ASHRAE GUIDE for Sustainable Refrigerated Facilities and Refrigeration Systems

Technology
Design
Systems
Controls
Modeling and Analysis
Commissioning

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ASHRAE GUIDE for

Sustainable Refrigerated Facilities and Refrigeration Systems

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1 · User Guide

WHO IS THIS GUIDE FOR?

This guide is for the following stakeholders:

- The designer of the facility
- The managers of construction and operation, and the contractors and operators who will build and run the facility
- The owner of the facility and the owner of the refrigerated product
- Regulators and the communities that host a refrigerated facility

Although much of this book focuses on design, it is also important to realize that achieving sustainability does not end with the design of the facility. The idea of sustainability must continue into the construction and ongoing operations and maintenance of the facility.

Likewise, as sustainability does not end with design, neither does sustainability begin with design. Sustainability begins with the specification and intent of the owner. This means that both the owner of the facility and the owner of the product that passes through the facility must engage to achieve sustainability.

Finally, refrigerated facilities, and the stored products, are hosted in a community and exist in a regulatory jurisdiction. Regulation or legislation can promote, subsidize, mandate, or hinder the adoption of different practices and technologies, which may affect the sustainability of a refrigerated facility. Ultimately, sustainability is to the benefit of the host community.

THE PURPOSE OF THIS GUIDE

The design and operation of any refrigerated facility is a balance of several competing factors, including the following:

- Function: Does the facility maintain temperature or provide the required cooling in specified operating conditions?
- Safety: Is the facility safe to operate? This includes safety for operators, the host community, and the eventual consumers of products from the facility.
- Economic: Can the owner afford to build the facility and to operate it profitably?
- Environmental: Is the facility's impact upon the local, regional, and global environment minimal?

- Social: Does the presence of the facility contribute positively or negatively to its host community? This can include factors such as direct employment, increasing opportunities for local producers and contractors, and the aesthetics of the facility.

As Chapter 2 demonstrates, all of these factors can contribute to the design and operation of a sustainable refrigerated facility. It is also important to realize that sustainability is not a fixed target that is either met or not. Instead, sustainability is a continuum within which it is possible to evaluate and compare options for design and operations.

For each facility, the balance of factors that is appropriate for sustainable design and operation will be different. Even at a very detailed level, the design or operational decisions that lead to the more sustainable option can depend on the specific circumstances. To take one example, the defrost method and defrost management program that is more sustainable depends upon numerous factors including the local utility and environmental costs of water and electricity, the latent heat load on the facility, the design of the evaporator heat transfer surfaces, the extent that there is excess cooling capacity in the facility, and the consequences of air temperature changes to the stored product. Thus, it is impossible for this guide to provide a definitive answer for the most sustainable defrost method and operating strategy. Similar considerations apply to most main design and operational decisions.

Therefore, the purpose of this guide is to help the reader evaluate for their own specific circumstances which options are more sustainable. The intent is not to provide a list of sustainable options that can be selected. The purpose of the guide is to introduce methods that readers can use for evaluating sustainability.

READING THIS GUIDE

Beyond this chapter (1) and the introduction (2), the guide consists of (3) an Introduction to the Basics of Refrigeration Technology, (4) Refrigerated Facility Design and Heat Load Calculation, (5) Design of the Refrigeration System, (6) Control and Control Strategies, (7) Energy Modeling and Performance Analysis, (8) Commissioning. Table 1.1 gives reading guidance for the various users of the guide.

The Introduction (Chapter 2) should be read by all users, because this chapter shows why sustainability is important and shows which considerations are the most important to sustainability. It also sets out methodologies to assess sustainability with a focus on environmental impact.

The Chapter 3 (Introduction to the Basics of Refrigeration Technology) should be read by all users who lack technical background upon refrigeration systems. This chapter is accessible to (and written for) those who have no technical background. Technically proficient readers may wish to revisit this chapter for clarity on technical terms.

All users should read the final chapter on commissioning (Chapter 8). This chapter details the various roles in the technological project of designing and operating a sustainable refrigerated facility. The chapter is particularly important for the facility owner and the facility designer as clear communication and understanding of responsibility between these roles is key to achieving a sustainable facility.

Chapter Summaries

Chapter 2: Introduction to Sustainable Refrigeration

The scope of the guide, definitions of sustainability in the context of refrigeration, high level strategies to improve sustainability, metrics and methods to assess sustainability, and a worked example that calculates the carbon footprint for a refrigerated facility.

Table 1.1 Reading Guide for Various Users of the Guide

User	Most Important Sections	Secondary Importance
Facility owner	Chapter 2 to understand what sustainability means for refrigerated facilities. Chapter 8 to understand the facility quality delivery process.	Facility design sections of Chapter 4 to understand how the OPR are used to establish the BOD.
Product owner	Chapter 2 to understand what sustainability means for refrigerated facilities. Chapter 8 to understand the facility quality delivery process.	The product-related sections of Chapter 4 to understand how product format and requirements and packaging design impact sustainability.
Facility designer	The whole guide.	
Construction contractor	Chapter 2 to understand what sustainability means for refrigerated facilities. Facility design sections of Chapter 4 and system design sections of Chapter 5 to understand how some construction choices impact sustainability.	Chapter 6 to understand how control will be implemented in the built-system. Also Chapter 8 to understand the commissioning process
Facility operator	Chapter 2 to understand what sustainability means for refrigerated facilities. Control and control strategies (Chapter 6) and the facility design sections of Chapter 4 to better understand the impact of operation changes in the refrigeration system and facility, respectively.	Energy performance analysis sections of Chapter 7 and benchmarking sections of Chapter 8 to better troubleshoot operations.
Facility maintainer	Chapter 2 to understand what sustainability means for refrigerated facilities. Facility design sections of Chapter 4 and system design sections of Chapter 5 to understand the facility and system can degrade over time and how to mitigate against this. Control and control strategies in Chapter 6 to understand the potential impact of control changes.	Energy performance analysis sections of Chapter 7 and benchmarking sections of Chapter 8 to better troubleshoot and schedule preventative maintenance.
Host community	Chapter 2 to understand what sustainability means for refrigerated facilities. The introductory sections of Chapter 8 (Commissioning) to understand the management of the facility design/construction/operation to best ensure the community's input is received and accounted for.	Representatives of the community consenting or certifying aspects of the design or construction should read the relevant sections of Chapter 4 and 5 to understand the sustainability rationale of design/construction decisions.

Chapter 3: Refrigeration Technology

The basic principles of refrigeration systems and the technologies applicable in both industrial and commercial installations, focusing on the vapor compression refrigeration cycle. Topics include refrigerants, typical system configurations, equipment options, and an overview of safety and rating standards relevant to refrigeration systems.

Chapter 4: Refrigerated Facility Design and Heat Loads

Design of the refrigerated facility excluding the refrigeration system but including product handling system and facility layout. Also includes estimation of refrigeration heat loads for design with an emphasis on their minimization to reduce refrigeration system-installed capacity and energy use.

Chapter 5: Refrigeration Components and System Design Considerations

Refrigeration system design, including use of a design scorecard to guide design choices, system layout selection, and the design and selection of system components including evaporators, compressors, and condensers and their design for efficient operation.

Chapter 6: Controls and Control Strategies

A description of factors affecting refrigeration system performance and the need for controls. An overview of the control strategies for major refrigeration components, and the control systems and equipment for implementation of these strategies, emphasizing both component (subsystem) and overall system optimization.

Chapter 7: Energy Modeling and Performance Analysis

A description of energy modeling approaches including model types, selection, implementation and validation. Descriptions and comparisons of software systems are included to assist with modeling and analysis of facility design and performance.

Chapter 8: Commissioning— A Process to Achieve Sustainable Refrigerated Facilities

An overview of the commissioning process in the context of the planning, design, construction/installation, start-up, and ongoing operation of refrigerated facilities. Consideration of benchmarking and performance monitoring to maintain sustainable operation is also discussed.

Appendix: Refrigerated Facility Design Example

The description of a refrigerated facility used to illustrate the techniques, methods, and approaches outlined in this guide. The design example is a food distribution center refrigerated storage facility that also has future capacity to freeze or chill product.

THE ROLES IN THE DESIGN AND OPERATION OF A SUSTAINABLE REFRIGERATED FACILITY

The main roles in the design and operation of a sustainable refrigerated facility are as follows:

- **Facility Owner.** The owner (or their agents) will articulate what the facility must do and outline the criteria for decision making (together, these are sometimes called the *owner's project requirements* [OPR]). In a sustainable facility, one of these criteria is sustainability. Sustainability is not achieved by accident, but by the conscious decision of the owner.
- **Product Owner.** The representative or owner of the products that will be stored or cooled in the facility. Sometimes this will be the facility owner, but frequently

the product owner is a different person, division, or organization. Often this will not be the literal owner of the product, but may be an internal stakeholder (or equivalent external stakeholder) such as production, research and development, sales, or manufacturing. The refrigerated facility provides a service to the product owner, and the sustainability of the refrigerated facility contributes to the sustainability of the product, and to its “provenance.” The product owner should contribute to the articulation of the OPR, because an important part of achieving sustainability (see Chapter 2) is ensuring that product quality is maintained. This information must also flow to the facility operators. Sometimes (in a contract facility, for example), the product (and therefore the product owner) may not be defined until after the facility is constructed, and may change during the lifetime of the facility. In this case, generic product requirements must be used for design (specified by the facility owner). However, to ensure sustainable operation, actual, specific product requirements should still be shared with the facility operators once the product is identified.

