NREL
Transforming ENERGY

NON-REFRIGERATED WAREHOUSE DESIGN GUIDE

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Acronyms

AEDG	Advanced Energy Design Guide
ASHRAE	American Society of Heating, Refrigerating, and Air-Conditioning Engineers
CI	continuous insulation
COP	coefficient of performance
Cx	commissioning
CxA	commissioning authority
DER	distributed energy resource
DHW	domestic hot water
DOAS	dedicated outside air system
DOE	U.S. Department of Energy
EUI	energy use intensity
GHG	greenhouse gas
HVAC	heating, ventilating, and air conditioning
HVLS	high-volume low-speed
IAQ	indoor air quality
LCOE	levelized cost of electricity
LED	light-emitting diode
OPR	owner's project requirements
PPL	plug and process loads
PV	photovoltaic
QA	quality assurance
RFP	request for proposal
SHGC	solar heat gain coefficient
SWH	service water heating
VSD	variable-speed drive

HOW TO USE THIS GUIDE

TABLE OF CONTENTS/HOME

QUICKLINKS

INTRODUCTION

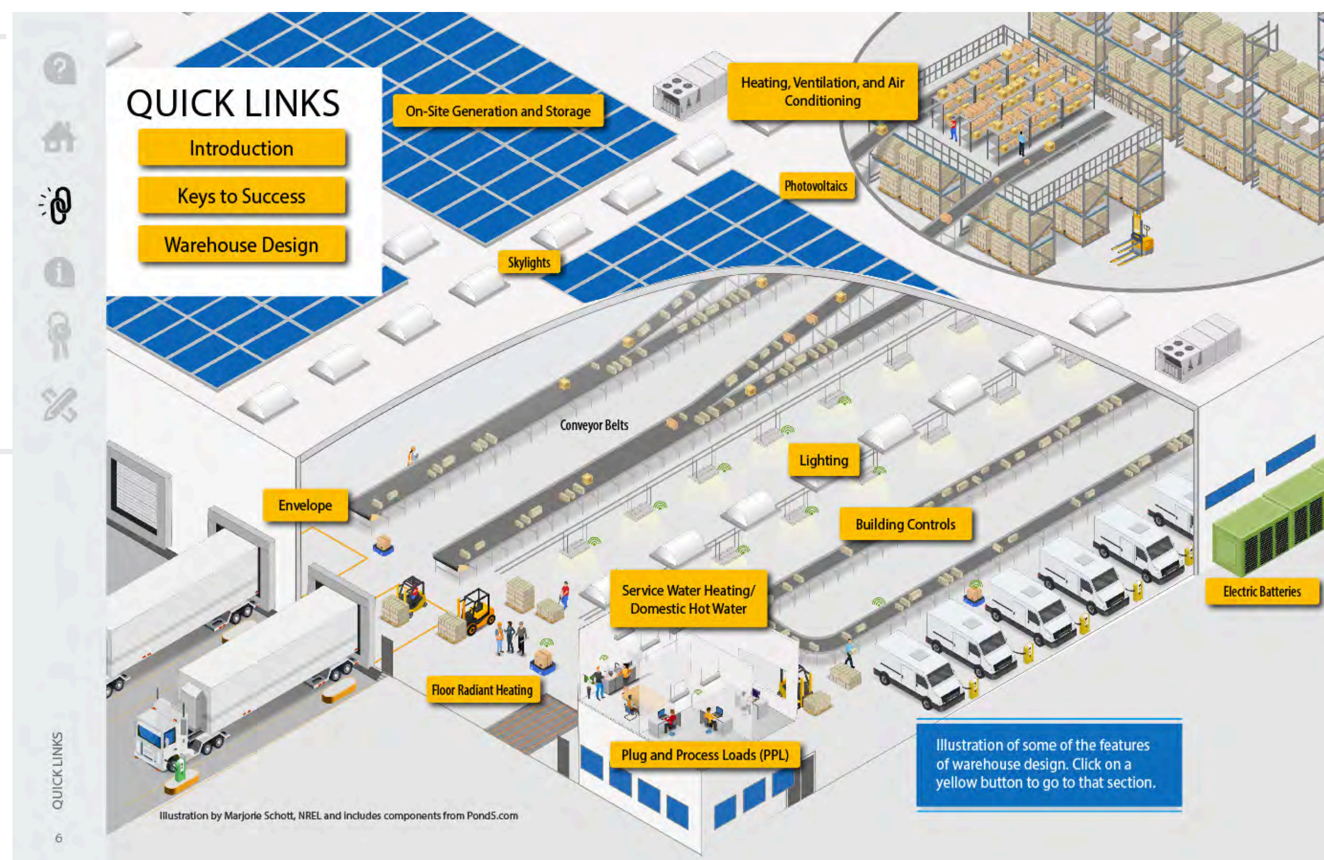
KEYS TO SUCCESS

WAREHOUSE DESIGN GUIDANCE

HOW TO USE THIS GUIDE

If you are viewing this document on your computer, with Acrobat Reader, there are interactive features to help you quickly navigate the document and go to specific information.

Use these icons on the side of the page to navigate to the major sections of the document. The icon in black indicates the current section.



Yellow buttons like these can be found on the QUICK LINKS page and they will take you to that section of the document.


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TABLE OF CONTENTS

QUICK LINKS

Introduction

Keys to Success

Warehouse Design

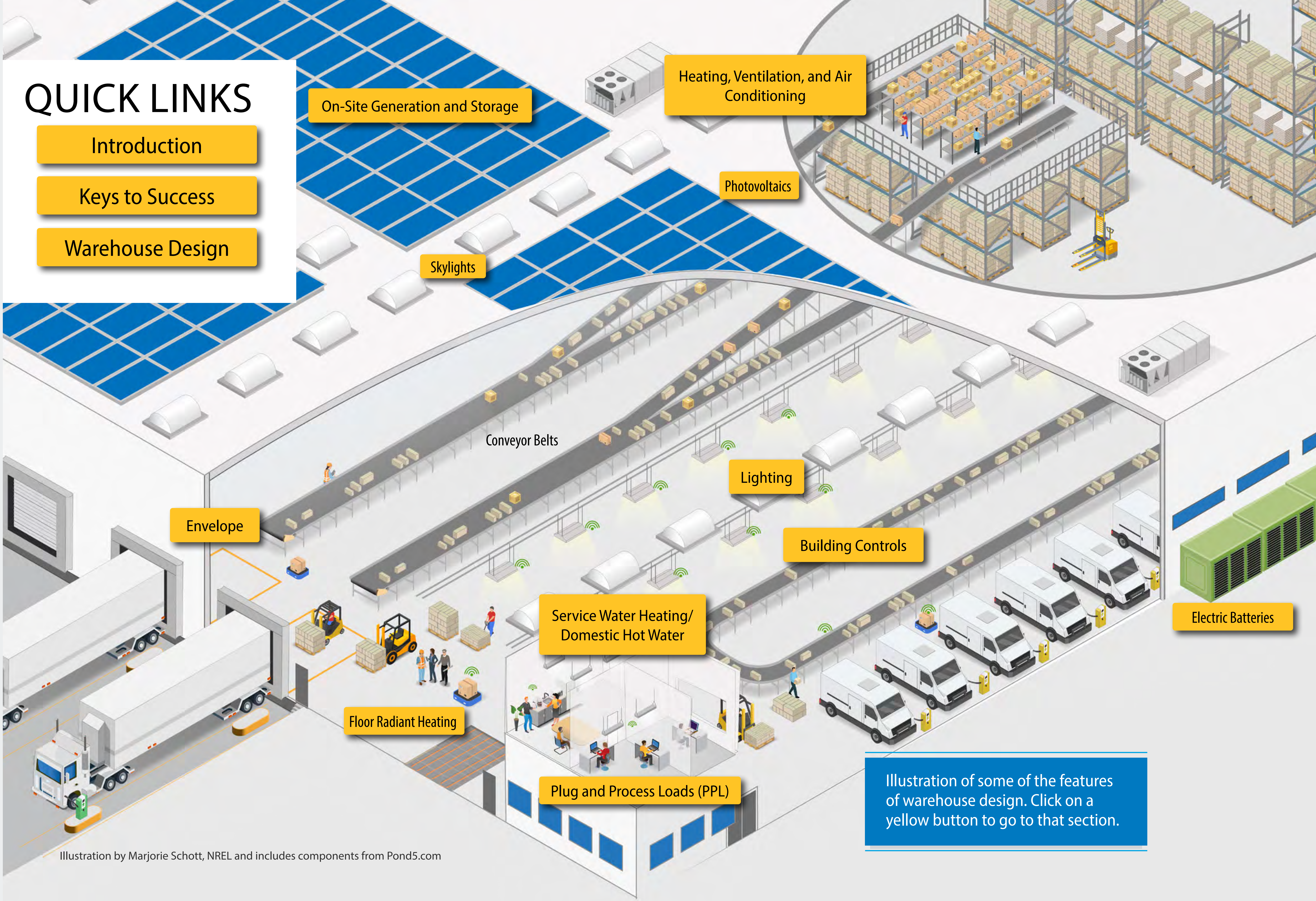

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Illustration of some of the features of warehouse design. Click on a yellow button to go to that section.

INTRODUCTION

Current trends in warehouse energy consumption and projected growth make warehouses great candidates for impactful decarbonization. The warehouse and distribution center sector currently makes up 15.5% of total commercial floor area (14.6 billion ft^2) across the United States. The sector consumes 0.43 quads of energy (126 TWh) annually, or 0.43% of the total U.S. energy consumption.[1] In 2018, the warehouse sector constructed over 183 million ft^2 of new warehouse space, compared to 100 million ft^2 annually in the preceding decade.[2] Growth is expected to accelerate in this sector, adding 6 billion ft^2 in the next 30 years.[2] Business-as-usual design might position high-energy-consuming warehouses to become a significant source of carbon emissions and load, and as a result, present a challenge for grid operation and achievement of decarbonization goals.

The United States has a goal to reach zero greenhouse gas emissions by 2050.[3] Decarbonization policy and codes are emerging in various cities and jurisdictions, making know-how related to carbon-reducing design crucial for warehouse owners. There is also a movement to improve grid reliability through load management and grid services.[4] This regulatory and business environment creates an opportunity to design energy-efficient and future-aware warehouses that are not only ready for the changing codes and standards but also resilient to future challenges from the weather, grid, or other unforeseen circumstances. Additionally, these warehouses could be compensated for providing grid services given the control capabilities for loads and behind-the-meter assets. For many warehouses, the roof area is large and energy use is relatively low as a function of floor area. Thus, warehouses have many design and retrofit opportunities to achieve zero energy operation by utilizing on-site solar. Going beyond zero energy operation, warehouses can produce a surplus of energy in many cases. With this excess generation, there is potential for implementation of electric vehicle integration, in the form of passenger and delivery vehicles, as well as distributed energy resources (DERs). These uses for excess generation present opportunities for warehouses to generate more revenue, reduce costs, and increase resiliency of these facilities, adding further value beyond greenhouse gas (GHG) reduction. These opportunities could make warehouses a key player in achieving emissions reductions and grid reliability.

