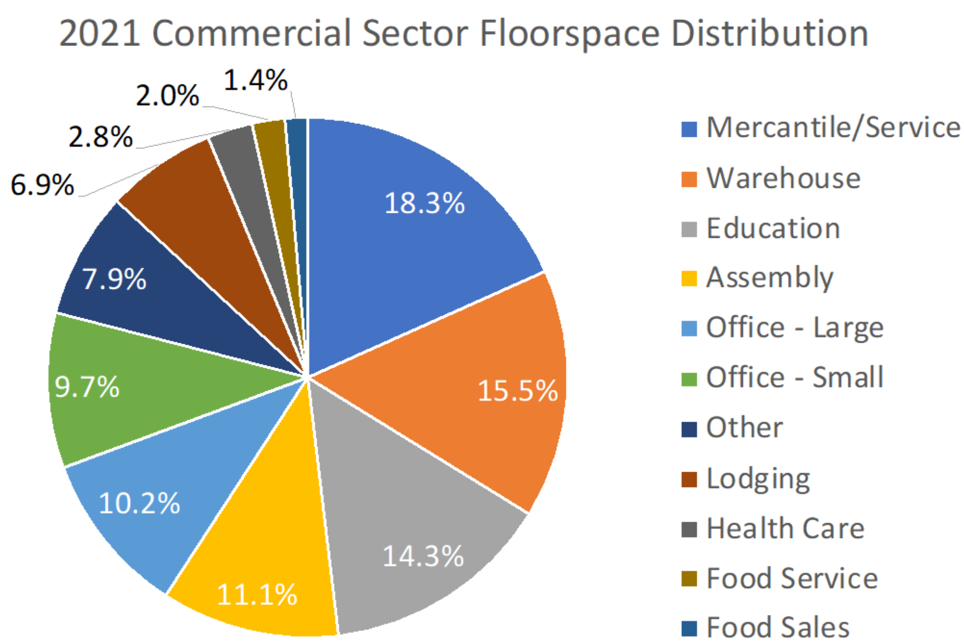

Figure 1. Breakout of commercial buildings sector in the United States according to the 2022 EIA Energy Outlook [1].

Warehouses significantly contribute to national energy consumption and consequent emissions, using 0.43 quads of energy annually [1]. Globally, the World Economic Forum estimated logistics activities in supply chains to be responsible for 5.5% to 13% of global greenhouse gas emissions in 2009 [4]. Food cold-chain, including transportation and cold storage in refrigerated warehouses, contributes approximately 1% of global carbon dioxide (CO_2e) emissions, and this number is likely to increase in upcoming years because of the impact of higher average temperatures from global warming on refrigeration equipment [5]. Refrigerated warehouses also have some of the highest energy use intensities in the commercial building stock, consuming on average 85.3 kBtu/ft^2 of electricity and 9.2 kBtu/ft^2 of natural gas; the refrigeration equipment can consume up to 70% or more of the total building electricity [6].

According to an international survey by Coyote Logistics, sustainability has become a focus for 81% of the surveyed logistics companies [7], in particular the key role that supply chains play in CO_2 emissions. Companies fear that lack of investments toward the reduction of supply chain carbon footprints will lead to negative feedback from consumers and affect their reputation and therefore competitiveness in the market. In response to that, 98% of logistics companies have a sustainability program in place, and 71% of them have measurable goals. A few examples of these sustainability programs include Amazon's pledge to become carbon neutral by 2030 [8]; USPS' investment in producing next-generation delivery vehicles that will include fuel-efficient internal combustion engines or battery electric powertrains [9]; and Amazon, AT&T, and DHL's partnership to put more electric vehicles on the road [10].

There are some obstacles to incentivizing sustainability. The major one is related to split incentives between landlords and tenants. Most leased warehouse business models include "triple net lease" structures where the tenant is responsible for paying all the operating expenses of the property (including real estate taxes), building insurance, utility bills, and maintenance. Thus, there is little to no incentive for landlords to retrofit their facilities for energy efficiency, nor for the tenants to invest in permanent energy-efficient solutions on a property they are temporarily renting.

In recent years, zero-energy buildings (ZEBs) have become more common [11]. We are seeing this in the warehouse sector as well. For example, from the in-person interviews conducted under this effort, the larger owner-occupied warehouse companies like IKEA are regularly updating buildings, installing state-of-the-art equipment, and using renewable energy sources to supply part of their energy needs. The outdoor retailer REI achieved LEED™ Platinum and zero-energy status in their 400,000 ft^2 facility outside of Phoenix [12], and other examples like this exist as well [14–18]. ZEBs produce at least as much renewable energy on-site as they consume over the course of a year. These companies recognize that energy efficiency is critical in reducing the amount of renewable energy required at the site to achieve ZEB status. It is also necessary for reducing the building's greenhouse gas emissions.

In 2007, Griffith *et al. [20]* published a study on multiple building types, analyzing the percentage of energy reduction a building needs to get to zero energy, covering 50% of rooftop area with PV panels. They found that the warehouses, being low-density and low-rise buildings, need little reduction in energy use to be converted to ZEBs. The technologies and efficiencies used in the study are outdated, so current warehouses could be converted to ZEBs with even less effort. It also shows that the large roof areas of warehouses could produce more energy than is required if uses for this energy can be identified.

The U.S. Department of Energy (DOE) has funded many research efforts that have established the feasibility of achieving zero energy in both new and existing buildings across multiple market sectors. Previous DOE-sponsored work pertaining to warehouses includes the 30% Advanced Energy Design Guide (AEDG) for Warehouses [18] and 50% Medium to Big Box Retail AEDG [19]. These design guides provide useful tips and energy consumption targets that could benefit warehouse stakeholders. The information was based on input from leading industry professionals coupled with energy modeling to validate the potential savings.