- **Facility Designer.** The designer of the facility who makes decisions in the course of the design to pursue the OPR, including sustainability criteria. Exactly how the design implements the OPR (the assumptions, calculations, and decisions made) should be articulated and recorded (sometimes called the *basis of design* [BOD]) and from this the detailed construction documents (CDs) should be derived along with detailed operating and maintenance procedures (called *standard operating procedures*, [SOPs]). Usually, commissioning/acceptance criteria for the construction of the finished facility will accompany the CDs. Often (but not always) the facility designer has greater technical expertise and experience than the facility owner, so the facility designer (or an intermediary project manager or consultant) may need to assist in refinement of the OPR. The facility designer may generate some design options for the facility owner to consider. These should include clear information on the sustainability impact of each option.
- **Construction Contractor.** The builder of the physical facility, in accordance with the CDs. Usually, the construction contractor has experience and technical expertise and so may be partly responsible for the facility design and/or propose variations during construction or bidding. To ensure that the sustainability of the

A Sustainable Refrigerated Facility as a Project

The design and ongoing operation of a refrigerated facility is a complex technological project and there are numerous schemes to organize and manage such projects. For example the *Refrigeration Commissioning Guide for Commercial and Industrial Systems* (ASHRAE 2013) describes one method (summarized in detail in Chapter 8, with additional commentary upon sustainability). Most engineering and architecture organizations, societies, and businesses recommend or use similar schemes. The central purpose of all such schemes is to articulate, record, communicate, and act so the purpose of the project is achieved as intended. As sustainability encompasses the lifetime of the system's operation (including construction and eventual dismantling and disposal), sustainability management and the flow of relevant information must continue beyond design, construction, and the initial period of operation.

Regardless of the scheme used for the management of the project, the main roles that must be accounted for in ensuring the sustainability of the refrigerated facility are listed in this chapter. Depending upon the scale and circumstances of the specific facility, some of these roles may be either individual people or organizations. Sometimes an individual (or organization) may take on several roles.

as-built facility is preserved (or increased), design variations should be carefully evaluated back through the BOD to the OPR.

- **Facility Operator.** The operator follows the SOPs. Most refrigerated facilities will operate for more than a decade and the facility operator may have little or no direct contact with the facility designer, so the BOD and the SOPs must be clear. It must also be clear how operator action contributes to (or is detrimental to) the sustainability of the facility and the other criteria articulated in the OPR. The product owner and facility operator must work closely with each other over the lifetime of the facility to refine the SOPs given the product properties, product requirements, and product volumes. Sometimes, the product owner and facility operator will lack the technical expertise for this task and will need to draw upon the expertise of others.
- **Facility Maintainer.** The maintainer of the facility follows the relevant maintenance procedures. As with the operation of the facility, how maintenance tasks contribute to the sustainability should be clear, and the relevant SOPs for maintenance may need to be revised numerous times over the lifetime of the facility.
- **Host Community.** The broader community and environment that hosts the facility. The community can be considered at a local, regional, or global level. The host community may not have direct control over the sustainability decisions made in the design, construction, and operation of the facility, but ultimately the main purpose of sustainability is to benefit the host community by minimizing the detrimental impacts of the facility. The host community may also benefit from the facility, in terms of employment, increased food access, or other opportunities. The facility owner and the facility designer should consult with the host community during the formulation of the OPR and the derivation of the BOD to ensure that the resulting facility is appropriate to the host community. Depending upon the legal jurisdiction, the host community may also be represented by a regional authority that consents or certifies aspects of the facility or its construction. Some of these consented or certified aspects may be driven by sustainability; safety is also often an important driver. Ongoing community interests are often embodied via expected compliance to local regulations, rules, and laws, as well as consents granted to the facility.
- **Consultant.** A technical specialist. The facility owner and construction contractor (or the other roles) may engage technical consultants to act on their behalf or to provide advice when specialist technical expertise is required.

In addition, there may be other roles to do with the management of the project. For example, Chapter 8 (based on *Refrigeration Commissioning Guide for Commercial and Industrial Systems* [ASHRAE 2013]), envisions a commissioning authority as the project manager largely responsible for facilitating communication between the roles listed previously.

Most refrigerated facilities operate for more than a decade, which means that many facilities will have multiple owners over the operating lifetime. Therefore, to be sustainable, the OPR, BOD, and consequent SOPs must be communicated to, preserved, and adopted by the new facility owners (albeit perhaps modified for new products). The decision to be sustainable may require subsequent decisions to be evaluated over a long planning horizon that even extends beyond the projected lifetime of the original facility-owning business. This need not be a problem, but indicates that sustainability can require different decision making criteria to usual business decisions.

GUIDANCE FOR OTHER COMMON SCENARIOS

Apart from the general task of designing and operating a refrigeration facility, some other common scenarios in which the sustainability of the facility might be considered are as follows:

- **Increase the sustainability of an existing facility with no budget for significant capital work.** In this scenario, the key to sustainability improvements is smarter operational management decisions. Review Chapter 4 for opportunities to cheaply reduce the heat load. Review Chapter 6 for opportunities to make control changes. Update and review SOPs and, in consultation with operators, audit and compare to actual operating practice. If available, historical data can be used to develop an energy performance model to compare against real performance (Chapter 7), but this can be very difficult if the measured data cannot be trusted (e.g., poorly calibrated sensors). Also, sufficient data to determine the heat load independently of compressor performance are not typically available. Benchmarking against similar facilities (Chapter 8) can also be attempted.
- **Redesign/retrofit an existing facility to increase sustainability (including significant capital expenditure where appropriate).** This scenario should be treated like a new design process, with all the usual roles and management processes (OPR, BOD, etc.). There will be a cost and benefit (economic and sustainability) to retaining or replacing parts of the original facility and systems. The key chapters are 4, 5, and 8. Options that do not affect the operation of the refrigeration system or the product logistics (for example, addition of renewable on-site power generation, such as solar photovoltaics) may require only a simpler, high level, cost-benefit analysis (for example, evaluating whether the reduced environmental impact of energy use and the changes in energy cost is worthwhile compared to the required capital investment).
- **Monitor the sustainability of a facility.** Review Chapter 7 and benchmarking sections of Chapter 8. An important element of monitoring performance is to have a good measure of the actual heat load, ideally, independently of the compressor performance. Review Chapter 4 (and BOD) to determine what the major heat loads for the facility are and to determine the information/measurements needed to estimate the main heat loads. Routine calibration of instrumental measurements is important. Update maintenance SOPs to include instrument calibration and update SOPs to include analysis of monitoring data.
- **Increase the rate of production sustainably.** Many facilities have spare capacity, but this can be critical for maintenance and efficient operation. Increasing production throughput can use spare capacity, but there may be constraints and using spare capacity may make sustainable operation more difficult. Review the BOD and the (product) OPR to determine the flexibility of capacity in the system and the actual requirements of the product. Be careful to distinguish between the volume capacity of storage spaces and the cooling capacity for the space. Review Chapter 4 for opportunities to reduce extraneous heat loads. Review Chapter 6 for opportunities to make control changes to increase capacity (but without compromising product quality). There will be a limit to the system capacity, so additional investment in precoolers may be considered (depending on product specifics) or temporary capacity can be hired and brought to site. Review and update SOPs.
- **Maintain/increase sustainability when the product changes.** Similar to increasing the rate of production the main task is around matching the new prod-

uct requirements to the capacity of the system (see advice for increasing rate of production). New product handling requirements may result in opportunities to reduce heat loads (see Chapter 4). Also review packaging decisions (see Chapter 4, for discussion on how packaging decisions can influence heat load and cooling rate). Review and update SOPs.

- **Conversion of the refrigeration system to a new refrigerant.** Review the BOD, CDs, and Chapter 5 to determine new refrigerant management options, pressure requirements, and equipment compatibilities. Modify the SOPs accordingly, paying special attention to safety and hazards and legislative requirements and notifications, and likely changes in energy efficiency.

REFERENCES

ASHRAE. 2013. *Refrigeration commissioning guide for commercial and industrial systems*. Atlanta: ASHRAE.

2 · Introduction to Sustainable Refrigeration

Improving sustainability is becoming a key business strategy and is essential for the future of humankind. *ASHRAE Guide for Sustainable Refrigerated Facilities and Refrigeration Systems* aims to help anybody involved in the design, ownership, operation, or commissioning of a refrigerated facility or refrigeration system to make decisions and take actions that result in more sustainable systems or facilities. The pursuit of refrigerated facilities that meet sustainability goals and objectives is challenging because of the complexity of these applications and the infrastructure necessary for their operation.

Many facets that influence sustainability are interconnected. This interconnectivity naturally creates options to choose from, and each option results in trade-offs. For example, an apparently sustainable decision made during design may result in unsustainable practices in operation (e.g., an unexpected cooling load profile may lead to higher energy use than expected). Because of this interconnectivity, good communication is critical to achieving sustainable refrigerated facilities and refrigeration systems. Designers need to know what owners intend to do with a facility, operators need to understand the design, commissioning agents need to be cognizant of the facility features that are important to sustainability, and so on. Thus, this guide shows how decisions flow from design to operation and how these decisions can either enhance or degrade the overall sustainability of refrigerated facilities. It is also important to keep in mind that what may be sustainable in design, construction, or operation in one part of the world may be unsustainable when used in a different region or context.

This guide provides not only up-to-date technology information, but also more general techniques that can be used to evaluate different equipment, designs, and operating strategies. It is hoped that this approach will enable readers to make informed decisions rather than rely upon a menu of canned options. As already noted, sustainability is a complex concept and there are no guaranteed solutions that can be uniformly applied in all situations. The responsibility for ensuring sustainability in a facility lies with all, including the designer, owner, operator, consultant, contractor, maintainer, and commissioning authority.