This guide helps warehouse designers, owners, and facility managers prioritize and identify opportunities to minimize utility bills, maximize impact from renewable energy sources, reduce carbon emissions, and integrate electric vehicles and DERs into their buildings. It also references several existing design resources published by industry organizations such as ASHRAE, the International Institute of Refrigeration, and the U.S. Green Building Council. These additional resources offer additional detailed design approaches to minimize energy consumption of warehouse and distribution center buildings.

GETTING TO ZERO

Zero energy and zero carbon buildings, as described in this guide, align with the Zero Emissions Building definition as defined by the U.S. Department of Energy.[5] The primary criteria that define these types of buildings are:

1. **Energy-efficient:** The building is among the most efficient.
2. **Free of on-site emissions from energy use:** The building's direct GHG emissions from energy use equal zero.
3. **Powered solely from clean energy:** All the energy used by the building, both on-site and off-site, is from clean energy sources.

The information in this guide provides insight into several topic areas that are outlined in the checklist in **Table 1**. The checklist is provided upfront as a means for project managers to ensure they are thinking through the sequential, critical components of a zero energy and zero carbon project. The checklist also acts as an overview of the content discussed in the following sections of this guide. These sections will go into more depth on each topic area and point to additional resources for specific design approaches.

On-site renewable generation can help reduce both energy use and electricity demand in a building.

Photo from Pond5.com 88708767

1 U.S. Energy Information Administration (EIA). "Annual Energy Outlook 2022."

2 EIA. 2018. "Commercial Buildings Energy Consumption Survey." U.S. Department of Energy.

3 White House. 2021. *The Long-Term Strategy of the United States: Pathways to Net-Zero Greenhouse Gas Emissions by 2050.* *https://www.whitehouse.gov/wp-content/uploads/2021/10/US-Long-Term-Strategy.pdf*

4 Kim, D. and A. Fischer. 2021. "Distributed energy resources for net zero: An asset or a hassle to the electricity grid?" IEA. *https://www.iea.org/commentaries/distributed-energy-resources-for-net-zero-an-asset-or-a-hassle-to-the-electricity-grid*

5 DOE. June 2024. National Definition of a Zero Emissions Building Part 1: Operational Emissions from Energy Use, Version 1. *https://www.energy.gov/sites/default/files/2024-06/bto-national-definition-060524.pdf*

Table 1. Checklist for a Zero Energy Project (bold text links to sections in document)

Group	Strategy	Checked (Yes/No)
Project Planning	**Plan for zero energy**	
	Align the organization with a goal	
	Align incentives between owner and tenant	
	Establish design standards	
	Identify the project champion	
	Define project goals	
	Determine the budget	
	Establish a schedule	
	Align procurement with performance	
	Hire an expert design team	
	Define and include energy targets in owner's project requirements (OPR) and request for proposal (RFP)	
	Have detailed OPR	
	Write a strong RFP	
	Develop a quality assurance strategy	
Building Energy Efficiency	**Improve building envelope (e.g., walls, windows, skylights, doors)**	
	Implement efficient **lighting** and **controls**	
	Establish **plug and process load management strategies** (e.g., computers, electric forklifts)	
	Improve domestic hot water (e.g., sinks, showers, bathrooms)	
	Design and improve heating, ventilating, and air conditioning (HVAC) and controls strategies	
	Investigate controls to reduce peak demand and continually manage demand throughout the day	
Integration of Renewables and Energy Storage	**Maximize opportunities for on-site or local renewable energy generation**	
	Coordinate building and electric vehicle loads with renewable generation and storage	
	Leverage energy storage to offset peak demands	
	Analyze opportunities to participate in utility load-shed programs and wholesale energy markets	
	Analyze opportunities to share energy resources with adjacent buildings or communities	
	Investigate controls to integrate and coordinate building loads with on-site generation, storage, and electric vehicle charge management	
Additional Actions and Benefits	**Investigate operational water savings**	
	Investigate strategies for reducing carbon through material selection	

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KEYS TO SUCCESS

In any building project, it is crucial to have an integrated approach that spans planning, occupancy, and postconstruction to ensure that the overall goals of high-performance, low-energy, and low-carbon design are achieved. This integrated approach is needed as the entire project must be planned and executed with the goal of zero energy in mind. For many warehouses, the cheapest first-cost solution is utilized, as the warehouse is usually built and owned by a company—which pays the upfront capital expenses—and then leased to a different tenant, who pays the operating expenses. Similarly for warehouses built and occupied by the owner, the first cost has been mitigated to make initial investments attractive without concern for operational energy costs. This approach usually does not integrate the building owner, design team, and construction team around specific goals, which results in inefficient designs and construction approaches that do not optimize cost and timeline. By pursuing an integrated approach, energy, cost, timeline, and construction can all be optimized to achieve the goal of zero energy along the quickest and most cost-effective pathway.

An integrated approach focuses on building a team and plan that results in a high-performing team that can make project decisions in a systematic and efficient way. The integrated approach is a methodology that is discussed in further detail in the ASHRAE Advanced Energy Design Guides (AEDGs) "Achieving Zero Energy" series.[6] This integrated approach builds upon itself, starting with the organization and a goal as the foundation, and working all the way up to verification of project performance upon completion.

This section will discuss the high-level concepts of the approach outlined in the Achieving Zero Energy AEDGs but with more information specific to warehouses. We focus on key process steps to make efficient design and zero energy a reality. Further detail on this integrated approach can be found in the ASHRAE AEDGs.[5] The AEDGs are design guides that aim to assist owners and designers in designing high-performance buildings. Most of the design guides are for other building types, but many of the concepts and recommendations in these AEDGs are applicable to warehouses as well. Certain design guidance found in the AEDGs for big box retail and office space should also apply to warehouses. We recommend adhering to the guidance outlined in the Zero Energy AEDGs rather than relying on outdated versions. This recommendation stems from the fact that current building codes and design standards have evolved, often surpassing the guidelines provided in older AEDGs. This is especially true for warehouses, as the most recent AEDG for warehouses was written in 2008 and was not intended for large warehouses that are being constructed today.

6 ASHRAE. "Advanced Energy Design Guides." *https://www.ashrae.org/technical-resources/aedgs*

PLAN FOR ZERO ENERGY

Achieving zero energy buildings within a typical construction timeline and within budgetary requirements has been done before. To successfully implement such projects, clear goals and strategies must be established throughout the organization. By having the goals and strategies determined before construction, efficient timelines and project plans can be established and executed. In this section, we will discuss how an organization can plan for zero energy to successfully execute these types of projects.

Align the Organization With a Goal

When attempting to achieve zero energy and zero carbon operation, it is critical that key players in an organization are on board and aligned with these goals. Ideally, the goals will be set by the leadership of the organization, so all decisions from the top down are in pursuit of the goals. This helps ensure there is less resistance to strategies necessary to make zero energy and zero carbon facilities a reality.

There are many goals that organizations are setting today that necessitate zero energy facilities. Some of these goals include GHG emissions reduction, energy reduction, sustainability, or other climate-related goals. Examples of these goals could be reducing GHG emissions by 50% by 2040 or achieving carbon-neutral operation by 2050. Establishing clear goals sets a foundation for an organization. From this foundation, we can develop effective strategies and plans in pursuit of those goals. An example of goal setting and a planning template can be found in the U.S. Department of Energy (DOE) *Framework for Greenhouse Gas Emissions Reduction Planning: Building Portfolios.*[6]

For further details on how to establish a GHG emissions reduction plan, refer to DOE's *Framework for Greenhouse Gas Emissions Reduction Planning: Building Portfolios.*[7]

Once the goals have been established, strategies should be developed and implemented. For many organizations, these goals are set, but the strategies are not well-defined and end up falling short on achieving the overall goal. For example, if the overall goal of the organization is to be carbon neutral by a certain date, not only do all new facilities built need to be zero energy or zero carbon, but existing facilities must also be renovated to be zero energy or zero carbon. This is because if you build buildings that are producing carbon emissions today, even if they are using less than current buildings, your overall portfolio's carbon emissions will still increase. As an analogy, building a new building that is efficient but is not zero carbon would be like filling a swimming pool with a hose with half the flow of other hoses—the pool's water level will still rise, but at a slower rate than it otherwise would have. It is important to set goals and craft the correct strategies for

7 Kramer, H., T. Abram, N. Hart, and J. Granderson. 2023. *Framework for Greenhouse Gas Emissions Reduction Planning: Building Portfolios.* U.S. Department of Energy. *https://betterbuildingssolutioncenter.energy.gov/sites/default/files/attachments/ERP_Framework_Building_Portfolios.pdf*

how to achieve them. These strategies can either be established by the in-house team or determined via an outside consultant or design team. By having set strategies, the organization can ensure it will achieve its overall goal.

Guidance on how to establish these strategies, as well as further planning for decarbonization, can be found in the DOE publication *A Guide for Creating a Building-Level Action Plan to Improve Energy Efficiency and Reduce Carbon Emissions.*[8]

Align Incentives Between Owner and Tenant

When planning for zero energy, it is important to consider the leasing or ownership arrangement that the organization has with the warehouse. In many cases, tenants occupy warehouse space, and often the tenant is responsible for paying rent and utility bills. When triple net leases are used, the tenant is also responsible for paying for insurance, maintenance, and taxes. This arrangement can pose a challenge as the tenant may not want to expend large amounts of capital for improvements to properties that they do not own. There is also the potential they might not see a return on investment (via energy savings) within the term of their lease. This "split incentive" creates an obstacle for tenants who have energy and carbon goals. Inversely, it can also be an issue for owners when working with tenants to achieve energy and carbon goals across their portfolio.

To overcome the split incentive problem, several leasing strategies have been investigated, tested, and deployed through "green leases." Green leases are leases that include clauses to help align incentives for both the tenant and owner. This helps both parties pursue efficient buildings and carbon reductions.[9] For example, a green lease provision might enable the landlord to recover some costs of energy upgrades from the tenant. By adding this provision, the landlord can amortize the cost of upgrades to the tenant. This provides an incentive for the owner to improve the building, gain more equity in the building, and recoup those upgrade costs, while the tenant enjoys reduced energy consumption that results in lowered costs and carbon. By utilizing green leasing strategies, we can align the incentives among all parties, which creates an easier path to zero energy and zero carbon.

The Green Lease Leaders program provides further information about green leases, as well as case studies of successful implementation of this leasing strategy.[10]

Establish Design Standards

Many warehouses have standard layouts that are far less complex than other construction types such as office buildings, schools, etc. Given the relatively simple layouts, an effective strategy is to establish internal design standards for an organization's warehouses. These design standards will lay out specific requirements and requests that design and construction teams should follow for the projects. These standards can range from simple things such as the color of paint for walls to specific design requirements for mechanical equipment. Some of the design requirements to consider are:

- Building energy use intensity (EUI)[11] requirements
- Design heating load
- Design cooling load
- Expected occupancy
- Ventilation requirements
- Expected plug and process loads
- Energy modeling requirements
- Mechanical equipment configurations
- Space temperature and humidity requirements
- Maximum lighting power density
- Control system types.