This report aims to expand on previous efforts to present a current landscape of advanced energy concepts in the warehouse sector. It also aims to recommend a prioritized list of research areas, based on market needs, that could advance the warehouse sector to achieving zero-energy, zero-carbon, and electrification goals more rapidly (Figure 2).

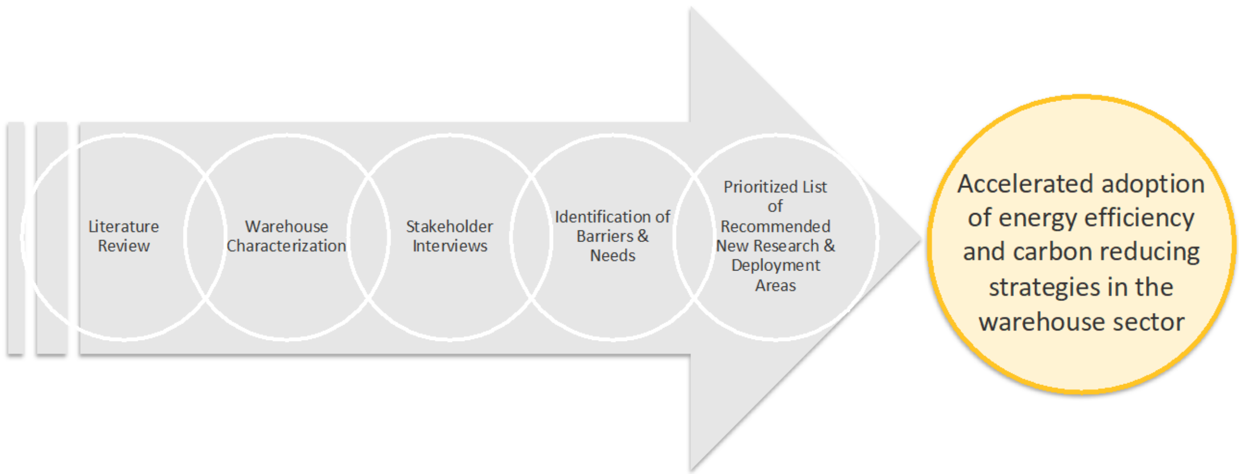

Figure 2. The approach taken and goals of the current research presented in this report

2 Literature Review

Over 50 documents were reviewed, including technical journals, online articles, case studies, and warehouse sector-related blog posts. The reviewed literature is organized into five different categories, corresponding to the major research areas that emerged:

1. Location Optimization
2. Operations Optimization
3. Social, Economic, and Environmental Management
4. Automated Warehousing
5. Warehouse Design Guidance

A common thread appeared around company goals to optimize sustainability in warehouses. As summarized in [15], this thread acknowledges that to reach global sustainability, social, economic, and environmental sustainability must be regarded as equally important components [21]. Key points related to this thread are discussed in the five categories below.

2.1 Location Optimization

Many articles in the reviewed literature focused on the impact of logistics operations on overall energy consumption and sustainability. He et al. [22] in 2018 and Bartolini et al. [23] in 2019 published extensive literature reviews about sustainability in the logistics sector, providing useful resources and case studies for warehouse operators to more sustainably manage operations and transport goods. From these publications, it is also shown that distribution centers and warehouses are growing rapidly in number and are experiencing so-called "logistic sprawl," moving from inner urban areas to the outskirts of cities (also confirmed in other publications [24], [25]). Recent growth of online commerce, especially during the COVID-19 pandemic, has caused warehouses to maintain larger inventories, forced expansion into suburban areas, and created the need for efficient volume usage and transportation [26]. In relation to transportation, the locations of the actual warehouses can be optimized to reduce the CO_2 emissions related to routes of delivery vehicles, whether powered by traditional internal combustion engines [27] or electric motors [28]. These lessons are applicable not just in a city or small region, but also at the national level [29] by optimizing long-distance shipment routes. Warehouse tenants want their centers to be close to urban areas and transportation hot zones (highway entries, ports, airports), in order to reduce both truck driving distance and employee commuting time and distance (both for environmental and social sustainability) [30].

2.2 Operations Optimization

Regarding warehouse logistics related to sorting and picking product, a study by Ene [31] in 2016 proposed a genetic algorithm to review storage assignment policies and consequent picking performances. Their results show a significant reduction in energy consumption (more than 20% for the example provided in their manuscript) when the optimized logistical sorting and picking operations are applied. In 2018, Burinskiene et al. [32] presented a mathematical model to optimize the travel times of products in a warehouse building, with consequent cost reductions and increases in energy efficiency. Analogously, Lorenc et al. [33] analyzed the effect of new storage assignment policies on retrieval time. Through the improvements they proposed, warehouse managers can make informed decisions to optimize the effectiveness of order picking, reducing related energy consumption and improving workforce utilization. Recently, Popovic et al. [34] proposed an innovative approach to optimize operations in warehouses, scheduling activities' execution together with workforce. Through their framework, it is possible to reduce the use of workforce, and therefore its cost (decreased by 20%), with better resource utilization that also drives social, economic, and environmental sustainability benefits.

2.3 Social, Economic, and Environmental Management

Holistic management of social, economic, and environmental systems in warehouses was another topic covered in the reviewed literature. Some papers focused mainly on maximizing economic sustainability of warehouse buildings [35]–[42], while other authors recognized the importance of integrating social and environmental sustainability as well in their analyses [38], [43]–[50]. Torabizadeh et al. introduced 33 key performance indicators to appraise the level of sustainability in a warehouse. The key performance indicators pertain to all three areas of sustainability—social, economic, and environmental—and can be used to maximize overarching warehouse sustainability [51]. Malinowska et al. [52] identified 22 criteria to assess the level of warehouse sustainability, and presented a roadmap to optimally evaluate each criterion. This roadmap comprises a number of specific activities to help guide the assessment. Other authors produced similar studies and offered additional sustainability frameworks or sustainability assessment methods [53], [54].