This chapter describes the scope of the guide, introduces and defines sustainability in the context of refrigerated facilities, compares refrigeration to other means of food preservation, examines potential metrics and methods to assess sustainability, and identifies which aspects, methods, and metrics are most important and effective when assessing the sustainability of refrigerated facilities.

SCOPE OF THIS GUIDE

This guide is aimed at refrigerated facilities and refrigeration systems, including the following:

- Refrigerated warehouses (often referred to as *coolstores* or *coldstores*) ranging in size from small warehouses to the largest refrigerated distribution or storage systems (500 m^2 [4500 ft^2] and larger). Small facilities may use multiple packaged split or rack-type refrigeration systems, whereas large facilities generally have custom-designed and field-erected multistage refrigeration systems in a central plant arrangement. More recently, there has been a high level of interest in pursuing self-contained distributed systems with comparatively small refrigerant charges to enable factory fabrication of the systems and reduce potential refrigerant leakage. For some horticultural products, the facility may also include controlled-atmosphere capabilities.
- Light industrial and commercial walk-in refrigerated storage rooms, including those used in supermarkets (50 m^2 [450 ft^2] and larger).
- Industrial refrigeration systems used in food processing plants (and other processing facilities) for product cooling, freezing, and liquid chilling, although they are not the prime focus.

The guide does not consider refrigerated display cases or the space heating and cooling requirements of supermarkets, data centers, and other commercial buildings such as office buildings. Neither does the guide specifically address transport or domestic refrigeration. Parts of the guide are still useful when considering these other applications, but they are not the focus. Although the guide is focused on refrigeration where the product is foodstuffs, the same principles are applicable to many other perishable products such as pharmaceuticals and biological samples.

As the guide is focused on sustainability, it does not directly address other detailed design criteria, such as pipe and valve sizing, or explicit requirements for safety and code compliance, except to the extent that these aspects impact sustainability (e.g., pipeline pressure drop and its effect on energy use or refrigerant selection). Safety and code compliance are extremely important, and an overview is included in Chapter 3, but familiarity with relevant regulations for specific jurisdictions is highly recommended.

SUSTAINABILITY

Definition of Sustainability

The general definition of sustainability used in this guide is as follows:

> *Providing the needs of the present without detracting from the ability to fulfill the needs of the future. (ASHRAE 2018a)*

It is generally considered that there are three dimensions to sustainability as shown in Figure 2.1: economic (prosperity), social (people), and environmental (planet). Some argue for culture as a fourth dimension, but it is usually deemed part of the social dimension. To be truly sustainable, all three dimensions should be satisfied, but in most cases there are trade-offs. For example, consider the labor needed to construct, maintain, and operate a facility. From an economic perspective, the labor cost, in terms of hours and skill level, should be minimized. From a social perspective, the employment opportunities need to be safe, financially lucrative, personally enjoyable, and rewarding to positively contribute to the local community. From an environmental perspective, it would be best if most of the labor could be sourced locally to avoid significant commuting. These ideal outcomes are often mutually exclusive, so compromise across the three dimensions is usually required.

This guide primarily focuses on environmental sustainability but addresses other dimensions whenever there is a significant trade-off (e.g., the choice of refrigerant in terms of safety and costs as well as environmental impact; the impact of condenser choice on neighbors in terms of noise and visual impact; impacts such as water use and energy efficiency).

Sustainability can be considered at a number of different levels and contexts—in an engineering sense, the "control volume" can be products, processes, organizations, countries, or the planet. This guide focuses on refrigerated facilities and associated refrigeration systems at a defined location as specific processes, but there are also wider product, organizational, national, and global implications.

In particular, it is important to emphasize that sustainability is a global issue and this has been recognized at least as far back as *Operating Manual for Spaceship Earth* (Fuller 1969). Many resources, such as fossil fuels, are distributed in uneven, finite quantities about the globe and are not renewable within the timeframe of human societies. In addition, modern societies act on such a scale that activity occurring within the borders of a single country can have a significant global impact. The global experience of ozone depletion is an example of such an activity, and has direct relevance to refrigeration. Therefore, discussion about sustainability must consider global impact and interactions.

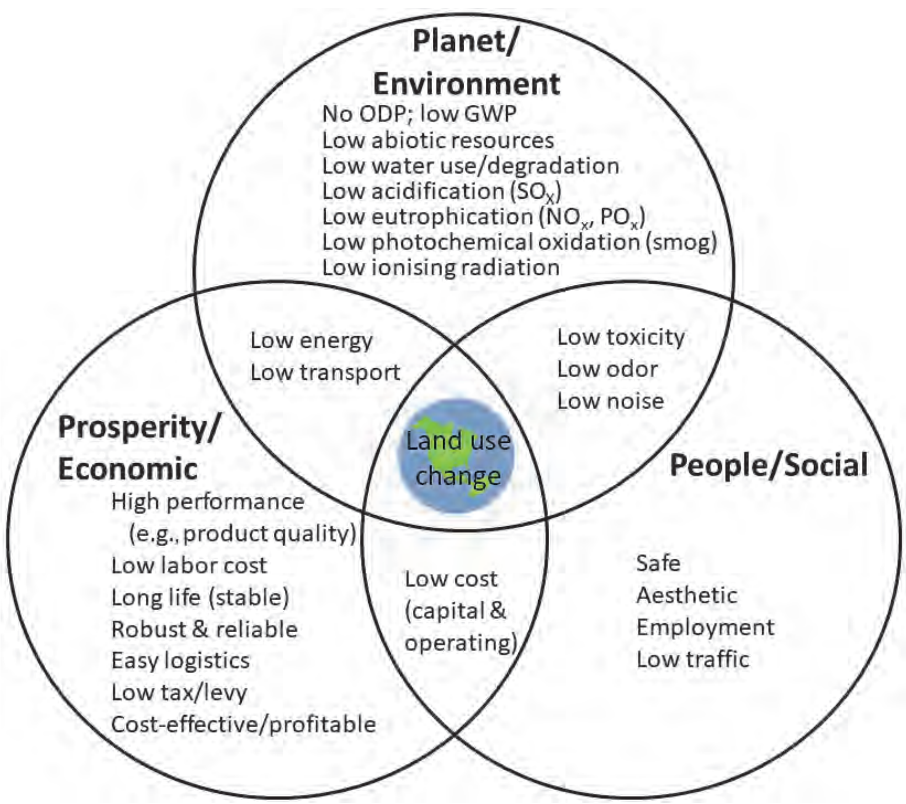

Figure 2.1 Dimensions of sustainability for refrigerated facilities and refrigeration systems, with examples of aspects and metrics for assessment.

Fortunately, this is something many parts of the refrigeration industry are well-practiced at, as the cold chain for many food products stretches around the globe.

Sustainability Methods and Metrics

It is generally accepted that evaluation of environmental sustainability should use life cycle assessment (LCA) methodologies as documented in the ISO 14040 series of standards (ISO 2006a, 2006b).

Table 2.1 and Figure 2.2 summarize the key LCA stages. Some metrics to help measure sustainability are listed in Figure 2.1 and some common environmental metrics (impact categories) are described in Table 2.2.

In assessing overall environmental sustainability, a key challenge is to evaluate the combined effect of a wide range of impact categories. One approach is to weight and normalize the impact categories so that comparisons of options can be made, as part of the impact assessment and interpretation stages of an LCA (Reap et al. 2008). This process is inevitably subjective to some extent, especially because the impacts can vary from local (e.g., noise, water use, water and air pollution) to global (e.g., climate change caused by

What is Sustainability?

Providing the needs of the present without detracting from the ability to fulfill the needs of the future. (ASHRAE 2018a)

Sustainability involves consideration of all of the economic, environmental, social, and cultural impacts of a facility using a full life cycle approach. A major focus of this guide is environmental impacts. There are often trade-offs between sustainability dimensions. These trade-offs can be location-specific.

Table 2.1 Stages in a Life Cycle Assessment

Stage	Description
Goal and scope definition	The goal and scope sets out the context of the study and explains how and to whom the results are to be communicated. Considerations include defining the functional unit, the system boundaries, any assumptions and limitations, the allocation methods to be used for coproduction partition, and the impact categories.
Life cycle inventory (LCI) analysis	Developing an inventory of input flows from and emissions to the environment for a product system based on the functional unit. Usually based on a flowchart and model of the technical system showing the system boundaries. All generic, industry-specific, and site-specific data can be used, but the focus should be getting accurate data for flows with likely high magnitude impact and to get reasonable closure of the mass and energy balance.
Life cycle impact assessment (LCIA)	Determining the significance of environmental impacts based on the LCI flow results by selection of impact categories, category indicators, and characterization models; assigning inventory to impact categories; and impact measurement where the flows are characterized into common equivalence units and summed to provide an overall impact category total. Often this is followed by normalization (specific impact is compared to the total impact for a region of interest), grouping (impact categories are sorted and ranked), and weighting of categories so a single number for the total environmental impact can be calculated. However, weighting is not officially recommended because of its subjective nature.
Interpretation	Interpretation includes identification of significant issues based on the LCI and LCIA phases; evaluation of completeness, sensitivity, and consistency; and making conclusions and recommendations incorporating consideration of uncertainty of the results.

greenhouse gas emissions, ozone depletion), and from short term/acute (e.g., human toxicity) to long term/chronic (e.g., climate change).

Methods for impact assessment are discussed further in Chapter 4 of *Life Cycle Assessment: Principles and Practice* (EPA 2006). This Environmental Protection Agency (EPA) guide does not attempt to fully assess the relative importance of different effects except in very general terms, because these are situation and location specific.