We recommend that these design standards be established by an organization's leadership with the help of a technical expert. This expert can either be an internal technical expert or an external technical consultant. When developing these standards, the technical expert needs to ensure that all design requirements established meet the goal of zero energy or zero carbon. By establishing these design standards upfront, the efficiency of the design process will be improved, reducing the timelines, and potentially, cost. This also ensures the streamlining of future projects and aids in the pursuit of the overall organizational goal. The **Warehouse Design Guidance** section of this guide discusses design practices that can help influence these design standard decisions in further detail.

Identify a Project Champion

When developing the project team, it is critical to ensure that everyone is aligned with an organization's zero energy and decarbonization goals. This sets the foundation for a successful project. The first step in developing the project team is to identify a "champion" for the project. The champion is the individual who will lead the project and team and ensure that all members are aligned with the project's goals. The ideal champion is a stakeholder with the ability to lead and support the project through planning, design, construction, occupancy, and ongoing measurement and verification. The champion needs support from the organization's leadership and enough authority to make decisions about the project's direction to meet the project's goals.

8 Torcellini, P. and H. Goetsch. 2023. *A Guide for Creating a Commercial Building-Level Action Plan to Reduce Energy Use and Carbon Emissions.* U.S. Department of Energy. DOE/GO-102023-5893. *https://www.osti.gov/biblio/1974574/*

9 Feierman, A. 2015. *What's in a Green Lease? Measuring the Potential Impact of Green Leases in the U.S. Office Sector.* Institute for Market Transformation. *https://www.imt.org/wp-content/uploads/2018/02/Green_Lease_Impact_Potential.pdf*

10 Green Lease Leaders. 2022. "How do I Green a Lease?" *https://greenleaseleaders.com/green-leasing/how-do-i-green-a-lease/*

11 EUI is defined as the annual energy consumption (thousands of British thermal units per square foot (kBtu/ft^2)).

Define Project Goals

Establishing project goals is crucial to project success. These goals need to be aligned with the high-level goals laid out by an organization, but also feature more detail regarding design and construction. The specifics of setting project goals are nuanced and outside of the scope of this guide, but additional details can be found in Chapter 3 of *Advanced Energy Design Guide for K–12 School Buildings–Achieving Zero Energy*[12] for how to develop these project goals. This AEDG discusses:

- Using a collaborative and iterative process
- Planning for full usage
- Developing the owner's project requirements (OPRs)[13]
- Engaging stakeholders.

Determine the Budget

Even with a strong focus and well-established team, zero energy buildings might be perceived as more expensive than typical construction budgets. However, zero energy buildings can often be built for little to no additional cost, and sometimes even for less. Many teams that have successfully completed other zero energy buildings believe that it is possible to spend no more on a facility that achieves the very low EUI required for zero energy—before purchasing renewable energy sources—than what it costs to build a typical high-performance facility.[14] This can be achieved through intentional design strategies such as investment in high-performance envelope measures. For example, increased insulation values will reduce building cooling and heating loads and the need for larger mechanical equipment. Smaller mechanical equipment will offset the investment in better insulation.

Establishing a realistic project budget upfront is crucial to set expectations both from an owner's perspective and for the design and construction team. We recommend setting a reasonable but firm budget, along with the established EUI and zero energy goals, before the design process begins. The balance of these goals influences the team to be creative and find ways to better utilize the budget available to them. This influence ensures that dollars spent contribute to achieving multiple goals at once. For example, the first cost for more efficient lighting will be greater than baseline lighting, but the reduced output from the lights will reduce the cooling load in the space, and subsequently the size of the mechanical equipment, balancing out the increased cost of the lights. This kind of integrated planning can allow for efficient design without excessive costs and helps ensure that items are not "value engineered" out of the design during detailed design/construction.

Establish a Schedule

Warehouses are key to many business and investor goals and, as a result, the timeline from warehouse conception to operation is critical. Ideally, layering in energy efficiency goals would not impact the project schedule, as that has soft cost implications. The pressure to complete a warehouse within a specific timeline to meet business and investor goals must be weighed against the need to provide adequate time during design and construction for quality assurance, which is essential to achieve optimal energy performance. Concept and schematic design phases for a zero carbon/energy warehouse may take longer than for a typical warehouse because integrated design is an involved and iterative process. This extended design timeframe traditionally leads to better designs and planning, allowing the construction phase of the project to be expedited and making overall timelines similar to other high-performing buildings. This phase includes site layout, building orientation, envelope design, HVAC selection, EUI predictions, and balancing EUI with available on-site generation. Each of these pieces affects the others, which results in the need to iterate design decisions that can prolong design schedules in many cases. However, in some cases, project schedules can be shortened through the use of higher-first-cost materials. This is illustrated in the 50% K-12 AEDG, comparing the increased cost of insulated concrete form wall construction over traditional wall block construction.[15] The insulated concrete form construction was more expensive on first cost, but the reduced schedule and lowered costs of running conduit resulted in net schedule and cost savings overall with the benefit of a more efficient envelope.

Permitting may take longer than normal because reviewers and inspectors may be less familiar with the construction assemblies and building systems specified for zero energy.[16] Adequate time is required to research utility provider incentives and requirements for zero energy and net metering, and to negotiate rates, connectivity and maintenance charges, and other conditions.

Scheduling an unrealistic timeline for construction can result in increased project risks, such as:

- Reduced quality of construction, such as improper installation of the building envelope or commissioning (Cx) of building systems
- Jeopardized indoor air quality (IAQ) by shortcutting steps that reduce the risk of mold and leaving insufficient time to ventilate the building properly prior to occupancy
- Errors in construction that result in redone work, further tightening construction schedules and increasing construction costs
- Rushed review of submitted equipment and materials by the design team that result in missing key requirements and reduced energy performance.

12 ASHRAE. *Advanced Energy Design Guide for K–12 School Buildings–Achieving Zero Energy*. https://www.ashrae.org/technical-resources/aedgs

13 The OPR is a written document that details the functional requirements of a project and the expectations of how it will be used and operated. An example can be found at https://www.ashrae.org/file%20library/about/new%20hq/ashrae-opr-attachment-to-design-services-rfp-signed.pdf.

14 ASHRAE. *Advanced Energy Design Guide for K–12 School Buildings–Achieving Zero Energy*, p. 26. https://www.ashrae.org/technical-resources/aedgs

15 ASHRAE. *Advanced Energy Design Guide for K–12 School Buildings–Achieving 50% Savings Towards Net Zero Energy Buildings*. https://www.ashrae.org/technical-resources/aedgs

16 ASHRAE. *Advanced Energy Design Guide for K–12 School Buildings–Achieving Zero Energy*. p. 29. https://www.ashrae.org/technical-resources/aedgs

With a rushed construction schedule, proper quality assurance cannot be performed, which jeopardizes the project's likelihood of achieving the goals set at the beginning of the project.

Align Procurement With Performance

The final step in building the team is to align the procurement strategy with the performance goals. Hire a construction contractor or construction management company that understands and is committed to achieving the energy goals for the project. They, in turn, need to find qualified subcontractors to execute the work. As an example, an envelope that fails infiltration requirements can have a large enough impact to single-handedly cause the energy goals to fail.

These methods are covered in further detail in Chapter 3 of *Advanced Energy Design Guide for K–12 School Buildings–Achieving Zero Energy*.[17] Any of the procurement methods can be successful, but all require upfront decisions during contract development. Some of these decisions include determining the expertise of the project team, amount of upfront budget, and level of input the team wants in the project design. These decisions help inform which procurement method best matches with the team's dynamics. The Design-Build Institute of America provides further information on these decisions in their publication *Choosing a Project Delivery Method*[18] and in other publications. The contracts must be developed carefully to protect the owner's interest and ensure adherence to the minimum performance criteria, including energy performance. These contracts can be used to align everyone to the energy goals of the project, as well as other critical success elements such as schedule, cost, and budget.

SEVERAL PROCUREMENT METHODS ARE AVAILABLE FOR CONSTRUCTION:

Design-bid-build is the traditional method of project delivery. In this procurement method, the owner will contract individual entities for design and construction. This method is linear in approach with the design happening first and the bidding for the construction of the project taking place after the design is complete. This methodology is well known but can have disadvantages due to the fact that the design team is not integrated with the construction team. This sometimes results in miscommunication of design intent and delayed construction timelines when issues arise. However, this approach does foster greater owner involvement, compared to other procurement methods, and offers natural decision points for the owner to make changes or decisions if desired.

Design-build is a project delivery method where construction and design teams are integrated. In this method, the architect, designer, or contractor is typically designated as the lead of the project. Design and construction are managed under the same team, either through the use of in-house resources or by contracting with outside partners. This procurement method can help reduce risk for owners by having the design and construction team work in tandem. By performing design and construction tasks at the same time, project timelines can be shortened and design intent can be achieved in a streamlined fashion.

Performance-based procurement is a project procurement method that emphasizes specific performance metrics in the contract. This method ties payment to specific performance criteria rather than completion of defined milestones. These performance metrics can be energy-related, testing-based, budgetary, timeline-based, and so forth. By tying the contract to specific performance metrics, the design and construction teams are incentivized to meet those metrics to maximize their profit. This methodology requires careful planning and decisions around what metrics are included in the project to ensure success. This procurement method can be integrated with a design-bid-build or design-build procurement methodology, providing further metrics to guide the design and construction.

17 ASHRAE. *Advanced Energy Design Guide for K–12 School Buildings–Achieving Zero Energy*. https://www.ashrae.org/technical-resources/aedgs

18 Design-Building Institute of America. 2023 *Project Delivery A Design-Build Done Right (R) Primer*. https://store.dbia.org/product/project-delivery/

HIRE AN EXPERT DESIGN TEAM

The next step is to hire a design team. No matter how convincing the project champion is about the goal for energy-efficient design, without an expert design team with the proper skill, creativity, and motivation, the goals may not be achieved. A design team traditionally consists of mechanical, electrical, structural, and civil engineers, as well as architects, each designing their respective systems. In addition, a successful team should include building modeling expertise and a commissioning agent. The role of the commissioning agent is described later in this section. The building modeling team includes building simulation expertise to help guide design decisions while keeping the energy goal in mind.

For typical building design teams, the architect is the project lead and often acts as a project manager. In some cases, architects do not have the technical skills related to energy-using equipment or may make design decisions that are architecturally ideal but do not further energy goals (e.g., not optimizing window-to-wall ratios, improper shading). Architects should be hired that are familiar with energy-efficient design and are willing to work closely with mechanical and electrical engineers to optimize energy consumption in the building. When zero energy and high performance are among the goals, it can also be advantageous to hire a design team where the mechanical engineer is a part of the project leadership. This helps foster decision making to reduce building energy use, as mechanical equipment is the primary energy consumer in most buildings. Mechanical equipment is impacted by the building envelope and other electrical systems in the building, making mechanical engineers keenly aware of the integration required for the entire building.

The process for hiring the design team has two primary paths. One path is utilizing a competitive bid process. This process typically involves writing a request for proposal (RFP) and soliciting bids from many teams. The second path is utilizing a sole source team to design and build your project. The first path is the preferred path in many cases, as the competitive process helps keep costs in check and can spark creativity among the project bidders to develop a strong design and proposal. Boths paths can lead to successful projects, but each requires a strong RFP or OPR to ensure the design teams are meeting your goals.