2.4 Automated Warehousing

Another line of research looks at the level of automation in warehouses. An energy efficiency model for automated storage and retrieval systems (AS/RSs) was proposed by Lerher in 2014 [55], concluding that the energy consumption and the consequent CO_2 emissions increase with the AS/RS speed: the faster the system speed, the more energy consumption and released CO_2 emissions. Similarly, Liu et al. [56] verified that lift velocity and acceleration of the AS/RS are the main factors that influence energy consumption in an automated warehouse. Meneghetti [57]–[60] is a pioneer in sustainable automated warehousing, and his work looked at optimization models for energy consumption, retrieval time, cold storage, and energy used by in-house cranes. Tappia et al. [61] argued that although environmental concerns are commonly in the warehouse sector community, the proposed solutions in automated warehouses mainly focus on operations and economical optimizations, lacking attention to energy use. They showed that by incorporating the energy dimension together with the economic dimension in an automated warehouse, the technology selection shifts from classical AS/RSs to autonomous vehicle storage and retrieval system. Lastly, in 2016, Freis et al. [62] developed synthetic models for three different types of warehouses, based on the level of automation. Their research showed that considering interrelations between the building design and the intra-logistics can reduce warehouse energy demand and CO_2 emissions. The higher the level of automation, the more the energy consumption can shift from HVAC systems to material and product handling equipment. However, this will be dependent on heating or cooling needs of the building. If the building is in a heating dominated climate, higher levels of automation will reduce heating needs and HVAC energy. If the building is in a cooling dominated climate, higher levels of automation will increase cooling needs and HVAC energy.

2.5 Warehouse Design Guidance

When it comes to warehouse building design, there are only a few resources available that provide guidance on high-performance warehouse design. ASHRAE's AEDG for Warehouses provide guidance on how to achieve 30% energy savings compared to ASHRAE Standard 90.1-1999; however, some of this guidance is outdated and applies to small warehouse and self-storage buildings [18]. Some recommended efficiency measures from the AEDG for Medium to Big-Box Retail Buildings, 50% more efficient than ASHRAE Standard 90.1-2004 [19], also could apply to the warehouse sector. The AEDGs help the building construction industry by providing prescriptive solutions to achieve significant energy savings over minimum building energy codes. The design recommendations in these guides are still relevant. However, updated design guidance specific for warehouses would be beneficial.

3 Warehouse Characterization and Stakeholder Input

Leveraging findings from the literature review, we developed a high-level characterization of warehouse buildings shown in Figure 3. This includes how the warehouses are conditioned, whether there is refrigeration, and to what degree the sorting and picking processes are automated. This characterization helps frame how we discuss warehouses, plan for improved building design and operations, and direct future research to create more impactful resources for specific warehouse audiences. The proposed characterization is shown in Figure 3. The research also involved conducting several one-on-one stakeholder interviews that included warehouse design firms and warehouse energy, sustainability, and facility managers. Key findings from these interviews were organized to highlight current sustainability, energy, and carbon reduction successes; barriers that those organizations face in implementing sustainability, energy, and carbon reduction strategies; and specific needs that would accelerate further implementation of those strategies. This final list of barriers and needs then fed into a prioritized list of recommended next steps that include additional research topic areas and deployment pathways to get to zero energy and zero carbon.

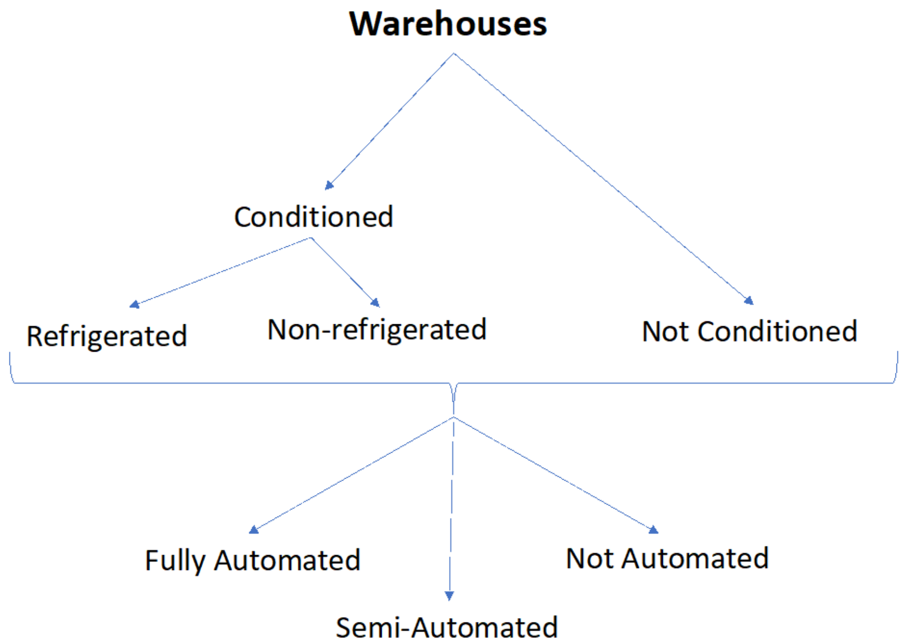

Figure 3. Categorization of warehouse as found in the literature

For the stakeholder interviews, the research team spoke to six stakeholders that included warehouse owners, architects, engineers, and logistics companies from IKEA, Bergmann, Link Logistics, Qurate Retail Group (QVC), Lynden Transportation, and River Valley Group. NREL interviewed these stakeholders in a series of 30- to 60-minute conference calls.