A simple method that can be used as a decision-making tool to assess decision impacts is the scorecard described in Chapter 5 of this guide. Categories are chosen to fit local circumstances and can include categories from all three sustainability dimensions. For each impact category, each option is scored on a standard scale and multiplied by the relevant weighting factor for that category. The weighted category scores are summed to give an overall rating. Clearly, the choice of weightings can highly influence the outcomes, so these weightings should be the result of extensive consultation with all stakeholders (a critical example of the communication imperative discussed previously), especially when they are situation specific.

Another common approach is to focus on a small number of metrics particularly relevant to the location and facility being analyzed. For example, the carbon footprint (CF) is relatively straightforward to estimate, measures the cumulative effect of greenhouse gas (GHG) emissions contributing to global climate change, and is motivated by the significance of climate change on humanity. Such simplification of the environmental impact analysis means that the huge effort involved in a full LCA of all environmental impacts can be avoided in many cases. This concept is further explored in the section titled Analysis of Refrigerated Facilities.

For a refrigerated facility, the life cycle includes defining the facility purpose, design, construction, acceptance commissioning and testing, operations, maintenance, retrofitting, demolition, and reuse/recycling (Figure 2.3a). A refrigerated facility only exists because of the product that it is processing or storing, so the sustainability of the facility must also consider the impact of the facility on the refrigerated product's sustainability to some extent (Figure 2.3b).

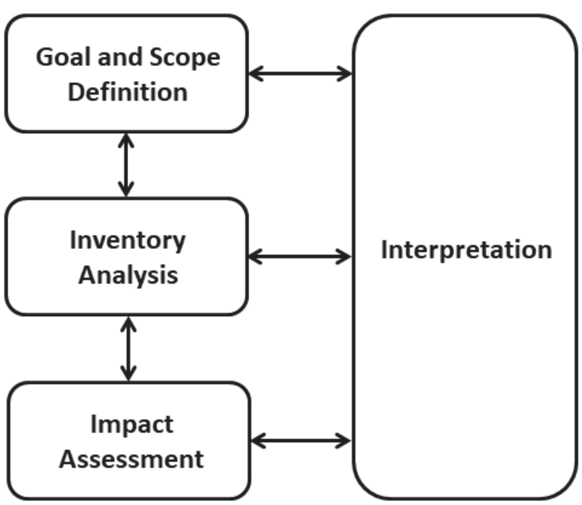

Figure 2.2 Life cycle assessment stages.

Adapted from ISO (2006a)

Table 2.2 Common Environmental Impact Categories Used in Life Cycle Assessments

Impact Category	Description	Possible Metric
Global warming	Increase in earth's average temperature caused by emissions of GHGs, leading to effects such as sea level rise, more severe weather events, and changed agricultural production.	kg CO_{2eq}[1] (lb_m CO_{2eq})
Ozone layer depletion	Decline in ozone in the stratosphere caused by emissions of ozone-depleting substances such as chlorofluorocarbons (CFCs) and hydrochlorofluorocarbons (HCFCs), leading to increased ultraviolet-B (UVB) radiation contributing to skin cancer, cataracts, and decreased crop and plankton yield.	kg CFC-12_{eq} (lb_m CFC-12_{eq})
Water use	Consumption of fresh water (surface water or groundwater) that may be scarce.	m^3 H_2O (gal H_2O)
Abiotic resource depletion	Nonrenewable use of nonliving natural resources, including energy such as fossil fuels and minerals, leading to depletion of reserves.	kg used; MJ (lb_m used; Btu)
Land use	Disturbance of the natural environment through changes in land use, leading to loss in biodiversity and ecosystem services.	Ha lost (acre lost)
Eutrophication	Increased nutrients, especially phosphates, nitrates, and chlorates, in natural waterways, leading to oxygen depletion and reduced water quality, which affect all forms of aquatic and plant life.	kg $PO_4^{3}{}_{eq}$ (lb_m $PO_4^{3}{}_{eq}$)
Acidification	Pollutants such as SO_2, N_2O, HClO, and NH_3 that are converted into acid substances that degrade the natural environment. Examples include poisoned lakes and forest damage, plus accelerated corrosion of metals, concrete, and limestone.	kg SO_{2eq} (lb_m SO_{2eq})
Human toxicity	Emission of substances harmful to human health.	kg emitted (lb_m emitted)
Photochemical oxidation	Air pollution (smog) caused by reaction between sunlight, N_2O, and volatile organic compounds, leading to respiratory health problems and damage to vegetation.	kg C_2H_{2eq} (lb_m C_2H_{2eq})
Particulates	Release of compounds harmful to the human respiratory system, including particulate matter (PM), carbon monoxide (CO), and volatile organic compounds.	kg PM, kg CO (lb_m PM, lb_m CO)
Ecotoxicity	Release of toxic substances (e.g., pesticides, herbicides, fluoride, heavy metals) into terrestrial, freshwater, and/or marine ecosystems, leading to accumulation of pollutants and harm to flora and fauna.	kg emitted (lb_m emitted)
Ionizing radiation	Release of radioactive substances and/or direct exposure to radiation, leading to human and animal health impacts.	radiation levels

1. Equivalent

Environmental Sustainability Metrics

The full list of impacts and metrics listed in Table 2.2 are often simplified to single-issue metrics, such as CF, and it is often assumed that other impacts are in proportion to these.

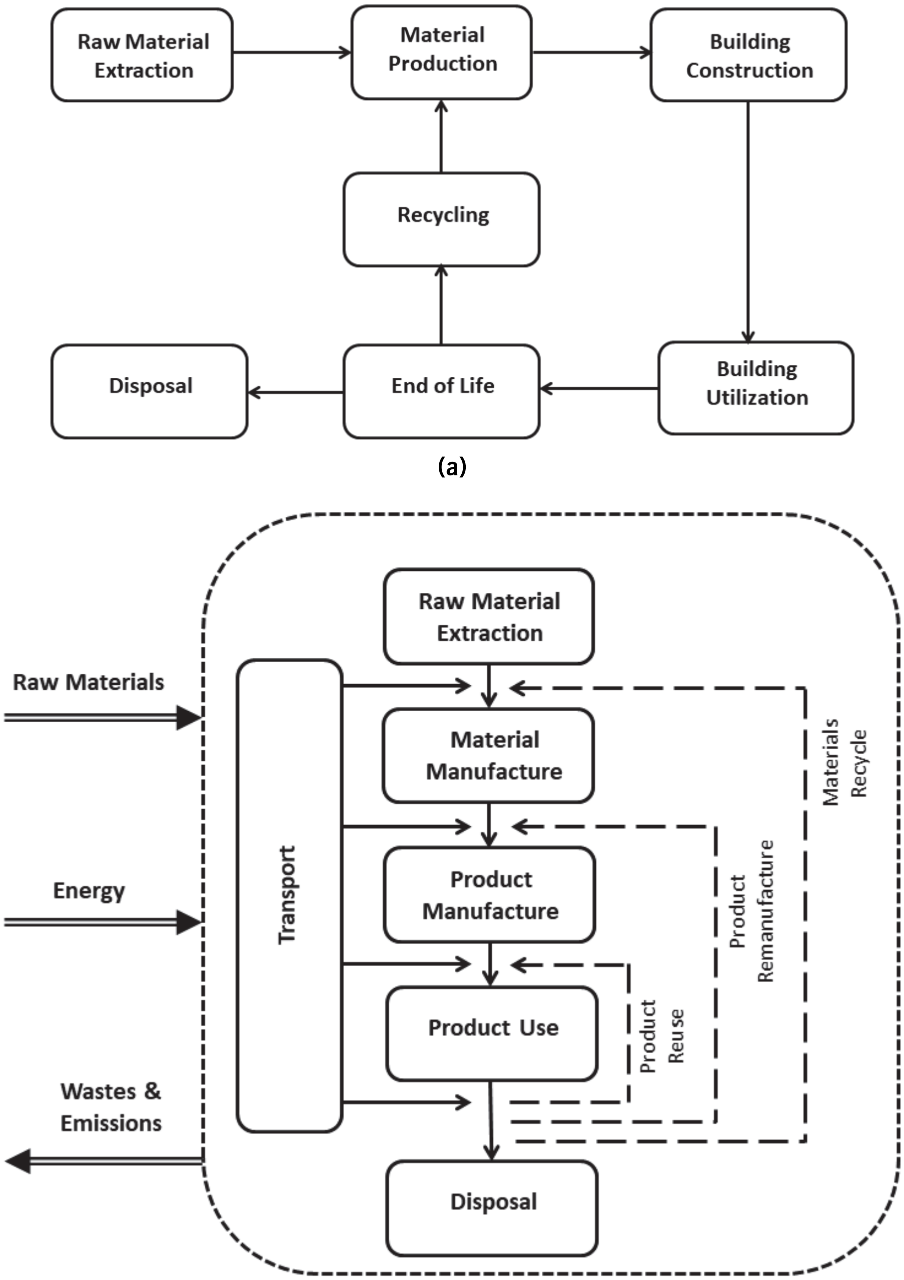

Figure 2.3 Life cycle assessment framework for (a) a building and (b) a product.

SUSTAINABILITY STRATEGIES IN REFRIGERATION

The general definition of sustainability implies a number of complementary strategies to improve sustainability in refrigerated facilities and associated refrigeration systems:

- Minimizing the need for refrigeration.
- Appropriately managing resources used in refrigerated facilities, including understanding the rate at which resources are renewed or become available for future use, or if they are renewed at all.

- Minimizing impact of the refrigerated facility and associated processes. This includes direct impacts and indirect impacts related to the use and availability of other resources.