Write a Strong RFP

After the project champion has assembled the team and all parties are on board and engaged in pursuing the efficiency and decarbonization goals, the team should write an RFP that will set the stage for demonstrating the project team's commitment to energy efficiency and decarbonization. A strong RFP provides a pathway to selecting design and contractor teams with the required expertise to achieve the goal. Along with the standard RFP language and the detailed scope of services required, the project team should include the following information:

- Established goals for energy efficiency, peak demand management, zero energy, or decarbonization as one or more of the key objectives
- The key target for the project, using metrics such as EUI or CO_2 reduction (EUI is recommended in most cases as this metric is easy to measure and quantify and aligns the project toward efficient design, resulting in an easier path to zero energy design)
- Whether renewable electricity generation is a part of the RFP and expectations regarding how much of the generation will be on-site versus off-site
- Project definition that considers the benefits and challenges of designing a facility with energy system integration such as photovoltaics (PV), energy storage, and demand response
- The selection process for the design and construction team as well as the construction procurement method in support of establishing an integrated team in line with project objectives (as discussed in **Align Procurement With Performance**).

A detailed RFP that shows the facility goals and commitment to the project goes a long way toward ensuring that an appropriate design team is hired for the project. The National Renewable Energy Laboratory successfully built a zero energy office building using this RFP process. The result was an office building built at the same construction cost as a conventional building, yet it uses half the energy. The remaining energy consumption is offset by on-site renewable energy generation.[19]

Create Detailed Owner's Project Requirements

If the organization has a preferred design team and does not want to pursue a competitive bid process, care must be taken to help meet the goals of the project. First, the organization should confirm that the internal team has the expertise and skills mentioned above to complete the project. Second, this team needs to have clear project requirements that lay out the goals and accustom the team to the fact that the project will not be a standard construction project. Even with a sole source team, the OPR should be robust and detailed, much like the RFP for the competitive bidding process. It is recommended to include the details listed above in the **Write a Strong RFP** section, but the selection process for the teams can be removed. Some design teams are not equipped with the capabilities to perform the design of a zero energy project. If the sole source design team pushes back on the OPR, it is recommended to pursue the RFP process and solicit further bids from teams with those capabilities.

19 National Renewable Energy Laboratory. 2008. Appendix A. Conceptional Documents. Solicitation No. RFJ-8-77550. *https://www.nrel.gov/climate-neutral/assets/pdfs/rfp-nrel-rsf-conceptual-docs.pdf*

QUALITY ASSURANCE

To help ensure the performance of a facility, a quality assurance (QA) plan is recommended. An effective QA strategy begins with designating roles to manage the QA process. The team should be made up of in-house technical experts and should include external expertise as well. At a minimum, the QA team should include those responsible for the operation and maintenance of HVAC systems, building automation systems, lighting systems, building envelopes, audio/visual systems, information technology, security, and warehouse logistics.

The QA strategy should establish specific criteria to help ensure that expected facility performance levels are achieved. This could include strategies such as measurement and verification, design reviews, construction reviews, commissioning, and so forth.

One critical role on the QA team, typically served by an external party, is that of the commissioning authority (CxA). The CxA should be a third-party agent who does not have an affiliation with the design firm. The commissioning process typically includes reviewing, testing, and validating the performance of various building systems. The following components are commonly assessed as part of the QA process:

- Building enclosure: walls, roof, fenestration, slab
- Building systems: HVAC, refrigeration, lighting, lighting controls, plug load management, renewable energy systems, security, etc.
- Indoor environmental quality: air quality, light quality, acoustical performance.

The importance of quality Cx cannot be understated. The CxA also operates as an owner's technical advocate during the design review process to help ensure that the OPRs are being met and that systems can be tested properly. They provide a technical peer review of the construction documents for the systems being commissioned. This review provides an additional layer of QA.

For warehouses, there are several unique factors for a CxA to consider during the design and post-installation commissioning phase. These points relate to the physical structure of the building, as most facilities such as office spaces have smaller enclosures compared to the open design of large warehouses, as well as to the unique operations of each warehouse.

- Infiltration design and performance. For many warehouses, infiltration is one of the primary deficiencies in the building envelope that has large energy and indoor air quality impacts. The CxA should ensure that the design includes key performance metrics for the envelope to define infiltration requirements. The CxA should also verify that the envelope is built according to and tests within the infiltration requirements set for the project. This is especially true for large bay doors. In these instances, infiltration should be minimized both when the door is closed and open. The CxA should ensure infiltration mitigation for these large doors meets the performance requirements for the design.
- Air mixing design, if applicable. Many open-space warehouse designs require some form of air circulation for proper IAQ and efficient design. The CxA should ensure the design has accounted for this and verify that the strategies are performing as anticipated. This could include, for example, taking multiple temperature measurements, at different elevations, during system startup to assess the performance of the equipment.
- Design of the warehouse layout as it relates to storage, operations, and equipment. The CxA should ensure these elements are well-coordinated. Given the unique operation of warehouses with heavy equipment and general product movement, the layout of the facility is uniquely important to ensure that safe and efficient operations can take place.
- Access to equipment for maintenance. Many warehouses have high roofs. If mechanical equipment is placed at higher elevations to preserve floor space, ensure proper safety measures are in place to access equipment for maintenance.
- Control strategies for HVAC and lighting. In addition, special care should be taken to ensure that control strategies are functioning properly for PV, battery storage, equipment charging stations, emergency ventilation, security, etc. Controls to integrate these systems controls should also be commissioned.

Further information on commissioning can be found in ASHRAE's Guideline 0 – The Commissioning Process.[20]

The QA process includes additional considerations and steps that go beyond the commissioning process described above. This information can be found in further detail in Chapter 3 of *Advanced Energy Design Guide for K–12 School Buildings–Achieving Zero Energy*[21] (p. 38–41) and in Chapter 3 of *Advanced Energy Design Guide for Multifamily Buildings–Achieving Zero Energy* (p. 34–41).[22] In these guides, the commissioning process is discussed further, and guidance on the following topics is provided:

- Cx during construction
- Measurement and verification
- Post-occupancy performance
- Ongoing Cx
- Confirming the EUI and on-site renewables
- Incentivizing the team to improve.

20 ASHRAE. 2019. *Guideline 0-2019 – The Commissioning Process.* https://store.accuristech.com/ashrae/standards/guideline-0-2019-the-commissioning-process?product_id=2076120

21 ASHRAE. Advanced Energy Design Guide for K–12 School Buildings–Achieving Zero Energy. *https://www.ashrae.org/technical-resources/aedgs*

22 ASHRAE. *Advanced Energy Design Guide for Multifamily Buildings–Achieving Zero Energy. https://www.ashrae.org/technical-resources/aedgs*

WAREHOUSE DESIGN GUIDANCE

Warehouses can be divided into four types: unconditioned, conditioned, partially conditioned, and refrigerated. Each of these types has its own design requirements and recommendations to save energy and achieve zero energy. For each of these warehouse types—except for refrigerated warehouses—we will discuss specific design guidance to achieve substantial energy savings, opportunities for on-site generation, DERs, controls, and some additional sustainability measures that can be deployed.

GENERAL OVERVIEW

The building operation, space conditioning requirements, construction, and climate each impact building energy use and associated carbon impact. To better define a building's energy use compared to similar facilities, it is useful to look at its EUI. EUI is defined as the annual energy consumption normalized by building area (measured in kBtu/ft²). This metric allows for comparison among facilities. **Table 2** provides median and ENERGY STAR® EUIs for various warehouse/storage property types using default operating parameters from the ENERGY STAR Portfolio Manager Platform.[23] An ENERGY STAR score of 90 indicates energy performance of a building that is better than 90% of similar buildings.

23 ENERGY STAR. 2021. *U.S. Energy Use Intensity by Property Type*. *https://portfoliomanager.energystar.gov/pdf/reference/US%20National%20Median%20Table.pdf*

Table 2. Median and ENERGY STAR 90 EUIs for Warehouse/Storage Property Types

Market Sector	Property Type	Median Site EUI (kBtu/ft²)	ENERGY STAR 90 Site EUI (kBtu/ft²)[a]
Warehouse/Storage	Distribution Center (Unconditioned/ Partially Conditioned)	22.7	10.6
Warehouse/Storage	Non-Refrigerated Warehouse (Conditioned/Partially Conditioned)	22.7	10.6
Warehouse/Storage	Refrigerated Warehouse	84.1	33.2

a. Based on ENERGY STAR Target Finder tool utilizing 100,000 ft² and default values for warehouse types.

As discussed in **Keys to Success**, EUI is a common metric that can be used to set targets for energy efficiency and decarbonization strategies. The median EUI values shown in Table 2 are the base values that should be achievable through traditional design and construction practices. More aggressive (lower) EUIs should be set if efficient design and decarbonization are to be achieved. In *Advanced Energy Design Guide for Small to Medium Office Buildings–Achieving Zero Energy*, the average EUI target for achieving zero energy determined through extensive energy modeling was 23.4 kBtu/ft².[24] These EUI targets are less than an ENERGY STAR score of 90 for an office building, which is approximately 34.7 kBtu/ft². For many warehouses, an ENERGY STAR score of 90 can be an achievable metric given the lower complexity of the typical warehouse compared to office buildings that have been modeled and built to achieve EUIs less than the ENERGY STAR 90 targets. Setting a target ENERGY STAR score of 90 or greater can align the project with an achievable target that will maximize energy efficiency and require less installed renewable energy to meet zero energy goals. These EUI targets should be updated to the site's specific parameters using ENERGY STAR's target finder if this route is chosen. Setting a more aggressive EUI beyond this value will further reduce the site's energy consumption, which will reduce the amount of on-site generation required to achieve zero energy, reducing project cost and helping offset additional costs of any efficiency upgrades. By minimizing the required renewable energy capacity for zero energy operation, the facility will have greater flexibility and available space to add additional on-site generation and energy storage to power increased loads such as electric vehicles or other excess renewable capacity strategies discussed in **On-Site Generation, Storage, and System Interaction**.

24 ASHRAE. *Advanced Energy Design Guide for Small to Medium Office Buildings–Achieving Zero Energy*. p. 32. *https://www.ashrae.org/technical-resources/aedgs*

This document provides an overview of three of the main categories of warehouses mentioned above: unconditioned, partially conditioned, and conditioned. Refrigerated warehouses are unique facilities with specialized equipment that will not be discussed as part of this guide. Within each category, the guide highlights the main energy-consuming building components and directs the reader to appropriate design and integration recommendations for high-performance, zero energy, and zero carbon operation. It should be noted that each of these high-level warehouse categories can have various levels of automation, leading to higher or lower energy intensity. Based on the level of automation, specific equipment, and specific requirements in the facility, an individual building's main energy end uses might be different from what is outlined in this document. The reader should evaluate the main energy consumers in their buildings and tailor the content presented in this guide to meet their design needs.

Unconditioned Warehouses

A variety of factors, such as economics and the impracticality of conditioning a building, might make an unconditioned warehouse the right choice for a company. Although their spaces are not conditioned, unconditioned warehouses can still have opportunities to save energy. Electric lighting often consumes the most energy in these buildings. Plug and process loads could be another leading energy consumer in unconditioned warehouses, depending on the type of processes, light or heavy manufacturing, or levels of automation that are required. High-efficiency lighting and daylighting designs with controls, and a commitment to procuring energy-efficient plug-in and process equipment can drastically reduce unconditioned warehouse energy consumption. Most unconditioned warehouses do require some level of mechanical ventilation; these systems are generally small but efficient equipment and appropriate controls should be in place for these systems.