To guide the conversation, we developed a framework of questions, including:

- What are your current energy and carbon emission reduction goals and practices? How do zero energy and carbon neutrality play into those goals?
- What is stopping you from achieving your energy and emission goals? What information, resources, or tools are missing?
- Who is most responsible for making decisions around energy and carbon?
- What is the best path to receive or incorporate new technological information about zero energy and carbon reduction strategies?

The data collected from these interviews were then synthesized to understand current successes, barriers, and needs, in order to accelerate progress toward more energy-efficient and lower-carbon-emitting warehouse buildings in the near future.

4 Results

We organized the feedback received from the stakeholders in three categories: successes, barriers, and needs. Because the needs suggest future research areas and resource development, they are also summarized at the end of the section in Table 1.

4.1 Successes

Four of the six companies that were interviewed have already committed to short-term goals for CO_2 reduction and environmental sustainability improvement. Two of them have sustainability and emission reduction plans in place at a corporate level. These include committing to 100% renewable energy consumption in the next 10 years; committing to cut CO_2 emissions by 40% in the next two years; reaching 85% of waste reduction through reuse, recycling, and sorting practices (examples of this include reusing pallets or employing cardboard pallets); and/or including CO_2 reduction as part of return-on-investment considerations.

Building equipment and technological upgrades have been adopted by most of the interviewed stakeholders (four out of six). The use of LED lighting and motion sensors to control lights proved to be the most popular energy conservation measures, followed by the complete electrification of space conditioning. Heating and cooling equipment have primarily transitioned to electric equipment, so loads can be offset with photovoltaics (PV). Large interior fans are also used to reduce facility cooling needs and consequent CO_2 emissions. One interviewee, has committed to installing 200 MW of solar power production by 2025, including deploying PV panels on the company's retail stores. Another interviewed company is also invested in strategically placing insulation in areas of high heat transfer (e.g., refrigerated warehouse areas).

On the front of sustainability in transportation, three companies have already implemented advanced strategies. A system was put in place to monitor and reduce carbon emissions associated with transportation through the SmartWay Transport Program [4], an EPA-sponsored program helping the freight transportation sector to increase efficiency in their supply chain. Fuel use and costs are also incorporated into a Green Benchmark report and included in periodic review process with upper management and board members. Similarly, one other stakeholder is on track for a zero-emissions transportation plan by 2025. To increase social and environmental sustainability, the same company also facilitates access to public transportation to and from their facilities for the employees. Three companies invested in electrifying lift trucks and forklifts. One refrigerated warehouse owner adopted high-efficiency plug-in refrigerated containers (known as "reefers") for frozen food transport, using 30% less energy than typical containers.

4.2 Barriers and Needs

All the interviewed companies highlighted economic factors that can inhibit the adoption of more sustainable solutions for their facilities. The cost of natural gas in the United States has historically been very low compared to electricity, which has disincentivized some in electrifying natural gas heating systems in warehouses. Electric demand charges can also be prohibitive to building owners looking to electrify certain systems and technologies. For example, there are high demand charges associated with charging plug-in refrigerated shipping containers (the "reefers" mentioned above). Often, some products available on the market offer great environmental benefit, but with long payback periods. Environmental and economic sustainability need to be taken into consideration at the same time, as also stated in the literature [63]. For this reason, ZEBs can be perceived as too costly with long payback periods that often exceed company business models.

Moreover, many warehouses are leased by tenants, and industrial landlords typically take a passive stance on managing and controlling energy (see the discussion on triple net leases in

Section 1). DOE has explored green lease language [64] in the commercial building sector at depth; however, there is a need to better connect this lease language to the warehouse center sector. In addition, it would be helpful if landlords could better control tenant energy use or incentivize tenant's energy conservation. Furthermore, some of the interviewed companies mentioned that better information on financing solutions, or an incentives database that apply to warehouses, would help overcome other economic struggles.

In terms of the contributions that could be provided by additional research and development in this area, many suggestions were offered by the stakeholders. Three logistics operators would be interested in better understanding the impact of thermal mass on thermal loads and HVAC equipment sizing. Although motion sensors are already widely adopted for lighting, a more detailed quantification of their impact on lighting loads in warehouses would help boost their utilization, as would guidance on how to improve ambient lighting levels to provide sufficient illumination while saving energy. Analogously, analysis of the energy impact of infiltration through warehouse fenestration would be beneficial for the warehouse energy managers. One stakeholder proposed computational fluid dynamics (CFD) modeling of air circulation in warehouses to better select and size equipment. That stakeholder also suggested that research into how willing people are to improve energy efficiency based on a potential carbon tax would help shape environmental public policies and incentives.

Two out of six stakeholders expressed difficulties in electrifying their fleet—either because large batteries impinge on freight truck weight limits for carrying goods, or because commercial electric vehicles can be very expensive. Often, companies lease electric vehicles; however, third-party management could potentially inhibit how electric vehicle charging could more optimally integrate with other building loads and distributed energy resources for maximized reductions in energy, demand, utility costs, and carbon.

Investments in PV and energy storage systems are important to many warehouse stakeholders. One stakeholder has a requirement that the investment needs to pay back in under 10 years. They also try to combine PV and energy storage together for cost-effectiveness, especially in states that offer financial incentives. Lack of information on PV recycling and on PV power acquisition (on-site or off-site, power purchase agreements) also inhibits PV adoption. Better information on the balance between investing in energy storage, PV, and emergency generation together to make financial returns, with more resources on best practices for battery management and for extending battery life, would also be helpful in implementing PV systems. Solar PV has also been reported as problematic on large open-span roofs due to weight limits; more information on weight considerations for installing more PV on large, expansive roofs would be beneficial to design teams. One stakeholder requested more information on fuel cell systems integration with warehouses.