Minimizing the Need for Refrigeration

About one-third of food produced is wasted (IIR 2009). In developing countries, this is often caused by deficiencies in the supply chain, whereas in the developed world it is often caused by the excesses of affluence (e.g., buying more food than can be consumed). Modern societies demand a year-round supply of most foods, and urbanization is a strong and ongoing trend. The net effect is longer food supply chains. Preservation technologies such as refrigeration reduce food waste through these supply chains. Therefore, food preservation inherently both enables and improves the sustainability of modern society. Economically, the cost of the preservation must be cheaper than the cost of the otherwise wasted food. Environmentally, the impact of the preservation technology must be lower than the avoided impact in the production of the food that would otherwise be wasted. This guide does not address losses in the consumption stage of the food life cycle, which occur virtually independently of upstream refrigerated facilities.

Table 2.3 illustrates the relative costs and benefits of refrigeration versus two other common food preservation options—canning and drying. In general terms, refrigeration provides higher-quality products and similar (or lower) processing energy but shorter shelf life and higher transport and storage costs than drying or canning. Clearly, refrigeration is likely to remain an important food-preservation technology for the foreseeable

Table 2.3 Comparison of Refrigeration to the Other Common Food Preservation Techniques of Drying and Canning

Preservation Method	Refrigeration	Drying	Canning
Perceived Quality	Fresh	Processed	Processed
Eating Quality	Fresh (chilled) Near fresh (frozen)	Inferior as reconstituted	Precooked
Transport	Extra cost of insulation, refrigeration system, and energy	Lower weight; dry freight	Extra weight of liquid and can; dry freight
Storage	Below ambient temperature, special facilities, high energy	Ambient temperature	Ambient temperature
Packaging	Cardboard and plastic (heavy)	Cardboard and plastic (light)	Metal
Shelf Life	Short to medium	Long	Long
Processing Equipment	Simple, moderate cost	High cost	High cost
Processing Energy	Low to medium (cool by about 30 K [54°R] or freeze water)	High (evaporate water) unless solar	Medium (heat by about 100 K [180°R] and cool)
Approximate Enthalpy Change	150 kJ/kg (65 Btu/lb$_m$) (chilled) 350 kJ/kg (150 Btu/lb$_m$) (frozen)	2500 kJ/kg (1080 Btu/lb$_m$)	400 kJ/kg (172 Btu/lb$_m$)
Typical Energy Efficiency	200% (COP = 2)	50% (drying) 300% (evaporation)	70% (boiler)
Losses/Wastage	Moderate	Low	Low

Is Refrigeration Inherently Sustainable?
Production of food and other perishables has high environmental impact. Preservation of perishables is important to urbanization and the needs of modern society. Refrigeration of perishable products is more sustainable than nonrefrigerated supply chains because the impact of the product wastage avoided is usually far greater than the impact of the refrigeration facilities.

future. This guide assumes there is a net sustainability benefit of refrigeration and focuses on improving the sustainability of refrigerated facilities, and does not attempt to further compare refrigeration with other preservation processes.

Assuming that the decision to use refrigeration has already been made, the general needs for refrigeration are as follows:

- Preserving qualities, particularly in food, to extend shelf life. The qualities preserved may include sensory, nutritional, biological viability, and/or food safety (such as microbiological).
- Adding additional, usually sensory, qualities to food products. For example, ice cream is served frozen because of the positive sensory impact.
- As a part of a manufacturing process. For example, cooling milk after pasteurization.

When considering a particular food product, process, or refrigerated facility, a combination of these needs will likely be encountered in a single application or site. In addition to accepting that refrigeration is an inherent requirement, this guide assumes the recommended processing and storage conditions given in reference guides such as *ASHRAE Handbook—Refrigeration* (ASHRAE 2018b) and the International Institute of Refrigeration (IIR) chilled and frozen food guides (IIR 2000, 2006) provide an effective way of expressing the product quality requirements so that normal refrigerated cold chain shelf-life expectations will be achieved.

The preservation of desirable qualities via refrigeration is an attempt to meet a future need (albeit usually the needs of a relatively near future). By preserving food, refrigeration allows it to be consumed at some future date and thus potentially reduces food wastage. This increases sustainability, because it avoids the need to incur further resource use and environmental impacts associated with the production, processing, storage, and distribution of more food to replace the wasted food.

At face value, refrigeration for food preservation seems inherently more sustainable than a supply chain with no form of preservation (unless there is a perfect balance of local supply and demand for a food product throughout the year). However, to be sustainable the refrigeration process must be effective. That is, the refrigerated facility must minimize resource demands and their external environmental impacts when compared to merely dumping and replacing products wasted because of the lack of refrigeration. One of the fundamental requirements for refrigeration systems is that they provide environmental controls to preserve the desirable qualities of food products before consumption. For example, a refrigeration system that damages stored products by being either too cold or not cold enough, subsequently resulting in the stored product being dumped, is not fundamentally sustainable. Similarly, a refrigerated facility that is able to produce/maintain environmental conditions to perfectly preserve stored products in one part of the cold chain only to have the product subsequently ruined by a poor distribution system may be sustainable in isolation, but the supply chain as a whole is not sustainable. Thus, the design and operation of a truly sustainable refrigerated facility must consider the response of the product to refrigeration and its relationship to the entire cold chain that stretches between harvest and the eventual consumption of the product. In particular, it needs to consider the loss of product quantity and quality that occurs in the refrigerated facilities being analyzed to the extent that they reduce or increase food waste and therefore reduce or increase the impact of the rest of the food production and supply chain.

It is beyond the scope of this guide to address all issues around minimizing the need for refrigeration. For example, issues such as waste minimization and efficient distribution (so that less food needs to be produced and refrigerated), the specific diet promoted to and desired by consumers, or the need within a society for the product of industrial processes that require refrigeration will not be addressed in detail (Garnett 2007, 2008; Roos et al. 2015). There is no doubt of the genuine need for refrigeration in food production and distribution as well as other industrial product processing (IIR 2009). This guide does address minimizing the amount of refrigeration used, given that a particular product or process is needed and requires refrigeration. This means considering what temperature the product really requires, ensuring that refrigerated facilities and systems are well designed (e.g., adequate insulation is used to minimize heat gain from the environment, layout and orientation of facilities to ensure efficient product handling logistics and minimal heat gains from the ambient, use of ambient cooling if possible), and ensuring that refrigeration facilities and systems are well operated (e.g., minimization of door openings and lowest possible refrigeration system temperature lift).

Appropriate Management of Resources Used in Refrigeration

Fundamentally, refrigeration is a means for moving heat from a low temperature (the source, which needs to remain cold) to a high temperature (the sink, usually the ambient environment). This applies equally to a domestic refrigerator, a refrigerated distribution warehouse, process cooling, or any other refrigeration application, and applies regardless of the particular refrigeration technology. Fundamental laws of thermodynamics state that moving heat from a low-temperature source to a high-temperature sink requires the input of energy.

The environmental impact of energy use depends on the energy source(s), location, and time of use. Many energy sources are not renewable, so their use depletes the resource (e.g., fossil fuels) and may also lead to environmental impacts (e.g., elevated CO_2 levels and climate change). Even energy generated from renewable sources (e.g., solar or hydroelectricity) still has some impacts embodied in the physical infrastructure whether it is part of a network or stands alone (e.g., electricity distribution systems, dams, land use, generation equipment, energy storage such as batteries). Therefore an important facet of sustainability in refrigeration is the minimization of energy input and, in addition, the choice of the type of energy resource. The impact of energy use is commonly defined by an emissions factor, which is the impact per kilowatt-hour of energy use (Table 2.4).

To satisfy the refrigeration requirements in most industrial and commercial applications, a mechanical vapor compression system is used (see Chapter 3 for more details on refrigeration technology). Regardless of the details of the refrigeration system design, the system will consist of components such as pipes, heat exchangers, valves, compressors, vessels, insulated walls, doors, controls, and so on, all of which require resources for their construction and, as a completed system, will occupy some footprint. The physical refrigeration plant also requires other operating inputs apart from energy, such as lubricating oil, and may produce waste, commonly in the form of wastewater streams.

Finally, the refrigerant circulating through the system is required. In most practical situations, refrigerant leaks occur, so the ongoing consumption and release of refrigerant must also be considered. Depending on the specific refrigerant, the impact of leakage can

Table 2.4 Indicative Embodied Specific Carbon Footprints for Materials and Resources Commonly Used in Refrigerated Facilities and Associated Equipment[1]

Material	Embodied CF, kg CO_{2eq}/kg (lb_m CO_{2eq}/lb_m)	Source and Comments
Aggregate (gravel)	0.003; 0.0052	EPLCA (2016); Hammond and Jones (2011)
Aluminum		
• Construction	9.2; 11 (virgin)	Hammond and Jones (2011); IBU (2016)
• Manufactured equipment	12.6 (virgin), 0.63 (recycled)	IIR (2016) (typically 67% for recycled)
Asphalt (6% bitumen)	0.076	Hammond and Jones (2011)
Cardboard packaging	1.0	Hammond and Jones (2011); Burke (2016)
Concrete	0.11–0.15	Hammond and Jones (2011); EPLCA (2016)
+ Reinforcing	+ 0.077	Hammond and Jones (2011)
+ Casting	+ 0.029	Hammond and Jones (2011)
Copper		
• Tube	0.98–2.7	Copper Alliance 2015; IBU (2016); Hammond and Jones (2011)
• Manufactured equipment	3.0 (virgin) 2.46 (recycled)	IIR (2016) (typically 40% for recycled)
Lubricating oils	23	Burke (2016)
Metal recycling	0.07	IIR (2016)
Steel		
• Construction	0.75–0.78	Hammond and Jones (2008); EPLCA (2016)
• Manufactured equipment	1.8; 2.5 (virgin) 0.54; 1.36 (recycled)	IIR (2016); EPLCA (2016) (typically 29% for recycled [IIR 2016])
Expanded/extruded polystyrene	2.55; 3.29; 3.54	IBU (2016); Hammond and Jones (2011); EPLCA (2016)
Polyurethane	3.48	Hammond and Jones (2011)
Stainless steel	1.68	Hammond and Jones (2008); IBU (2016)
Timber (no credit for embodied carbon)	0.13	Hammond and Jones (2008)
Water	0.0006; 0.001	ECLA (2016) (groundwater); Hammond and Jones (2011)
Plastic		PlasticsEurope (2016)
• Equipment components	2.8 (virgin) 0.12 (recycled)	IIR (2016) (typically 7% for recycled)
• Packaging—Polyethylene terephthalate (PET)	2.2–3.4	EPLCA (2016); Burke (2016)
• High-density polyethylene (HDPE) piping and packaging	1.9–3.4	IBU (2016); Ghenai (2012)