Areas to Consider

- Lights
- Plug and process loads
- Envelope
- Service water heaters
- Ventilation equipment.

Conditioned Warehouses

Conditioned warehouses are storage facilities designed to maintain the environment to meet storage requirements of the stored product and a habitable environment providing thermal comfort for the facility workers. For this guide, we categorize conditioned warehouses as facilities that maintain indoor air temperatures of greater than 55°F and/or less than 80°F year-round. For this guide, the warehouse can also be a semi-conditioned warehouse such as a facility that conditions only part of the warehouse or only heats the warehouse in the winter to 55°F and does not cool during the summer months.

Areas to Consider

- Envelope
- Infiltration
- Plug loads
- Automation
- Lighting
- HVAC technologies
- Controls
- Service water heaters
- IAQ.

Refrigerated Warehouses

Refrigerated warehouses are facilities designed to store food, medical supplies, or other goods that need a refrigerated environment. They can operate at very cold temperatures, between -4° and 14°F for low-temperature (freezer) storage, and between 30° and 55°F for medium-temperature (cold) storage.[25] Refrigerated warehouses often consist of fully refrigerated sections as well as office space. The office space sections follow recommendations similar to those for conditioned warehouses, as well as guidance provided in the Zero Energy AEDG for small to medium office buildings.[26] In the fully refrigerated sections, energy-efficient design is more extreme. Given the inherent energy required to refrigerate such a large space 24/7, it is imperative to have an expert team design the facility for the most efficient operation possible to achieve the highest probability of offsetting energy and carbon emissions via on-site generation and storage. These facilities are quite complex, and it is recommended to work with professionals who are familiar with these types of refrigeration systems. Given the complexity of these facilities, this document will not cover this type of warehouse in detail. Information on how to efficiently design and operate these types of facilities can be found in resources such as the AEDG for Grocery Stores,[27] as well as through resources from institutions such as the International Institute of Refrigeration and the Industrial Refrigeration Consortium.

25 ASHRAE. 2018. *ASHRAE Guide for Sustainable Refrigerated Facilities and Refrigerated Systems*. https://www.techstreet.com/ashrae/standards/ashrae-guide-for-sustainable-refrigerated-facilities-and-refrigeration-systems?product_id=2016211

26 ASHRAE. *Advanced Energy Design Guide for Small to Medium Office Buildings–Achieving Zero Energy*. https://www.ashrae.org/technical-resources/aedgs

27 ASHRAE. *Advanced Energy Design Guide for Grocery Store–Achieving 50% Savings Towards Net Zero Energy Buildings*. https://www.ashrae.org/technical-resources/aedgs

Photo from Pond5.com 130890853

ENVELOPE

Energy-efficient envelope design is the most important factor for reducing energy consumption and costs, and for achieving zero energy and zero carbon status in conditioned or partially conditioned warehouse spaces. A tight, well-insulated envelope that minimizes thermal bridges can drastically reduce heating and cooling loads, and result in smaller mechanical systems requirements for heating and cooling. Envelope design decisions should also include optimum placement of fenestration and access to daylighting to reduce electricity use associated with electric lighting. Attention to high-efficiency installation practices is also critical with fenestration to reduce infiltration, maintain high insulation levels, and avoid thermal bridging.

Infiltration is a key area when trying to reduce building loads and energy consumption. Infiltration is the movement of unconditioned air into and out of the building through the envelope. This infiltration results in increased load on the mechanical equipment and in some cases, reduced IAQ. Care should be taken to seal the exterior envelope (i.e., walls, windows, envelopes) to mitigate the amount of infiltration that occurs. Warehouses pose a unique challenge as many facilities include high bay doors to allow for large vehicles to load and unload into the facility. When these high bay doors are open, large amounts of infiltration can occur. When planning a warehouse with these large doors, designs to mitigate this infiltration should be implemented. This can include proper sealing for the door when closed, weather sealing to mitigate infiltration when the door is open and a truck is in place, automated control to ensure the door is closed when needed, or the addition of an unconditioned vestibule space to stage product and mitigate the amount of conditioned space exposed to infiltration from the high bay doors.

Envelope design in unconditioned warehouses is still important. ASHRAE 90.1 requires all enclosed spaces to be designed with an envelope suitable for air conditioning regardless of the presence of mechanical or electrical equipment.[28] A well-insulated building can provide a more comfortable space for building occupants by reducing the impact of outside weather conditions. This can also have the added benefit of reducing temperature impacts on electrical equipment such as lights and forklifts, resulting in higher efficiency, less maintenance, and prolonged equipment life. The incorporation of cool roofs could reduce the impact of summertime heat on the interior of the warehouse and, similarly, warm roofs could make the space more thermally comfortable during winter months. Strategic placement of windows and skylights can bring daylight into the space and help reduce lighting loads during the day. Care should be taken when implementing skylights—the benefits and placement of skylights should be coordinated with and weighed against the ability to install more rooftop solar.

28 DOE. n.d. "FAQ: Does energy code compliance need to be shown for a warehouse?" *https://www.energycodes.gov/technical-assistance/faqs/does-energy-code-compliance-need-be-shown-warehouse*

Table 3. Recommendations and Resources for Envelope Component Efficiency

Item	Component	Recommendation[a]	Additional Information[b,c]
Roof	Overall U Factor	U = 0.039–0.027[d]	Office Zero Energy Design Guide (ZEDG) Tables 5-4 and 5-5 Office ZEDG EN2, EN12, and EN13
Walls–Exterior	Mass walls above grade Framed walls above grade	U = 0.171–0.039 continuous insulation (CI)[d] U = 0.124–0.035 CI[d]	Office ZEDG Tables 5-4 and 5-5 Office ZEDG EN3–EN5
Walls–Interior	Partition walls (between semi-heated and conditioned spaces)	Mass Walls U = 0.58–0.104 CI Framed Walls U = 0.352–0.051 CI	ASHRAE 90.1-2022 Table 5-5
Slabs	Unheated Heated	F = 0.73–0.4[e] F = 1.020–0.671[e]	Office ZEDG Tables 5-4 and 5-5 Office ZEDG EN8 and EN37
Doors–Opaque	Swinging	U = 0.370–0.352[d]	Office ZEDG Table 5-6 Office ZEDG EN24–EN29
	Vehicular/dock thermal transmittance	Heated U = 0.37[d] Semi-heated U = 0.7[d]	ASHRAE 90.1-2022
	Vehicular/dock infiltration – door closed	0.28 cfm/ft^2 of door area	EN1
	Vehicular/dock infiltration – door open with truck in place	Weather seals for dock levelers and trailer hinges	EN1, EN13
Vertical Glazing (Including Doors)	Thermal transmittance	U = 0.48–0.25[d]	Office ZEDG Table 5-6
	Solar heat gain coefficient (SHGC)	0.21–0.38	Office ZEDG Table 5-6
	Exterior sun control (S, E, W only)	Projection factor (PF)>0.5	EN1, EN20–21, EN23, EN26
Skylights	Area (percent of gross roof)	5%–7% prismatic diffusing skylights required in warehouse areas (except in self-storage areas)	EN1, EN18–20
	Thermal transmittance	U = 0.48–0.25[d]	Office ZEDG Table 5-6
	SHGC	0.21–0.38	Office ZEDG Table 5-6
	Minimum ratio of visible transmission (VT)/SHGC	1.10	Office ZEDG Table 5-6

a. Recommendations show the range for all climate zones. Refer to referenced AEDG or ASHRAE 90.1-2022 for climate-zone-specific information.
b. Reference the Warehouse AEDG unless otherwise stated.
c. Refer to ASHRAE 90.1-2022 for minimum recommended values.
d. U factor units are Btu/hr·ft^2·F
e. F factor units are Btu/hr·ft·F

PLUG AND PROCESS LOADS

Plug and process loads (PPL) are energy-consuming devices that fall outside the categories of lighting and HVAC. PPLs include computers, data centers, refrigerators, personal heaters, conveyor belts, and tools. PPLs make up 33% of total energy consumed in commercial buildings.[29] For many warehouses, equipment like conveyor belts, forklifts, and other automation equipment can make PPLs an even larger percentage of the building's energy consumption. This adds to the importance of efficient PPL design and control to reduce the energy consumption of these devices. For many buildings, PPLs are designed based on an anticipated need or standard contracted amounts. Frequently during office building design, PPLs are requested by building owners/tenants between 5 and 10 W/ft^2 due to lack of accurate references and the desire to be conservative, but when buildings were measured, peak loads were 0.41–1.25 W/ft^2.[30] When designing mechanical equipment, the requested PPL densities will be used to calculate heat loads. If those heat loads are over specified, that can result in systems that are overdesigned, further increasing building energy consumption as well as increasing the cost for electric infrastructure on-site to accommodate the requested PPL density. This point highlights the need to accurately identify the PPLs that are required on-site and their actual consumption during the design phase.

When looking to evaluate and reduce PPLs, the following steps are recommended[31]:

1. Establish a Plug and Process Load Champion
2. Institutionalize Plug and Process Load Measures
3. Benchmark Current Equipment and Operations With a Walkthrough
4. Develop a Business Case for Addressing Plug and Process Loads.

This methodology above, applied intentionally to the building, will help designers and operators improve the efficiency of the PPLs in the facility and reduce the building's overall consumption and heating load.

A common type of equipment in many warehouses is forklifts. Forklifts come in many different types—some are powered by propane or other fossil fuel and some are all electric. As part of electrifying a warehouse operation, swapping existing fossil-fuel-powered forklifts to all-electric equivalents is recommended to reduce scope 1 emissions and allow for on-site renewables to provide clean energy for powering this equipment. In lieu of propane tanks or other fossil fuel storage on these forklifts, batteries store the energy to power the forklift while not actively being charged. Efficiency measures for this equipment are centered around improving the utilization of the energy stored in the battery as well as efficiently charging these batteries. Efficiency recommendations for forklifts can be found in **Table 4**.

As mentioned above, warehouses can have higher levels of automation compared to office buildings and other commercial buildings. This automation generally results in larger and more numerous PPLs in the building. For many processes other than typical office PPLs, solutions are unique to the facility based on how these systems are utilized and designed. For custom processes, a design team with expertise in that process should be engaged to find efficiency improvements related to these systems. Some of these system types can include conveyor belts, packaging, compressed air, automated picking, and robotics.

Electric forklifts help to move heavy items around the warehouse and load and unload trucks for transporting items.