In terms of facility management, many concerns were raised. Lack of metering appeared to be the most common issue for identifying inefficiencies. Facility manager training in energy management, and implementation of energy efficiency measures is often not prioritized, because it may not align with business goals and often facility managers are busy enough in maintaining existing building operations. Furthermore, it takes significant time and proper analysis to examine building energy data accurately. Therefore, facility managers often have poor understanding of energy consumed in their buildings. For example, lack of knowledge in using a building automation system can lead to certain equipment running all day every day, such as air conditioning, or equipment left on in vacant buildings, etc. An overarching platform to monitor energy performance and operations of portfolio could help significantly in these regards, as well as training programs for waste and water reduction, building management, etc. One stakeholder required more direction for the next tier of efficiency strategies after the “low-hanging fruit” strategies were implemented. Another stakeholder lamented a disconnect between design and operational performance of zero-energy buildings, which creates uncertainty risk to building owners. Lastly, retrofits can be difficult—there is no stock recipe for retrofits. The age of certain facilities and types of certain equipment can make retrofits challenging and more expensive to implement. More resources on retrofit options would be beneficial.

Regarding real-world examples, two companies stated that case studies were missing on the e-commerce world and on electric energy measures adoption with a payback period of 1–3 years. More regular information and updates on warehouse efficiency via online communications such as newsletters, and partnerships with trusted industry organizations, as well as access to better information about specific vendors and their solutions for warehouses would be helpful. Similarly, one stakeholder suggested the implementation of a repository of third-party technology evaluations depicting energy and cost savings.

More general comments from the interviews included needing better information on life cycle analysis on products. Stronger partnership with ASHRAE for more information dissemination about warehouses and distribution centers would also be beneficial to design teams. One stakeholder requested more information on efficient motor upgrades for fans and more efficient heating technologies that move away from natural gas hanging space heaters. Information on how to phase out high global warming potential refrigerants would also be appreciated by another stakeholder.

The needs expressed by these stakeholders have been summarized in Table 1. They have been sorted by relevant categories and prioritized subjectively by this research team based on communicated warehouse needs.

Table 1. Different areas of needs expressed by the interviewed stakeholders

Category	#	Needs	Priority
Economics	1	**INCENTIVES:** Database of incentives that apply specifically to warehouses	Low
	2	**FINANCING SOLUTIONS:** Better information on financing solutions for energy efficiency	Low
	3	**LANDLORDS INITIATIVE:** Landlords to take a more active stance to control or better influence/incentivize tenant energy consumption	Low
Research & Development	4	**THERMAL MASS IMPACT:** Analysis of thermal mass impacts on heating and cooling loads, and impact on space-conditioning equipment	High
	5	**CFD:** computational fluid dynamics analysis to understand airflow circulation and infiltration through warehouse envelope and fenestration, and those impacts on space-conditioning equipment	High
	6	**LIGHTING LEVELS CONTROL:** Guidance on how to best control and minimize lighting levels	High
	7	**CARBON TAX EFFECT:** Research to understand how willing warehouse owners and tenants are to improve energy efficiency based on a potential carbon tax	Low
Renewables and Storage	8	**PV FOR FINANCIAL RETURNS:** Better information on the value and financial benefit in investing in energy storage and PV versus traditional emergency generation	High
	9	**BATTERIES:** Resources on best practices for battery management and extending battery life	Low
	10	**FUEL CELLS:** Better information on fuel cell technology	Low
	11	**PV STRUCTURAL INFO:** Information on considerations for installing more PV on a large, expansive roof, from a weight standpoint	High
Asset Management	12	**ENERGY MONITOR PLATFORM:** Overarching software platforms to monitor energy performance and operations of warehouse portfolios	Med
	13	**ENERGY+COST SAVINGS REPOSITORY:** Repository of third-party technology evaluations depicting energy and cost savings	High
	14	**BUILDING MANAGEMENT TRAININGS:** Training for implementation of waste reduction, water reduction, building management, etc.	Med
	15	**RETROFITTING INFO:** More information on retrofitting warehouse/distribution centers	High
	16	**REFRIGERANT PHASE OUT INFO:** Information on how to phase out high global warming potential refrigerants	High
General	17	**CASE STUDIES:** Case studies of actual buildings including energy performance and energy strategies	High
	18	**WAREHOUSE EFFICIENCY NEWSLETTER**: More regular information on warehouse efficiency via online communication such as newsletters, etc. and partnerships with trusted industry organizations	Low
	19	**WAREHOUSE VENDORS REPOSITORY:** Repository of vendors and product/equipment for warehouses	Low
	20	**LCA INFO:** Better information on life cycle analysis	High
	21	**ASHRAE PARTNERSHIP:** Stronger partnership with ASHRAE for information dissemination	High
	22	**MOTOR UPGRADES INFO:** Information on efficient motor upgrades for fans	Med
	23	**ELECTRIC HEATING INFO:** Information on more efficient heating technologies that move away from natural gas hanging space heaters	Med

5 Conclusions

Warehouses represent a substantial and growing share of the U.S. building stock, and therefore analyzing their energy consumption and emissions is critical for lowering carbon emissions and greening our supply chain of food and goods. Our literature review highlighted how warehousing spaces are growing, especially during the COVID-19 pandemic, and they are transitioning closer to more densely populated areas in cities. Literature also showcased many different research areas related to sustainability in warehouses and logistics, underlining how this topic has been receiving more and more attention, encompassing the 3 pillars of sustainability (social, economic, environmental). Through a number of stakeholder interviews, sector needs and barriers were identified. These are presented in Table 1 and aim to guide future research and resource development to help enhance energy efficiency, sustainability, and zero-carbon goals in the warehouse sector.