Table 2.4 Indicative Embodied Specific Carbon Footprints for Materials and Resources Commonly Used in Refrigerated Facilities and Associated Equipment[1] *(continued)*

Material	Embodied CF, kg CO_{2eq}/kg (lb_m CO_{2eq}/lb_m)	Source and Comments
• Packaging—Low-density polyethylene (LDPE)	2.1–2.5	EPLCA (2016); Burke (2016)
• Recycling	0.01	IIR (2016)
Food products (to farm gate)		Sonesson et al. (2010)
• Red meat (beef/lamb)	29/23	EPLCA (2016)
• Pork	6.7	EPLCA (2016)
• Poultry	3.4	EPLCA (2016)
• Fish	3.4	EPLCA (2016)
• Milk	1.1	EPLCA (2016)
• Cheese and butter	8.6	EPLCA (2016)
• Fruits	0.3–0.7	EPLCA (2016)
• Vegetables	1.2–1.7	EPLCA (2016)
Refrigerant manufacture		Myhre et al. (2013)
• Ammonia (R-717)	2 (GWP_{100} = 0)	Campbell and McCulloch (1998)
• CO_2 (R-744)	— (GWP_{100} = 1)	
• Propane (R-290)	0.05 (GWP_{100} = 3)	IIR (2016)
• R-1234yf	13.7 (GWP_{100} < 1)	IIR (2016)
• R-134a	5 (GWP_{100} = 1300)	IIR (2016)
• R-22	5 (GWP_{100} = 1760)	Campbell and McCulloch (1998)
• R-404A	16.7 (GWP_{100} = 3943)	IIR (2016)
• R-407C	— (GWP_{100} = 1624)	Value not found, but likely to be similar to that for R-404A
• R-407F	— (GWP_{100} = 1674)	Value not found, but likely to be similar to that for R-404A
• R-507A	— (GWP_{100} = 3985)	Value not found, but likely to be similar to that for R-404A
Electricity emission factor (selected countries)	kg CO_{2eq}/kWh (lb_m CO_{2eq}/kWh) (average for 2012)	
• Australia	1.083(2.388)	Itten et al. (2014)
• Brazil	0.170 (0.375)	Itten et al. (2014)
• Canada	0.296 (0.653)	Itten et al. (2014)
• Chile	0.547 (1.206)	Itten et al. (2014)
• China	1.164 (2.566)	Itten et al. (2014)
• France	0.099 (0.218)	Itten et al. (2014)
• Germany	0.638 (1.407)	Itten et al. (2014)
• Japan	0.644 (1.420)	Itten et al. (2014)
• India	1.122 (2.474)	Itten et al. (2014)

Table 2.4 Indicative Embodied Specific Carbon Footprints for Materials and Resources Commonly Used in Refrigerated Facilities and Associated Equipment[1] *(continued)*

Material	Embodied CF, kg CO_{2eq}/kg (lb_m CO_{2eq}/lb_m)	Source and Comments
• Mexico	0.681 (1.501)	Itten et al. (2014)
• Malaysia	0.737 (1.625)	Itten et al. (2014)
• Russia	0.654 (1.442)	Itten et al. (2014)
• Saudi Arabia	0.829 (1.828)	Itten et al. (2014)
• South Africa	1.036 (2.284)	Itten et al. (2014)
• Sweden	0.052 (0.115)	Itten et al. (2014)
• UK	0.639 (1.409)	Itten et al. (2014)
• USA (average)	0.765 (1.687)	Itten et al. (2014)
• USA (Eastern interconnection)	0.790 (1.742)	Burke (2016 [2004 data])
• USA (Western interconnection)	0.595 (1.312)	Burke (2016 [2004 data])
Transport (freight)	kg CO_{2eq}/ton-km (lb_m CO_{2eq}/ton-mi)	
• Road (truck)	0.05–0.13 (0.161–0.418)	EPLCA (2016)
• Rail	0.02 (0.064)	Burke (2016); EPLCA (2016)
• Shipping (container)	0.014 (0.045)	Burke (2016)
• Air	2.09 (6.727)	EPLCA (2016)

1. Ranges and values are typical and may not be representative of local circumstances (country, region, and year).

be substantial. Many refrigerants are ozone-depleting substances or potent GHGs. In a sustainable facility, the designer might attempt to mitigate refrigerant leaks or choose a less environmentally damaging refrigerant. Phasing out ozone-depleting refrigerants as required under the Montreal Protocol is well advanced in most countries (Ozone Secretariat 2018). However, as is discussed later in this guide, choosing a less environmentally problematic refrigerant may require trade-offs in terms of either energy efficiency or operator safety. For example, refrigerants such as ammonia or hydrofluoroolefins (HFOs) have very low global warming potential (GWP) relative to hydrofluorocarbons (HFCs), but some are mildly flammable (and toxic, in the case of ammonia). Therefore, determining which strategy is the most sustainable can be challenging.

In summary, the main resources used in refrigeration are as follows:

- Mineral resources and energy embodied in the manufacture and construction of the refrigeration equipment and the refrigerated facility.
- Energy to run the refrigeration plant. Usually the largest energy consumer is the compressor(s), but energy required to collectively run fans, pumps, and control systems is also significant. Typically, externally generated electrical energy is supplied to the plant, but sometimes energy is generated on site from either a fuel source or a local renewable source. Occasionally, motive power is generated directly on site via engines. The embodied energy in the energy generation and

Strategies to Improve Refrigeration Sustainability

- Reduce product wastage (e.g., minimize loss of product quality)
- Minimize resources used to create and operate refrigerated facilities (e.g., reduce refrigerant charge and energy use)
- Minimize the impact of these resources (e.g., design, install, and maintain safe refrigeration systems; use refrigerants with low GWP; and obtain energy from renewable energy sources where possible)

transmission infrastructure and the environmental impacts associated with the electrical energy generation infrastructure and processes may all be significant. As electricity generation infrastructure is typically a regional- or national-level infrastructure, this guide does not critically evaluate alternatives, except as a point of comparison when considering local on-site generation options.

- The refrigerant. This will ideally be contained within the refrigeration system throughout its entire life, but in practice most refrigeration systems inevitably leak refrigerant to the atmosphere (often slow, ongoing leakage over time, but occasionally major leaks caused by catastrophic events). As a result, refrigerant must periodically be added to the system to ensure efficiency and capacity are maintained. This means that refrigerant is effectively "consumed" by the refrigeration system. Therefore, the environmental impact embodied in the refrigerant must be accounted for, as must the direct impact of the refrigerant that escapes the system. There is a wide range of possible environmental impacts caused by refrigerant, dependent on the leakage rate and the precise chemical nature of the substance used as the refrigerant (see Chapter 3 for details).
- Other resources could be used during the operation of the refrigeration plant depending on the configuration. These include (but are not limited to) lubricant oils, cooling water, and water treatment chemicals. The supply of these resources must be considered, as must the associated disposal of any waste expelled from the refrigeration plant.

Minimizing of the Impact of Resources Used in Refrigeration

The standard approach to assess environmental impacts is as follows:

- Quantify the resources used by the facility or activity in the facility.
- Quantify the emissions released, depending on the metric being used, for each resource or activity (often expressed as emission factors for the resource or activity). Emission factors can be found in data sets such as those provided by ecoinvent (2017), the European Platform on Life Cycle Assessment (EPLCA 2016), and the U.S. Life-Cycle Inventory Database (USLCI 2017). For example, if minimizing the impact of climate change is important, then emissions of the six main GHGs under the Kyoto Protocol (UNFCCC 2014) (carbon dioxide [CO_2], methane [CH_4], nitrous oxide [N_2O], HFCs, PFCs, and sulfur hexafluoride [SF_6]) might be quantified for each resource or activity.
- Multiply each emission by a characterization factor to estimate the total impact for specified impact categories (such as climate change, eutrophication, and acidification). For example, the characterization factor for calculation of climate change is 28 kg CO_{2eq} per kg methane (28 lb_m CO_{2eq} per lb_m methane) and 264 kg CO_{2eq} per kg nitrous oxide (264 lb_m CO_{2eq} per lb_m nitrous oxide) released into the atmosphere (Myhre et al. 2013). Characterization factors can be found

in data sets such as the European Platform on Life Cycle Assessment (EPLCA 2016) and the University of Leiden (2016).

- It is often convenient to combine the summed products of the emission factors and characterization factors into a specific impact or footprint per unit of resource and/or activity. Thus the calculation is simply the sum of the amount of resource/activity times the specific impact or footprint factor. For example, a specific CF is the sum of the emission factors multiplied by the characterization factors for each of the GHGs. Typical values of some of these final impact assessment results for climate change, often called the *carbon footprint* or *global warming potential*, are given in Table 2.4 for different materials and activities relevant to refrigerated facilities.