Photo from Pond5.com 195439834

29 Sheppy, Michael, Chad Lobato, Shanti Pless, Luigi Gentile Polese, and Paul Torcellini. 2013. "Assessing and Reducing Plug and Process Loads in Office Buildings." Golden, CO: NREL. *https://www.nrel.gov/docs/fy13osti/54175.pdf*

30 DOE. 2014. "Plug and Process Loads in Commercial Buildings." *https://www.nrel.gov/docs/fy14osti/60265.pdf*

31 NREL. 2020. "Assessing and Reducing Plug and Process Loads in Office Buildings", *https://www.nrel.gov/docs/fy20osti/76994.pdf*

Table 4. Recommendations and Resources for PPL Efficiency

Item	Component	Recommendation[a]	Additional Information[b,c]
Office PPLs	Desktop computer	Purchase ENERGY STAR-rated equipment Implement sleep mode software	Table 5-3
	Laptop computer—use where practical instead of desktops to minimize energy use	Purchase ENERGY STAR-rated equipment Implement sleep mode software	Table 5-3
	Computer monitors (may include point-of-sale monitors)	Purchase ENERGY STAR-rated equipment Implement sleep mode software	Table 5-3
	Printer	Purchase ENERGY STAR-rated equipment Implement sleep mode software	Table 5-3
	Copy machine	Purchase ENERGY STAR-rated equipment Implement sleep mode software	Table 5-3
	Water cooler	Purchase ENERGY STAR-rated equipment	Table 5-3
	Refrigerator	Purchase ENERGY STAR-rated equipment	Table 5-3
	Vending machines	Purchase ENERGY STAR-rated equipment De-lamp display case	Table 5-3
Electric Forklifts	Charging	High frequency charger Power conversion efficiency ≥92% PF ≥96%	
	Battery	Technology with energy conversion efficiency of 90%–95%	
	Maintenance	Service forklifts regularly Inflate tires regularly to ensure optimal rolling efficiency	
	Operations	Optimize forklift paths to reduce run time and distance traveled	
	Controls	Timed auto-off function Time charging to limit peak demand (i.e., stage forklift charging to avoid simultaneous charging of all forklifts together or during peak hours)	

a. Recommendations show the range for all climate zones. Refer to referenced AEDG or ASHRAE 90.1-2022 for climate-zone-specific information.
b. Reference the Warehouse AEDG unless otherwise stated.
c. Refer to ASHRAE 90.1-2022 for minimum recommended values.

Item	Component	Recommendation[a]	Additional Information[b,c]
Data Centers	Information technology	Consolidate lightly used servers Implement efficient data storage Utilize built-in server power management features	ENERGY STAR[32]
	Power infrastructure	Utilize high-efficiency power distribution units Utilize high-efficiency uninterruptable power supplies with "eco-mode"	
	HVAC	Manage airflow efficiently and utilize hot aisle and cold aisle layout Utilize water- and air-side economizers Install in-rack or in-row cooling Utilize sensors and controls to match cooling capacity with information technology loads	

a. Recommendations show the range for all climate zones. Refer to referenced AEDG or ASHRAE 90.1-2022 for climate-zone-specific information.
b. Reference the Warehouse AEDG unless otherwise stated.
c. Refer to ASHRAE 90.1-2022 for minimum recommended values.

The High-Performance data center, at NREL, uses warm-water liquid cooling to achieve its very low power usage effectiveness, then captures and reuses waste heat as the primary heating source throughout the building's offices and laboratory spaces. These technologies substantially reduce the amount of energy used by the entire building, saving energy and money in new and effective ways.

Photo by Dennis Schroeder, NREL 53842

32 ENERGY STAR. n.d. "16 More Ways to Cut Energy Waste in the Data Center." *https://www.energystar.gov/products/16_more_ways_cut_energy_waste_data_center*

LIGHTING

Another important building energy end use in conditioned warehouses is electric lighting. Efficient light-emitting diode (LED) lighting systems and automated lighting control strategies are recommended to greatly reduce lighting energy consumption. Less heat (given off by the lights) in the space also then reduces the cooling load, reducing mechanical equipment size and energy consumption. Combining lighting efficiency improvements with appropriate daylighting design can further reduce lighting energy consumption. Given that warehouses are usually large open spaces, interaction with the layout of space should be taken into consideration when designing lighting systems. If rows of storage are planned, it is recommended to design lights to align with areas for forklifts or other occupied areas and to include zoned controls. In this case, a "hallway" between rows of storage should have lights along the hallway and be individually controlled. By designing lighting systems in this manner, zoned occupancy control can be utilized to turn on lights only in the zones that are occupied and turn off the other zones when not in use. This strategy can be compared to typical occupancy controls in offices where each zone is described by the walls of the room.

Table 5. Recommendations and Resources for Lighting Efficiency

Item	Component	Recommendation[a]	Additional Information[b,c]
Interior Lighting	Lighting power density	Warehouse (bulky and self-storage) = 0.34 W/ft^2	Office ZEDG Table 5-12
		Warehouse (fine storage) = 0.45 W/ft^2	ASHRAE 90.1-2022
		Office area = 0.42 W/ft^2	Office ZEDG Table 5-12
	Lighting fixtures	LED Fixtures End of Life L70 50,000 hours <125 LPW 80+ CRI Specify dimming driver	Office ZEDG EL8
	Controls for daylight harvesting	Automatic dimming or switching of all luminaires in daylighted areas	Office ZEDG DL9-DL11 Office ZEDG LC1-LC10
	Occupancy controls	Auto-on/off for all luminaires in the warehouse and self-storage areas. Zone storage bays to only turn on banks of lights when occupancy in that bank of lights is detected. Manual-on/auto-off for all office areas	Office ZEDG LC1-LC10
	Reflectance	Ceiling = 80%–90% Wall = 50%–70% Floor = 20%	Office ZEDG DL9
Exterior Lighting	Canopied areas	0.252 W/ft^2	EL19–21

a. Recommendations show the range for all climate zones. Refer to referenced AEDG or ASHRAE 90.1-2022 for climate-zone-specific information.
b. Reference the Warehouse AEDG unless otherwise stated.
c. Refer to ASHRAE 90.1-2022 for minimum recommended values.

HEATING, VENTILATING, AND AIR CONDITIONING

In many cases, some level of ventilation might be required in unconditioned warehouses to meet health and safety requirements per Occupational Safety and Health Administration or local mechanical code requirements. Ventilation systems in these buildings tend to be simple, consisting of mechanical equipment such as exhaust fans or makeup air units that ensure that the proper amount of ventilation air is provided. These systems typically do not cool or dehumidify the air and will only partially temper the air during the winter months, unlike most ventilation equipment found in other buildings. Even though these systems are relatively simple, design practices can reduce their overall energy consumption. These design practices could include controls to properly schedule the system based on building occupancy, detailed review of the ventilation requirements to ensure the units are not oversized, or design updates to existing mechanical equipment to reduce the overall energy used by the building.

Along with general envelope design on the exterior of the warehouse, the interior of the warehouse should be considered as well. For example, if occupancy is required, does it make sense to provide a conditioned area for employees while the rest of the warehouse is either left unconditioned or tempered to less strict requirements? This could lead to a smaller load on the mechanical equipment, resulting in further reduction in the size, cost, and energy use of the equipment. Creative approaches to utilizing the space and adjusting requirements through design should be considered to optimize and reduce the energy consumption of the warehouse.

Given the volume of the conditioned space in most warehouses, heating and cooling is a leading source of energy use in these facilities. Systems can include forced-air systems, radiant heating, natural ventilation, and destratification fans. All the heating and cooling systems need to be designed with the operation of the facility in mind, including loads and occupancy. Systems should be designed for high efficiency with the appropriate technology for the specific application, as certain design choices can lead to significant energy savings. For example, a building simulation for an aircraft hangar utilizing in-floor radiant heating showed savings of 40% to 55% for heating energy compared to a standard forced-air unit.[33]

Ventilation in conditioned warehouses is traditionally one of the biggest components of mechanical energy use and contributes significantly to the load and size of the mechanical equipment. Strategies to limit the ventilation load of the space should be considered, including but not limited to control strategies, heat recovery to temper ventilation air, or envelope designs such as transpired solar collectors[34] to preheat the ventilation air. This will provide an effective avenue for reducing equipment size requirements and overall energy use and provide more flexibility in terms of technologies to assist in further reducing carbon emissions.

For example, in a big box retail store, the owners used the ASHRAE Standard 62.1 IAQ procedure instead of following the Standard 62.1 prescriptive ventilation rate method for determining ventilation requirements. This performance-based method looks at the actual air quality in the space and determines the amount of ventilation that is required to meet the code requirements for acceptable air quality rather than predetermined numbers. In this instance, the facility was able to lower their ventilation rate to 0.08 cfm/ft^2 from the standard 7.5 cfm/person and 0.12 cfm/ft^2.[35] This significantly reduced the overall ventilation load in the space, and in tandem with other measures, helped the facility achieve 50% reduced energy consumption compared to the code baseline. Based on the types of materials and other building requirements, this methodology should be investigated to determine if the overall ventilation requirements, and consequently equipment size, can be reduced.

When looking at reducing carbon emissions in warehouses, mechanical ventilation and heating traditionally has been achieved utilizing gas-fired heating in the form of ceiling-hung radiant heat, direct-fired ventilators, unit heaters, and other systems because of their low cost and simplicity. When thinking about removing natural gas systems from a building or designing a facility without them, creativity and integrated design play a major role in the success of a project. The first step in achieving the goal of removing on-site natural gas use is to reduce a building's heating load as much as possible. Some methods for achieving this load reduction are:

- Envelope design
- Energy recovery
- Reducing the need for ventilation air through operational changes—for example, replacing propane forklifts with electric forklifts to reduce inside emissions
- Utilizing zoned heating and control strategies to reduce the overall space that is heated
- Lowering the heating set point when possible
- HVAC system scheduling.

Putting these practices into place will allow for other solutions to become viable. One of the current solutions to replace natural gas heat is a heat pump system. Heat pumps are traditional refrigerant-based air conditioners that can operate in reverse in the heating season and provide heat to the building. These technologies are relatively new in larger systems and are limited in capacity. As such,

33 Westlund, Ryan. n.d. "Efficiency in aircraft hangar heating." REHAU. *https://www.rehau.com/us-en/efficiency-in-aircraft-hangar-heating*

34 DOE. June 2006. Transpired Air Collectors Ventilation Preheating, *https://www.nrel.gov/docs/fy06osti/29913.pdf*

35 ASHRAE. 2011. *50% Advanced Energy Design Guide for Medium to Big Box Retail Buildings*, p. 23. *https://www.ashrae.org/technical-resources/aedgs/50-percent-ae-dg-free-download*

reducing the overall load in the space will provide an easier application for these systems. Configurations for heat pump systems could include:

- Radiant cooling/heating system served by an air-source or geothermal heat pump boiler and chiller with a heat pump dedicated outside air system (DOAS) with energy recovery
- Geothermal heat pumps distributed throughout the warehouse with a heat pump DOAS and high-volume low speed (HVLS) fans for air mixing
- Water-source heat pump system that heats the water via heat recovery from data centers and other loads in the space and cools the water via a cooling tower in the summer, with a DOAS for ventilation and HVLS fans for air mixing.

Heat pumps are a great solution for helping to decarbonize your building as they can eliminate gas-fired systems and provide heating without the significant electrical load increase of equivalent electric resistance heaters. However, current air-source heat pump technologies do have limitations in colder climates. As temperatures drop, air-source heat pumps can begin to lose capacity and efficiency depending on the technology and manufacturer. Care must be taken to ensure that designs have strategies in place to ensure consistent operation at low outdoor air temperatures. These include selecting cold-climate heat pumps or utilizing backup heating systems. If backup systems are needed, water-source and ground-source heat pumps, when designed properly, do not face the cold weather limitations that air-source systems have but are typically more expensive than air-source options. Another option could be to utilize an air-source heat pump with thermal storage to store energy during lower load periods and meet peak load demands in locations with intermittent cold weather events. In some cases, it could be viable to utilize heat pumps during much of the year and keep a natural gas backup system for use in extreme weather conditions. This dual-fuel solution can reduce first cost and eliminate the majority of the facility's natural gas consumption.