Some of the needs and barriers suggested in the interviews are higher priority than others. Similarly, some could be tackled by federal investments, while others could be addressed by industry organizations. Research and resource areas more appropriate for federal funding include those listed in Table 2.

Table 2. Research areas that emerged in the interviews with stakeholders

<table>
<tr><th></th><th>Project Areas</th><th>Needs Met</th></tr>
<tr><td rowspan="3">Detailed Design Strategies</td><td>Analysis of thermal mass impacts on heating and cooling loads, and impact on space-conditioning equipment</td><td>4</td></tr>
<tr><td>CFD analysis to understand airflow circulation and infiltration through warehouse fenestration, and those impacts on space-conditioning equipment</td><td>5</td></tr>
<tr><td>Guidance on how to best control and minimize lighting levels in warehouses based on occupancy and automation levels</td><td>6</td></tr>
<tr><td rowspan="3">Generalized Retrofit Design Strategies</td><td>Develop repository for third-party technology evaluations depicting energy and cost savings</td><td>13, 19, 22, 23</td></tr>
<tr><td>Develop guidance on retrofitting warehouse and distribution centers that would include design guidance and building management training modules</td><td>14, 15</td></tr>
<tr><td>Create information on how to phase out high global warming potential refrigerants</td><td>16</td></tr>
<tr><td rowspan="2">Renewables and Storage</td><td>Provide better information on the balance of investing in energy storage, PV, and emergency generation to make financial returns</td><td>8</td></tr>
<tr><td>Develop information on considerations for installing more PV on a large, expansive roof, from a weight standpoint</td><td>11</td></tr>
<tr><td rowspan="2">Deployment</td><td>Case study development:
• Highlighting successes of real projects
• Providing information on lifecycle analysis</td><td>17, 20</td></tr>
<tr><td>Information dissemination:
• Develop a warehouse accelerator through Better Buildings
• Provide regular online updates such via newsletters, bulletins, blog posts, etc.
• Develop and strengthen partnerships with warehouse industry organizations for information dissemination</td><td>18, 21</td></tr>
</table>

These new project areas will help address the (1) lack of technical resources and information available to warehouses, (2) warehouse ability to improve short- to medium-term return on investments, and (3) offer better information on using new technologies and managing warehouse energy performance.

References

[1] Bipartisan Policy Center, "Annual energy outlook 2022," *Energy Information Administration, Washington, DC*, vol. 12, 2022.

[2] U. EIA, "Commercial buildings energy consumption survey," *United Sates Department of Energy, Ed., ed*, 2018.

[3] D. Egan, "U.S. MarketFlash Going Large: Warehouse Sizes Increase for Modern Logistics," *CBRE*, 2017, [Online]. Available: https://www.cbre.us/real-estate-services/real-estate-industries/industrial-and-logistics/industrial-and-logistics-research/us-marketflash---going-large-warehouse-sizes-increase-for-modern-logistics--november-2017

[4] E. Blanco and K. C. Tan, "EPA SmartWay Transport Partnership," *Cambridge, MA: Massachusetts Institute of Technology Center for Transportation and Logistics*, 2009.

[5] S. J. James, "The food cold-chain and climate change," *Food Research International*, p. 13, 2010.

[6] O. B. S. Center, "Warehouses." [Online]. Available: https://ouc.bizenergyadvisor.com/article/warehouses

[7] D. Sparkman, "Logistics Commitment to Sustainability Grows," *Material Handling and Logistics*, Dec. 2020, [Online]. Available: https://www.mhlnews.com/global-supply-chain/article/21150525/logistics-commitment-to-sustainability-grows

[8] M. Moralez, "Amazon Vows to be Carbon Neutral by 2030," *SDC Executive*, Sep. 2019, [Online]. Available: https://www.sdcexec.com/sustainability/news/21087764/amazon-vows-to-be-carbon-neutral-by-2030

[9] K. Frum, "U.S. Postal Service Awards Contract to Launch Multi-Billion-Dollar Modernization of Postal Delivery Vehicle Fleet," *USPS*, Feb. 2021, [Online]. Available: https://about.usps.com/newsroom/national-releases/2021/0223-multi-billion-dollar-modernization-of-postal-delivery-vehicle-fleet.htm

[10] SDC, "Big-named companies join together to get more electric vehicles on the road," *SDC Executive*, Jan. 2020, [Online]. Available: https://www.sdcexec.com/transportation/news/21112119/bignamed-companies-join-together-to-get-more-electric-vehicles-on-the-road

[11] N. B. Institute, "GETTING TO ZERO BUILDINGS DATABASE." 2022.