The equations for the standard and simplified approaches are as follows:

$$\text{TIF} = \sum_i M_i \Big(\sum_j EF_{i,\,j} ChaF_j\Big) \quad \text{(standard)} \tag{2.1}$$

$$\text{TIF} = \sum_i M_i SF_i \quad \text{(simplified)} \tag{2.2}$$

where

TIF = total impact footprint, kg impact (lb_m impact)
M_i = mass of resource *i* used, kg (lb_m)
$EF_{i,\,j}$ = emission factor for emission *j* from resource *i*, kg of *j* emitted/kg of resource *i* (lb_m of *j* emitted/lb_m of resource *i*)
$ChaF_j$ = characterization factor for emission *j*, kg impact/kg emitted (lb_m impact/lb_m emitted)
SF_i = specific impact or footprint for resource *i*, kg impact/kg resource (lb_m impact/lb_m resource)

Other units for impacts, resources, activities, and emissions can be used as long as they are internally consistent.

The ideal situation when assessing environmental sustainability is to consider all of the impacts listed in Figure 2.1 and Table 2.2 using an LCA approach for the facility and/or the products being refrigerated in the facility. In reality, this may not be straightforward for reasons including the following:

- It is time consuming to collect all the data.
- Data for many impact categories may not be available or may be inaccurate, especially as impact can be country or region specific.
- The impacts may not be significant for all refrigerated facilities.

The assessment can occur in two parts—estimation of the cumulative environmental impacts and interpretation of the cumulative impact on the environment against economic and social dimension indicators. Again, mechanisms to quantify and weight the economic, environmental, and social impacts can be used, but there is no common agreement on the approach and the best approach can be situation- and location-specific (e.g., the importance of noise will probably be more critical in an urban than a rural location).

Seemingly obvious mechanisms to minimize environmental impacts include reducing resource use and changing to resources with lower emission factors/footprints. However, the best overall approach may not be obvious because of different impacts that may not be easily or directly comparable. Some examples of the trade-offs, including some that will be examined in more detail in later chapters, are as follows:

- Thicker insulation increases embodied energy and impact and reduces product storage volume for the same total land footprint but results in reduced required capacity (size) of the refrigeration system (reduced embodied impact) and reduced ongoing energy use.
- Replacement of a refrigerant with a high GWP and high inherent energy efficiency with one with low GWP but poorer inherent energy efficiency may not improve the overall CF.
- Air-cooled condensers generally have higher fan power (but no pumps), zero water use, lower capital cost but result in higher compressor energy use because of the condensation temperature approaching the ambient dry-bulb temperature than evaporative condensers. Evaporative condensers, by comparison, generally have moderate water use and moderate fan and pump costs and result in lower refrigeration system energy use because of the condensation temperature approaching the ambient wet-bulb temperature. However, they have high capital costs, have higher water treatment and/or disposal costs, and also have risk of *Legionella*.
- Designing air coolers and features of the refrigerated facility affecting latent and sensible heat loads to increase air relative humidity (RH) to minimize weight loss from unpackaged product can incur higher capital costs, possibly making frosting and defrost more critical and increasing the risk of condensation/frosting in undesirable locations.
- Orientating a facility for ease of access of vehicles from local roads may expose doorways into refrigerated spaces to prevailing winds, causing greater air infiltration heat loads.

Surange (2015) provides an inventory of more sustainable options for refrigerated facilities, including aspects such as facility location and layout, building shape and orientation, use of renewable energy sources, use of eco-friendly and recycled materials, energy-saving accessories, ambient cooling, noise control, fire safety, rainwater harvesting and recycling, advanced controls, and waste heat recovery, among others.

ANALYSIS OF REFRIGERATED FACILITIES

This section analyzes food supply chains, including cold chains, and refrigerated facilities to identify the key components affecting sustainability and therefore the best assessment metrics.

Food Supply Chains

Williams et al. (2009) conducted LCAs to estimate the CFs for a number of supply chains to the United Kingdom for refrigerated foods including red meat and subtropical fruit, while Garnett (2007, 2008, 2011) considered options to reduce emissions. Across the whole food supply chain, refrigeration contributed less than 20% of the footprint and direct refrigerant emissions were less than 15% of the refrigeration component. The refrigeration component was dominated by energy use and the retail and consumer sectors were far bigger contributors than processing, wholesale storage, and distribution.

For red meat, the on-farm production CF was about 75% of the total, once estimates of retail and consumer CFs were added (Williams et al. 2009). Even if all of the remaining 25% was caused by refrigeration, reducing the refrigeration impacts by 5% would only reduce overall impacts of the whole supply chain by 1.25% (5% of 25%). In comparison, a 1.67% reduction is spoilage/wastage would also provide 1.25% reduction in overall impact (1.67% of 75%). Therefore, expending slightly more resources on refrigeration to reduce meat wastage may be more sustainable than trying to further reduce the refrigeration related impacts.

For fruits such as apples, the overall CFs were less than 20% of those for meat, but both the fractional and absolute amounts caused by orchard operations were much smaller (Williams et al. 2009). The fraction caused by transport and refrigeration was 50% to 70% of the total CF for imported product, with up to half of this because of refrigeration in the various stages of the supply chain. While refrigeration is a larger fraction of the total impact, reductions in refrigeration impacts should not be at the expense of increased product loss or else the overall sustainability may not improve.

In summary, while the impacts of the refrigerated facilities considered by this guide (in processing plus wholesale and retail storage) are a relatively small fraction of the impact of the full supply chain, if their performance negatively affects food spoilage then sustainability may be significantly reduced.

Refrigerated Facilities

The following is a high-level analysis of the most likely and significant impacts and/or costs arising from the construction and operation of refrigerated facilities and the associated refrigeration systems:

- **Construction.** The capital costs of the facility and equipment are significant. There are impacts because of land use change and the direct water use and energy to build the facility, including labor transport to the site. The physical footprint of a facility is usually small compared to the agricultural land footprint required to produce the products transitioning through the facility, so it can often be ignored. Similarly, the water and energy use during construction is normally small compared to that during operation of the facility. Overall, the environmental impact of the construction phase is likely to be negligible.
- **Materials and Equipment.** There are impacts embodied in the refrigerated facility construction materials and associated refrigeration system equipment including transport to the site. Table 2.4 gives embodied CFs for many materials used in refrigerated facilities and equipment. Most facilities and equipment have economic lives of more than 10 years, and often more than 20 years. The embodied impact amortized over such a period often means that it is small relative to the impact caused by operating the facility.
- **Operational Water Use.** The main water uses are for heat rejection (cooling water), cleaning, and sometimes defrost. Costs and impacts include those embodied in the water delivered to the site, any on-site water treatment (e.g., treatment chemicals), plus water disposal, including stormwater runoff. Cleaning water use is usually low for refrigerated facilities relative to food production facilities, but heat rejection and defrost use can be very high. The water costs and impacts are highly variable depending on local water availability, quality, and the type of heat rejection and defrost systems employed, but they are often significant and should not be ignored by default.

- **Operational Energy Use.** The energy (normally electricity) to operate the facility, including refrigeration compressors, fans, pumps, lights, controls, forklift battery charging, trace heating, office operations, and HVAC, usually has significant cost and impact. The impact of electricity use is highly dependent on the emission factor for the location, which in turn depends on how the power is generated, the proportion of renewable generation, and to some extent the time of the use in a day, week, or year.
- **Refrigerants.** The costs and environmental impacts of refrigerants depend on the refrigerants used, the charge size, and the leakage rate requiring top-up. There are direct impacts (measured via GWP) plus those due to their manufacture and transport to site (Table 2.4). For sites with low-GWP refrigerants (such as HFOs or natural refrigerants), small charges and/or low leakage, the impacts can be negligible, but for sites using high-GWP synthetic refrigerants this aspect can seldom be ignored unless they are completely gastight.
- **Stored Product and Packaging.** As discussed previously, there are costs and impacts associated with direct product weight loss and loss of quality of the product being refrigerated. These are mainly the indirect impacts incurred in the production, processing and distribution of the product. Only the impacts associated with loss or wastage of product attributable to the refrigerated facility are relevant. Direct product weight loss in the refrigerated facility is typically only significant for products with unsealed packaging such as fresh fruits and vegetables. Quality loss is only significant if the shelf life reduction in the refrigerated facility is significant relative to the total supply chain duration (i.e., when product wastage due to quality loss becomes significantly more likely due to the poor performance of the refrigerated facility).
- **Oils.** Some refrigeration systems require top-up (e.g., replace oil removed from oil pots in ammonia systems) and/or maintenance related replacement of lubricating oils to ensure reliable operation. Because refrigeration systems are sealed, rates of contamination and breakdown of lubricants are generally low, so the oil use is low. Further, there are well-established routes for disposal or recycling of oil reducing the cost and impact. Therefore, usually the impact of oil use is minimal.

In general terms, because of the long life of most refrigerated facilities and the associated refrigeration systems, the impacts due to operational energy use, refrigerants, and water use dominate over the other aspects, whereas the impacts of stored product and packaging depend on the product of interest. For example, a generic LCA for buildings in the United Kingdom found that, of the total CF, 0.5% was caused by design, 15% by materials (including their manufacture), 1% by transport, 1% by construction, 83% by operation over the life, and 0.4% by refurbishment and demolition (UK Government

What Refrigeration Resources have the Biggest Impacts on Sustainability?

- Construction materials (embodied impacts)
- Refrigerants (both direct impacts and inherent energy efficiency)
- Energy use (especially nonrenewable electricity)
- Water use (if there is local water scarcity)

The following resources generally have relatively minor impacts: materials in refrigeration equipment, oils, and water treatment chemicals.