HVAC systems are used to control space comfort and air quality. These systems can be key contributors to building energy consumption and need to be designed to achieve maximum efficiency. All the other building systems (envelope, lighting, and PPLs) will impact the required size of HVAC equipment. Energy efficiency measures for those systems, like improved envelope efficiency and reduced lighting loads, will reduce the size of HVAC equipment needed, and reduce costs for equipment and energy expenditures.

Warehouse HVAC systems provide comfort for occupants and may help to preserve items being stored.

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Table 6. Recommendations and Resources for HVAC Efficiency

Item	Component	Recommendation[a]	Additional Information[b,c]
HVAC	Cooling system (conditioned storage, all sizes)	Heat pump packaged systems for low sensible load Spaces; variable-speed supply fan; inverter compressor Heat pump dedicated outdoor air system for high latent load spaces, energy recovery ventilator, variable-speed supply fan; inverter compressor. Couple with return-air-only heat pumps for sensible loads.	HV4 Office ZEDG Table 5-20
	Air-cooled heat pump cooling/heating (0–65 KBtuh) (>65–135 Kbtuh) (>135–240 Kbtuh) (>240 KBtuh) Supply fan Exhaust heat recovery	≥15 SEER/≥12.5 EER/≥8.5 HSPF ≥11.1 EER/≥14.1 IEER/≥3.4 Coefficient of performance (COP) ≥10.7 EER/≥13.7 IEER/≥3.3 COP ≥10.0 EER/≥12.5 IEER/≥3.2 COP Variable-speed drive (VSD) minimum turndown 30% Humid and marine zones 72% enthalpy reduction Dry zones 72% dry bulb temperature reduction	Office ZEDG Table 5-20 Office ZEDG Table 5-20 Office ZEDG Table 5-20 Office ZEDG Table 5-20 ASHRAE 90.1-2022 Table 6.8.1
	Ground-source heat pump cooling efficiency Heating efficiency Supply fan Compressor capacity control Water circulation pump Cooling tower/fluid cooler (for hybrid systems) Boiler efficiency (for hybrid systems)	>18.0 EER >3.7 COP VSD motor VSD compressor minimum turndown <30% VSD and NEMA Premium efficiency <20 W/gpm at design VSD on fans Condensing boiler, >92% efficiency	Office ZEDG Table 5-20
	Destratification	Install High Volume Low Speed Fans (HVLS) or Ceiling Fans	HV7

Item	Component	Recommendation[a]	Additional Information[b,c]
DOAS	Cooling efficiency	>5.2 Integrated Seasonal Moisture Removal Efficiency (ISMRE)	Office ZEDG Table 5-20
	Capacity control	VSD Compressor Minimum Turndown 20%	Office ZEDG Table 5-20
	Supply fan	VSD Minimum Turndown 30%	Office ZEDG Table 5-20
	Exhaust energy recovery	Humid and Marin Zones 72% Enthalpy Reduction Dry Zones 72% Dry Bulb Temperature Reduction	Office ZEDG Table 5-20
	Air-cooled heat pump (0–65 KBtuh) (>65–135 Kbtuh) (>135–240 Kbtuh) (>240 KBtuh)	≥15 SEER; ≥12.5 EER / ≥8.5 HSPF ≥11.1 EER/≥14.1 IEER / ≥3.4 COP ≥10.7 EER/≥13.7 IEER / ≥3.3 COP ≥10.0 EER/≥12.5 IEER / ≥3.2 COP VSD Minimum Turndown 30%	Office ZEDG Table 5-20
	Gas heat	Only as backup heating system AFUE >80%, modulating	Office ZEDG Table 5-20
	Boiler efficiency	Only as backup heating system Condensing boiler, >92% efficiency	Office ZEDG Table 5-20
	Water circulation pumps	VSD and NEMA Premium efficiency <12 W/gpm at design	Office ZEDG Table 5-20
Economizer	Air conditioners and heat pumps	Cooling capacity >33 kBtu/hr Enthalpy control	HV24 Office ZEDG HV33
Ventilation	Outdoor air damper Air leakage through relief dampers Demand control ventilation	Motorized control 3 cfm/ft^2 at 1 in. water gauge (wg) CO_2 and OCC Sensors	HV9–10 Office ZEDG HV19
Ducts	Friction rate Sealing location Insulation level	0.08 in. water column (w.c.)/100 ft Seal class B interior only R-6	HV11, 20 HV13 HV11 HV12

a. Recommendations show the range for all climate zones. Refer to referenced AEDG or ASHRAE 90.1-2022 for climate zone specific information.
b. Reference the Warehouse AEDG unless otherwise stated.
c. Refer to ASHRAE 90.1-2022 For minimum recommended values

SERVICE WATER HEATING/ DOMESTIC HOT WATER

Service water heating (SWH) or domestic hot water (DHW) is provided in most warehouses for end uses such as hand washing, showers, cleaning, safety wash stations (e.g., eye wash, showers). These systems utilize a heating system, pipes, and occasionally pumps to heat and move water throughout the facility. Generally, these systems are small and use a relatively low amount of energy on-site. However, if poorly designed, there is potential for considerable energy waste for these systems. Care should be taken in locating heating equipment to minimize long runs of hot water pipes. If code permits, options to eliminate hot water end uses should also be explored. For example, if an eye wash station is required in an unconditioned warehouse, instead of utilizing hot water to temper the eye wash station for freeze protection and code requirements, a portable eye wash station that does not require DHW could be used, reducing the need for hot water pipes or equipment. DHW, and SWH in some cases, are heated via natural gas, adding to scope 1 emissions for the facility. Electric resistance water heaters are available to provide electrified solutions as well as heat pump water heaters. Both of these technologies provide a means to reduce scope 1 emissions and allow for on-site solar to offset the increased electrical consumption and scope 2 emissions of the facility. Heat pump water heaters have increased efficiency (200%–400% more) over the electric resistance water heaters and should be utilized when possible. Given the relatively low load of DHW and SWH systems and their consistent use, heat recovery is a viable option to cover the load of these systems. Utilizing waste heat from things like cooling equipment or data centers can reduce the heating requirements by preheating the DHW, reducing the load on the heating equipment and therefore reducing consumption overall by utilizing waste heat from necessary processes.

In some cases, facilities might have more stringent cleaning requirements which necessitate larger hot water systems that provide steam or high-temperature hot water. This guide does not cover these systems, which are typically more complex custom systems that expert design professionals should investigate for efficient design options. DHW and SWH, at a minimum, should follow ASHRAE 90.1-2022 values. The table below provides recommendations for DHW and SWH systems from the ZEDG that are applicable to warehouses.

Table 7. Recommendations and Resources for SWH and DHW Efficiency

Item	Component	Recommendation[a]	Additional Information[b,c]
Service Water Heating	Efficiency	Uniform Energy Factor ≥3.0 COP ≥4.0	ASHRAE 90.1-2022 W02
	Point-of-use heater selection	Avoid pumped return for distributed light loads. If there are multiple long runs of pipe to end uses, consider distributed point-of-use water heaters instead to avoid pipe losses.	WH5
	Water heater sizing	Avoid oversizing and excessive supply temperatures	Office ZEDG WH3
	Pipe insulation	1 in. - 3 in.	ASHRAE 90.1-2022 Table 7.4-2
	Water consumption	Avoid water consumption with low-flow end use devices	Office ZEDG WH2

a. Recommendations show the range for all climate zones. Refer to referenced AEDG or ASHRAE 90.1-2022 for climate-zone-specific information.
b. Reference the Warehouse AEDG unless otherwise stated.
c. Refer to ASHRAE 90.1-2022 for minimum recommended values.

ON-SITE GENERATION, STORAGE, AND SYSTEM INTERACTION

It is important to consider both energy consumption and demand impacts in warehouse design. Energy consumption is the total amount of energy consumed by a building, and demand refers to the rate of electricity provided to a building. On a utility bill, the demand (kW) is based on the highest rate of electricity provided to the building over the billing period. For many commercial buildings, demand is measured based on a 15- to 30-minute peak interval and is reflected as a $/kW charge each month based on this 15- or 30-minute peak. Demand charges can also be ratcheted, where some fraction of the highest peak demand per month will be charged for the remaining 11 months of the year, unless actual demand is higher. Demand charges are a major contributor to utility bill costs, often accounting for more than 50% of a commercial utility bill, and should be managed to the extent possible.

On-site renewable generation can help reduce both energy use and electricity demand in a building. Considering the relatively low cost of PV for electricity generation, the addition of rooftop PV in warehouses could result in a significant levelized cost of electricity (LCOE)[36] reduction. The low energy intensity of warehouse buildings coupled with their large roof area enables zero energy or net-positive PV sizing design, which significantly reduces the operational cost. In addition, energy management and the integration of PV with building loads are also critical. As much as possible, the building electrical load should align with the daily PV generation profile. To help accommodate mismatches between building load and generation, electric battery and thermal energy storage solutions should also be considered and integrated into the building's overarching energy management system.

36 LCOE refers to the average net present cost of electricity over the lifetime of the panels.

In the traditional design of DERs (e.g., PV panels and battery systems), designers consider factors such as the energy use and demand of the building, electricity rate structure, and initial capital cost of the system. Depending on the building loads and level of automation, the size and cost of these DER systems can vary greatly, usually resulting in selection of the smallest, least-expensive system that meets basic requirements for the building. However, increasing the level of on-site generation and energy storage could provide additional value by increasing resiliency of the building in the event of loss of electrical service, or by enabling larger opportunities for the building to provide revenue-generating grid services.

With recent utility programs (many enabled by the Federal Energy Regulatory Commission [FERC] Order 2222-A[37]) and the pressing need for demand flexibility or grid-interactive efficient building operation, warehouses equipped with DERs can play a major role in providing energy and ancillary services, also known as "grid services." Incentives for demand reduction and on-site generation, as well as opportunities for net metering, are some examples of how larger PV systems could benefit warehouses. In addition, utilities are starting to partner more with industrial and commercial customers who can provide flexibility in their energy consumption and demand to foster a more resilient grid. This guide recommends working closely with utilities to learn about their programs and incentive offerings that facilitate the addition of DERs in the warehouse.

Maximizing on-site PV generation by leveraging large areas on warehouse rooftops and surroundings could result in other valuable opportunities for the warehouse owner and operator, as well as the community. Excess generation, beyond what is used to cover the building's loads, can be used to offset electric vehicle charging needs. The current trends in fleet electrification position warehouses as key facilities that can provide renewable energy to the transportation sector. In addition, excess generation could be used for resource sharing with adjacent buildings or to meet potential surrounding community needs.

37 FERC 2222-A enables participation of DERs in the wholesale energy market, providing another value stream for interactive operation of the warehouse electricity generation and energy storage systems.