[12] B. Buildings, "REI NET ZERO ENERGY DISTRIBUTION CENTER," *Better Buildings - U.S. DOE*, Jul. 2016, Accessed: Aug. 12, 2021. [Online]. Available: https://betterbuildingssolutioncenter.energy.gov/showcase-projects/rei-net-zero-energy-distribution-center

[13] B. TIMOTHY B. WHEELER, "McCormick warehouse cuts energy bill to zero," *THE BALTIMORE SUN*, Apr. 2012, Accessed: Aug. 12, 2021. [Online]. Available: https://www.baltimoresun.com/news/environment/bs-gr-netzero-energy-20120414-story.html

[14] B. JOHN YEWELL, "Grand opening celebrates NIEHS net-zero energy warehouse," *National Institute of Environmental Health Sciences*, Jan. 2018, Accessed: Aug. 12, 2021. [Online]. Available: https://factor.niehs.nih.gov/2018/1/beyond-the-bench/warehouse/index.htm

[15] B. Jenni Roder, "SSOE Completes LEED® Platinum Net Zero Energy Warehouse and Distribution Center for the National Institute of Environmental Health Sciences," *SSOE.com*, Oct. 2018, Accessed: Aug. 12, 2021. [Online]. Available: https://www.ssoe.com/press-

releases/ssoe-completes-leed-platinum-net-zero-energy-warehouse-and-distribution-center-for-the-national-institute-of-environmental-health-sciences/
[16] JLL, “How the push towards net zero is raising the bar for warehouses,” *JLL*, Oct. 2020, Accessed: Aug. 12, 2021. [Online]. Available: https://www.jll.co.uk/en/trends-and-insights/workplace/how-the-push-towards-net-zero-is-raising-the-bar-for-warehouses
[17] K. Pocock, “The net-zero warehouse - closer than you think,” *Linkedin*, Aug. 2020, Accessed: Aug. 12, 2021. [Online]. Available: https://www.linkedin.com/pulse/net-zero-warehouse-closer-than-you-think-kevin-pocock
[18] B. Liu, R. E. Jarnagin, W. Jiang, and K. Gowri, “Technical Support Document: The Development of the Advanced Energy Design Guide for Small Warehouse and Self-Storage Buildings,” Dec. 2007, doi: 10.2172/921429.
[19] E. Bonnema *et al.*, “50% Advanced Energy Design Guides,” National Renewable Energy Lab.(NREL), Golden, CO (United States), 2012.
[20] B. Griffith, N. Long, P. Torcellini, R. Judkoff, D. Crawley, and J. Ryan, “Assessment of the technical potential for achieving net zero-energy buildings in the commercial sector,” National Renewable Energy Lab.(NREL), Golden, CO (United States), 2007.
[21] A. D. Basiago, “Economic, social, and environmental sustainability in development theory and urban planning practice,” *Environmentalist*, vol. 19, no. 2, pp. 145–161, 1998.
[22] M. He, J. Shen, X. Wu, and J. Luo, “Logistics Space: A Literature Review from the Sustainability Perspective,” p. 24, 2018.
[23] M. Bartolini, “Green warehousing: Systematic literature review and bibliometric analysis,” *Journal of Cleaner Production*, p. 17, 2019.
[24] K. A. Student, “Impacts of logistics sprawl on the urban environment and logistics: Taxonomy and review of literature,” *Journal of Transport Geography*, p. 9, 2016.
[25] T. Sakai, “Location factors for logistics facilities_ Location choice modeling considering activity categories,” *Journal of Transport Geography*, p. 10, 2020.
[26] N. McCulloch, “Building Sustainable Warehouses of the Future,” *Rubicon*, Sep. 2019, [Online]. Available: https://www.rubicon.com/blog/warehouses-of-the-future/
[27] J. C. Vélazquez-Martínez, J. C. Fransoo, E. E. Blanco, and J. Mora-Vargas, “Transportation cost and CO2 emissions in location decision models,” *BETA publicatie: working papers*, vol. 451, 2014.
[28] A. Muñoz-Villamizar, J. R. Montoya-Torres, and J. Faulin, “Impact of the use of electric vehicles in collaborative urban transport networks: A case study,” *Transportation Research Part D: Transport and Environment*, vol. 50, pp. 40–54, 2017.
[29] Y. Bouchery, C. J. Corbett, J. C. Fransoo, and T. Tan, *Sustainable supply chains: A research-based textbook on operations and strategy*, vol. 4. Springer, 2016.
[30] Kaplan, S. and Tran, A., “More than 40 percent of Americans live in counties hit by climate disasters in 2021,” *The Washington Post*, Jan. 05, 2022. [Online]. Available: https://www.washingtonpost.com/climate-environment/2022/01/05/climate-disasters-2021-fires/
[31] S. Ene, “A genetic algorithm for minimizing energy consumption in warehouses,” p. 8, 2016.
[32] A. Burinskiene, A. Lorenc, and T. Lerher, “A simulation study for the sustainability and reduction of waste in warehouse logistics,” *International Journal of Simulation Modelling*, vol. 17, no. 3, pp. 485–497, 2018.