2010). Similarly, a life cycle climate performance (LCCP) study that estimated the CF for a generic residential heat pump using R-410A in the United States showed that energy consumption was dominant (81% to 93% of the total emissions depending on location), while direct refrigerant-related emissions were 7% to 18% (higher for locations with more moderate climates), and equipment manufacture, installation, maintenance, and disposal were less than 1.1% of the total impact (IIR 2016). A refrigerated facility is more energy intensive than most other buildings, so the impact caused by operating energy is likely to be even more dominant over the other stages and aspects.

Sustainability Metrics

To simplify the impact assessment, a common approach is to consider critical metrics/indicators or single-issue (combined) footprints. Common examples are as follows:

- **Carbon Footprint.** The CF is an indicator of the cumulative contribution to global climate change. It usually includes emissions of all six of the GHGs in the Kyoto Protocol (CO_2, CH_4, N_2O, HFCs, PFCs, and SF_6) and considers both direct effects (i.e., emissions of the GHG directly from the facilities of interest, such as refrigerant leakage) and indirect effects (i.e., embodied emission due to resources used by the facility, such as CO_2 and other emissions caused by electricity generation). It is convenient because it addresses what many consider to be the world's most important environmental problem, most data are readily available, and other environmental impacts such as those given in Table 2.2 are often strongly correlated to CF. For refrigerated facilities, the CF is usually dominated by CO_2 and other indirect emissions caused by energy use, direct refrigerant emissions (particularly from high GWP fluorocarbons), product losses, and possibly the CF embodied in the materials of construction of the facilities and associated equipment. This makes CF estimation practical. LCCP is essentially a CF in a refrigeration context.
- **Total Equivalent Warming Impact (TEWI).** TEWI has frequently been used for refrigeration systems. It sums the GWP caused by refrigerant leakage and energy use but ignores embodied footprint in materials of construction, equipment and refrigerant manufacture, and end-of-life disposal (IIR 2016). Therefore, it is effectively a slightly simplified CF/LCCP.
- **Water Footprint (WF).** A WF is the water equivalent of a CF. The WF sums direct water use and indirect water use by resources used. The total water use is then weighted by a water stress index (WSI) depending on where the water is used. The WSI is generally higher for regions with low rainfall and high water demands (e.g., parts of California). Therefore, the WF is a local impact. International Standards Organization (ISO 2017) provides a practical guide to estimation and use of WF.
- **Ozone Depletion Potential (ODP).** ODP is very relevant for refrigerated facilities using ozone depleting substances as refrigerants or insulation-foam-blowing agents. Under the Montreal Protocol, most countries in the developed world will have already or will phase out use of ozone depleting substances by 2020, whereas developing countries have until 2030 (Ozone Secretariat 2018). Given that ODP is a known environmental problem and that zero ODP alternatives are available, use of ozone depleting substances as refrigerants or insulation-foam-blowing agents in new facilities is clearly not sustainable. Therefore, consideration of ODP is only required for existing facilities until phase-out under the Montreal Protocol is completed.

Example

The reference facility described in detail in the appendix at the end of this book can be used to illustrate the simplified approach to calculate CF using Equation 2.2. In summary, the facility has 22,500 m^2 (242,190 ft^2) of refrigerated warehouse space and is located in Chicago. It is 9 m (30 ft) high and stores up to 26,000 tonnes (28,660 tons) of frozen and chilled food with average embedded emissions of 6 kg CO_{2eq}/kg (6 lb_m CO_{2eq}/lb_m) in its supply chain prior to the refrigerated facility. The design heat load is approximately 1300 kW (369 tons), leading to facility energy use of about 2,493,000 kWh per year for the reference refrigeration system of a two-stage expansion, pump-circulation ammonia system with evaporative condensers. There are an estimated 13 net turnovers of product per year, the average annual RH is 76.9% in the cooler, and the average weight loss in the warehouse is 2.3% per month for the 10% of chilled product that is not in sealed packaging (this equates to 0.0482% of total product throughput per year). The energy specific footprint is 0.790 kg CO_{2eq}/kWh (1.742 lb_m CO_{2eq}/kWh) (as Chicago is a part of the U.S. Eastern Interconnection). The refrigerant charge is 3400 kg (7496 lb_m), the refrigerant has a GWP <1, and the leakage rate is 2% per year. Lubricating oil charge is 500 kg (1102 lb_m) and ongoing oil use is 50 kg (110 lb_m) per year. Water use is 12,100 m^3 (3,196,500 gal) per year. The facility incorporates 23,000 tonnes (25,353 tons) of aggregate, 25,000 tonnes (27,558 tons) of concrete, 2300 tonnes (2535 tons) of structural steel, 2000 tonnes (2205 tons) of racking steel, 330 tonnes (364 tons) of polystyrene and 3900 kg (8598 lb_m) of plastic, and the refrigeration equipment incorporates 1600 kg (3527 lb_m) of aluminum, 500 kg (1102 lb_m) of copper, 70.4 tonnes (77.6 tons) of steel, and 2000 kg (4409 lb_m) of plastic. The average distance for road transport of equipment and materials to a site is 400 km (240 mi) (excluding aggregate and concrete that is transported 20 km [12 mi] on average). Much more detail about the facility and its refrigeration system is provided in the appendix at the end of this book.

An alternate refrigeration system scenario for the facility is the use of three separate direct-expansion (DX) refrigeration rack systems using R-507A with air-cooled condensers. The total refrigerant charge is 2900 kg (6393 lb_m) (15% lower than for the reference system), the refrigerant has a GWP (100 year horizon) of 3985 (Myhre et al. 2013), the leakage rate is 10% per year, the water use is a minimal 100 m^3 (26,400 gal) per year, and the annual lubricating oil use is 7 kg (15 lb_m) for an oil charge of 340 kg (750 lb_m). A lower refrigerant charge would be possible if multiple unitary systems were selected for each group of evaporators in each room. The average energy use is 71% higher (4269 MWh per year) than for the reference system due to a combination of the following:

- Use of DX evaporators (higher temperature difference to get superheat, so lower compressor suctions)
- Use of air-cooled condensers (ambient dry bulb higher than wet-bulb temperature, so higher compressor discharge)
- The thermodynamic and transfer properties of R-507A relative to ammonia
- Different compressor technologies (semihermetic compact screws with slide valve capacity control and hermetic scrolls rather than large open drive screws with speed control for the reference system) with different inherent and part-load efficiencies
- Small differences in the system configurations (two-stage expansion and one stage compression for ammonia is similar to economized for R-507A for low temperature loads; both use single-stage expansion and compression for high-stage loads although the ammonia system has a common suction, whereas the R-507A system had separate suctions),

- Greater restrictions on floating head pressure because of DX and compressor technology constraints (e.g., minimum of 30°C [86°F] saturated discharge temperature for scroll compressors)
- Evaporator selections with higher fan power (about 0.094 kW_e per kW_r [0.44 hp per ton] versus about 0.039 kW_e per kW_r [0.18 hp per ton] for the reference system)
- Condenser selections with higher fan power (about 0.044 kW_e per kW [0.017 hp per MBh] versus about 0.017 kW_e per kW [0.0067 hp per MBh] for the reference system)
- Use of electric rather than hot-gas defrost
- Avoidance of the refrigerant and water pumping required for the ammonia system

The refrigeration equipment incorporates 22.1 tons (24.4 tons) of copper, 2700 kg (81,600 lb_m) of aluminum, 7900 kg (17,420 lb_m) of steel and 700 kg (1540 lb_m) of plastic. It is also estimated that the unsealed chilled product weight loss is 2.8% per month (22% higher than for the reference system) because of the extra sensible heat load from the evaporator fans and the larger evaporator temperature differences, lowering the RH in the cooler to about 71.9% on average over the year.

Table 2.5 summarizes the energy use and CF for the main aspects discussed above for the two refrigeration system design scenarios assuming a 15 year lifetime and use of virgin materials for manufacture. The methodology used is described in detail by IIR (2016), and the typical emission factors given in Table 2.4 were used (where ranges are given, the average of the range was used).

The energy use for the reference system corresponds to a normalized energy consumption per gross storage volume of 12.2 $kWh/m^3 \cdot y$ (0.349 $kWh/ft^3 \cdot y$), while that for the alternative system is 21.1 $kWh/m^3 \cdot y$ (0.588 $kWh/ft^3 \cdot y$). Chapter 8, in the subsection titled “Using Benchmarking Data,” suggests the benchmarks for such a facility are in the range of 17.7 to 88.3 $kWh/m^3 \cdot y$ (0.5 to 2.5 $kWh/ft^3 \cdot y$). The reference system’s energy use is well below these benchmarks, indicating a very energy-efficient design/selection that is likely to be significantly more sustainable than the benchmark facilities. The alternative system is in the lower end of the range of the benchmark, indicating that, while not as energy efficient as the reference system, it is still well-performed relative to similar existing facilities. This example shows the value of designing a facility to minimize the need for refrigeration and not just installing an efficient refrigeration system.

The loss of product caused by weight loss in the facility, while totaling only about 3% out of 10% of the whole chilled product per month (0.3%) has significant indirect (embodied) emissions relative to other emissions from the facility—about 20% of the total CF. This illustrates the value of refrigeration to reduce food losses. The example also illustrates the need to consider food production impacts where the refrigerated facility design and operation can have significant effect on product weight loss and/or quality leading to food waste. The 22% higher weight loss for the alternative scenario increases the overall emissions by 3171 tons (3496 tons) CO_{2eq}, which is nearly a 6% increase in impact relative to the reference facility.

For the reference facility using ammonia, there are no direct emissions, whereas for the alternative scenario using R-507A, the direct emissions are 18% of the total and account for most of the difference in emissions between the scenarios other than energy use and product-related emissions. The alternative system has the benefit of avoiding the risks and costs associated with the toxicity and flammability of ammonia as a refrigerant. It is also likely to have significantly lower initial cost, although this is potentially offset