System control is important to maximize the value of integrating various DER systems. It is essential to set goals in order to be able to choose and implement the control systems. Operational goals vary based on an organization's mission, system size, and utility bill structure. These goals may include reduction of utility costs, enabling fleet charging, peak shaving, and providing grid services. In addition to the type of control algorithm and technology, the goal informs the design of the components and connection points, such as inverter configuration, to allow seamless integration of systems.[38]

Maximizing the building rooftop area for PV, along with building load flexibility and energy storage, can be a strong solution to decarbonizing the e-commerce and transportation sectors. It should also be noted that there are some barriers that could interfere with this strategy, such as the structural integrity of warehouse roofs to support the weight of large PV systems. Proper design of electrical panels and upgrading electrical infrastructure for needed capacity can also be a challenge, as can ensuring that the building design can impactfully integrate PV systems, rooftop units, and skylights.

38 Rezaeimozafar, Mostafa, Rory Monaghan, Enda Barrett, and Maeve Duffy. 2022. "A review of behind-the-meter energy storage systems in smart grids." *Renewable and Sustainable Energy Reviews* 164: 112573.

BUILDING CONTROLS

Building controls can provide a building's owners and operators with the ability to automate and control processes from HVAC, PPLs, lighting, shading, access control, security systems, and other interrelated systems. During the building's design phase, the design team, CxA, and project champion should ensure that the controls are meeting the owner's goals from both an operational and energy perspective. Controls allow for integrated systems to fulfill the intent of design decisions. For example, when skylights or other daylighting opportunities are designed into the building envelope, proper daylighting controls will allow lights to dim or turn off in response to daylight, reducing energy costs.

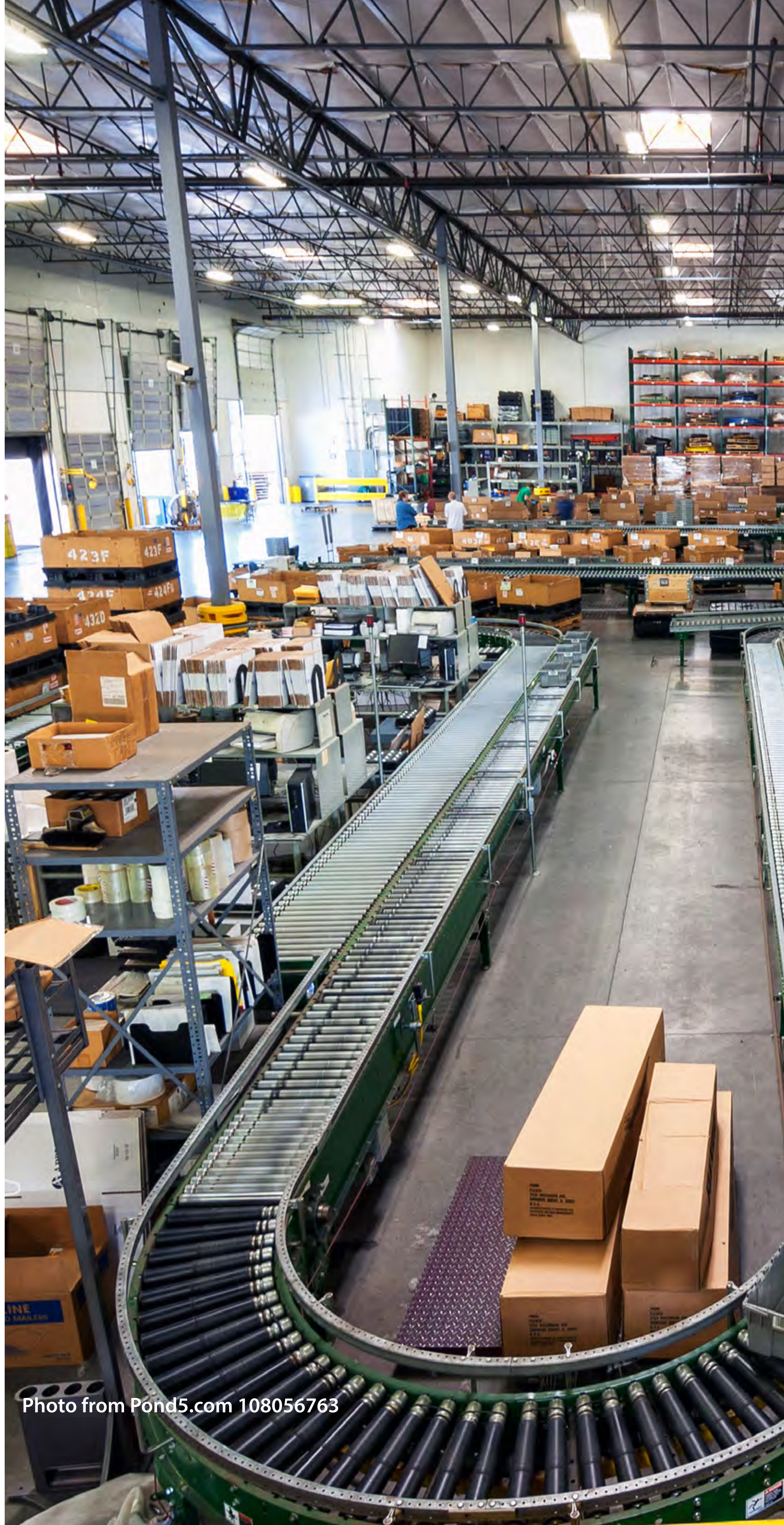
The primary function of a building's controls is to monitor and automate equipment operation. Controls systems monitor the equipment and adjust the operation in response to changes detected by the monitoring devices. A common example of controls is a thermostat controlling an air conditioner in response to changes in space temperature. At a base level, the control system ensures equipment is running when it needs to and is operating as intended.

Many efficient control strategies are available and should be explored to help maximize equipment efficiency. For HVAC equipment, these strategies can include on/off scheduling, temperature setbacks, or optimized space temperature set points. More advanced HVAC control schemes are also available. For example, demand control ventilation in locations with intermittent occupancy can allow the air handling equipment to reduce the ventilation load in the space in response to decreased occupancy. Many controls strategies exist for HVAC and other equipment and should be explored by the design engineers. As a baseline, when applicable, the controls should align with ASHRAE Guideline 36, *High-Performance Sequences of Operation for HVAC Systems*.[39] This guideline provides industry-vetted sequences of operation and resources for controls to help design functioning controls schemes for mechanical equipment.

Controls offer many opportunities to reduce the energy consumption of the equipment in the space, but they also provide opportunities to control power generation and storage in the building, as well as help coordinate a demand response program for the facility. Controls can help curtail power generation when needed, coordinate the charge or discharge rate of on-site batteries, manage thermal storage systems, and implement other demand response strategies. By optimizing the timing of these systems, the facility can minimize demand charges and operate in a more resilient manner. Battery storage on-site can be used to store excess energy and discharge this energy at the times when demand charges are at their highest levels. Demand response control could also focus on the equipment inside the building, such as adjusting space temperature set points to reduce heating or cooling loads in the space to lower demand charges.

Not only do controls provide the opportunity for further energy savings, but they also offer the ability to monitor equipment. This allows operators to understand how a system is performing compared to expectations, as well as to know when certain maintenance tasks need to be completed. This adds to a site's overall resiliency and ability to maintain the original project goal of energy efficiency, zero energy design, zero carbon, or zero design.

39 ASHRAE. 2021. "Guideline 36-2021 -- High-Performance Sequences Of Operation For HVAC Systems"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ADDITIONAL ACTIONS AND OPPORTUNITIES

While this guide has primarily emphasized energy efficiency, electrification, on-site renewable energy, and storage as key strategies for decarbonization, it's important to recognize that there are other aspects of facility construction and operation that also contribute to greenhouse gas (GHG) emissions. This section explores additional areas to consider in order to comprehensively reduce GHG emissions at a facility.

Water

Water is another operational expense and resource that has an impact on the carbon footprint of a warehouse because of the energy that goes into the treatment and delivery of the potable water. In many warehouses, water is used for drinking, cleaning, irrigation, and showers, as well as some light manufacturing processes. There are many ways to save water in a facility, including:

- Install low-flow fixtures.
- Utilize air-based, rather than water-based, cleaning methods when possible—for example, blowers or vacuums to remove dust.
- Collect rainwater or water from other drainage sources to use in irrigation, cleaning, or rinsing applications, if possible.
- Identify, detect, and repair leaks.
- Reduce makeup water for boiling or chilled water applications.
- Reduce or eliminate irrigated areas.
- Utilize automatic shut-off or controls on water-using equipment to reduce use.

Other water conservation ideas and strategies can be found in the U.S. Environmental Protection Agency document *Using Water Efficiently: Ideas for Industry.*[40] By implementing water reduction strategies, the site's overall carbon impact, in addition to operational expenses, can be reduced.

Embodied Carbon

This guide has focused on energy efficiency, electrification, and storage strategies which help reduce operational carbon emissions. This is a significant portion of the carbon footprint of a building and is ongoing throughout a building's life. However, when looking at the overall carbon emissions of a building, embodied carbon can be substantial. Embodied carbon is the carbon that is inherent in the raw material extraction, manufacturing, construction, and transportation of building materials and components. This embodied carbon accounts for all the inputs that go into a building's construction and captures the overall carbon impact of building a facility.

For warehouses, embodied carbon is significant because of the high-embodied-carbon materials that typically serve as the primary materials in their construction, such as steel and concrete. Thus, embodied carbon should be accounted for when looking at carbon reduction in buildings. Strategies to reduce embodied carbon include:

- Using concrete mixes optimized for reduced carbon
- Using rebar with high recycled steel content
- Selecting insulation products with low embodied carbon
- Selecting glazing products with low embodied carbon
- Selecting finish products with low embodied carbon
- Sourcing construction materials from locations close to the project site
- Using construction byproducts in construction, such as rocks and dirt from digging the foundation.

Further information on embodied carbon can be found in the *Embodied Carbon Resource Navigator*,[41] DOE webinar *Sustainability and Decarbonization Inside Warehouses and Distribution Centers*,[42] as well as in the RMI report, *Reducing Embodied Carbon in Buildings.*[43]

40 EPA. 2000. "Using Water Efficiently: Ideas for Industry." https://www.epa.gov/sites/default/files/2017-03/documents/ws-ideas-for-industry.pdf

41 Goetsch, Heather, Paul Torcellini, Sammy Houssainy, and Julia Sullivan. 2023. *Embodied Carbon Resource Navigator*. U.S. Department of Energy. DOE/GO-102023-5774. *https://www.nrel.gov/docs/fy23osti/83427.pdf*

42 DOE. 2022. "Sustainability and Decarbonization Inside Warehouses and Distribution Centers." Better Buildings Webinar Series. https://betterbuildingssolutioncenter.energy.gov/sites/default/files/slides/Warehouse%20Decarbonization%20-%20Slides.pdf

43 Matt Jungclaus, Rebecca Esau, Victor Olgyay, and Audrey Rempher. 2021. Reducing Embodied Carbon in Buildings: Low-Cost, High-Value Opportunities. RMI. https://rmi.org/wp-content/uploads/dlm_uploads/2021/08/Embodied_Carbon_full_report.pdf

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