[33] A. Lorenc and T. Lerher, "Effectiveness of product storage policy according to classification criteria and warehouse size," *FME transactions*, vol. 47, no. 1, pp. 142–150, 2019.
[34] V. Popović, M. Kilibarda, M. Andrejić, B. Jereb, and D. Dragan, "A New Sustainable Warehouse Management Approach for Workforce and Activities Scheduling," p. 20, 2021.
[35] M. De Koster and B. M. Balk, "Benchmarking and monitoring international warehouse operations in Europe," *Production and Operations Management*, vol. 17, no. 2, pp. 175–183, 2008.
[36] G. Kayakutlu and G. Buyukozkan, "Assessing performance factors for a 3PL in a value chain," *International Journal of Production Economics*, vol. 131, no. 2, pp. 441–452, 2011.
[37] D. M. Gutierrez, L. F. Scavarda, L. Fiorencio, and R. A. Martins, "Evolution of the performance measurement system in the Logistics Department of a broadcasting company: An action research," *International Journal of Production Economics*, vol. 160, pp. 1–12, 2015.
[38] A. Johnson and L. McGinnis, "Performance measurement in the warehousing industry," *IIE Transactions*, vol. 43, no. 3, pp. 220–230, 2010.
[39] N. Litvak and M. Vlasiou, "A survey on performance analysis of warehouse carousel systems," *Statistica Neerlandica*, vol. 64, no. 4, pp. 401–447, 2010.
[40] P. Ribino, M. Cossentino, C. Lodato, and S. Lopes, "Agent-based simulation study for improving logistic warehouse performance," *Journal of Simulation*, vol. 12, no. 1, pp. 23–41, 2018.
[41] S. T. Hackman, E. H. Frazelle, P. M. Griffin, S. O. Griffin, and D. A. Vlasta, "Benchmarking warehousing and distribution operations: an input-output approach," *Journal of Productivity Analysis*, vol. 16, no. 1, pp. 79–100, 2001.
[42] A. C. Cagliano, A. DeMarco, C. Rafele, and S. Volpe, "Using system dynamics in warehouse management: a fast-fashion case study," *Journal of Manufacturing Technology Management*, 2011.
[43] C. Chen, X. Xu, and J. K. Day, "Thermal comfort or money saving? Exploring intentions to conserve energy among low-income households in the United States," *Energy Research & Social Science*, vol. 26, pp. 61–71, 2017.
[44] J. D. Linton, R. Klassen, and V. Jayaraman, "Sustainable supply chains: An introduction," *Journal of operations management*, vol. 25, no. 6, pp. 1075–1082, 2007.
[45] K.-S. Tan, M. D. Ahmed, and D. Sundaram, "Sustainable enterprise modelling and simulation in a warehousing context," *Business Process Management Journal*, 2010.
[46] M. Shafiee, F. H. Lotfi, and H. Saleh, "Supply chain performance evaluation with data envelopment analysis and balanced scorecard approach," *Applied mathematical modelling*, vol. 38, no. 21–22, pp. 5092–5112, 2014.
[47] J. Bloemhof-Ruwaard, J. Quariguasi-Frota-Neto, J. Nunen, and E. Heck, "Designing and evaluating sustainable logistics networks," *International Journal of Production Economics*, vol. 111, no. 2, pp. 195–208, 2008.
[48] E. Garriga and D. Melé, "Corporate social responsibility theories: Mapping the territory," *Journal of business ethics*, vol. 53, no. 1, pp. 51–71, 2004.
[49] M. Calzavara, C. H. Glock, E. H. Grosse, A. Persona, and F. Sgarbossa, "Analysis of economic and ergonomic performance measures of different rack layouts in an order picking warehouse," *Computers & Industrial Engineering*, vol. 111, pp. 527–536, 2017.

[50] N. Foroozesh, R. Tavakkoli-Moghaddam, and S. M. Mousavi, "A novel group decision model based on mean–variance–skewness concepts and interval-valued fuzzy sets for a selection problem of the sustainable warehouse location under uncertainty," *Neural Computing and Applications*, vol. 30, no. 11, pp. 3277–3293, 2018.
[51] M. Torabizadeh, "Identifying sustainable warehouse management system indicators and proposing new weighting method," *Journal of Cleaner Production*, p. 11, 2020.
[52] M. Magdalena, R. Andrzej, and S. Mariusz, "Roadmap to sustainable warehouse," *SHS Web of Conferences*, p. 9, 2018.
[53] W. Al-Wakkal and Z. Ding, "A Framework for Sustainable Cold Chain Logistics in Over-The-Counter (OTC) Drugs," 2020.
[54] T. W. Amjed and N. J. Harrison, "A Model for sustainable warehousing: from theory to best practices," in *Proceedings of the International Decision Sciences Institute and Asia Pacific DSI Conference*, 2013, pp. 1–28.
[55] T. Lerher, Y. Ekren, Z. Sari, and B. Rosi, "Simulation analysis of shuttle based storage and retrieval systems," *International journal of simulation modelling*, vol. 14, no. 1, pp. 48–59, 2015.
[56] Z. Liu, Y. Wang, M. Jin, H. Wu, and W. Dong, "Energy consumption model for shuttle-based Storage and Retrieval Systems," *Journal of Cleaner Production*, vol. 282, p. 124480, 2021.
[57] A. Meneghetti and L. Monti, "Sustainable storage assignment and dwell-point policies for automated storage and retrieval systems," p. 11.
[58] A. Meneghetti and L. Monti, "Multiple-weight unit load storage assignment strategies for energy-efficient automated warehouses," *International Journal of Logistics Research and Applications*, vol. 17, no. 4, pp. 304–322, 2014.
[59] A. Meneghetti, E. D. Borgo, and L. Monti, "Decision support optimisation models for design of sustainable automated warehouses," *International Journal of Shipping and Transport Logistics*, vol. 7, no. 3, pp. 266–294, 2015.
[60] A. Meneghetti, "Greening the food supply chain: an optimisation model for sustainable design of refrigerated automated warehouses," *International Journal of Production Research*, p. 22.
[61] E. Tappia, G. Marchet, M. Melacini, and S. Perotti, "Incorporating the environmental dimension in the assessment of automated warehouses," *Production Planning & Control*, vol. 26, no. 10, pp. 824–838, 2015.
[62] J. Freis, P. Vohlidka, and W. A. Günthner, "Low-Carbon Warehousing: Examining Impacts of Building and Intra-Logistics Design Options on Energy Demand and the CO2 Emissions of Logistics Centers," p. 36, 2016.
[63] B. Jaekel, "How Logistics Takes on Sustainability," *SDC Executive*, Jun. 2020, [Online]. Available: https://www.sdcexec.com/sustainability/article/21135481/how-logistics-takes-on-sustainability
[64] DOE, "Green Lease Leaders - Creating Sustainable Landlord-Tenant Relationships." 2022. [Online]. Available: https://www.greenleaseleaders.com/