Egyptian Journal of Chemistry

http://ejchem.journals.ekb.eg/

Water and Carbon Footprint for Different Technologies of HVAC Systems (Vapor Compression and Gas Absorption)

A.Q. Abdelhamid[a*], A.M. Abdel-Basier[a], M.K. Zakaria[a,b], H.A. Abdelhalim[c]

[a] *Engineering Science -Graduate School of Environmental Studies and Research- Ain Shams University,Cairo*

[b] *Environmental Science Department, Faculty of Graduate Studies and Environmental Research, Ain Shams University*

[c] *Mechanical Power Engineering, Faculty of Engineering, Ain Shams University*

Abstract

Heating, ventilation, and air conditioning (HVAC) systems are critical for ensuring indoor air quality and thermal comfort; however, their operations significantly contribute to global energy consumption and carbon emissions. According to the International Energy Agency (IEA), HVAC systems are responsible for approximately 30% of global energy use and greenhouse gas emissions. This includes direct emissions from electricity consumption and indirect emissions from energy-intensive water treatment processes used in cooling systems. Therefore, assessing the carbon footprint of HVAC systems is essential for understanding their environmental impact and implementing strategies to enhance sustainability within the sector.

This study focuses on evaluating the carbon footprint of HVAC systems through a detailed analysis of their energy consumption, including electricity use, water evaporation, and wastewater discharge. The study highlights the significant contribution of electricity consumption to greenhouse gas (GHG) emissions and compares emissions from different HVAC technologies, such as natural gas-powered chillers versus electric-powered chillers.

By quantifying carbon emissions, this study aims to identify the key sources of GHG emissions from HVAC systems and provide insights into effective strategies for emission reduction. The findings contribute to the development of sustainable practices in the HVAC sector, offering valuable recommendations for mitigating the environmental impact of these systems.

Keywords: Climate change ; Greenhouse gases ; Carbon footprint ; HVAC ; Cooling

1. Introduction

The research focuses on the lack of studies assessing the carbon footprint and environmental impact of Heating, Ventilation, and Air Conditioning (HVAC) systems, despite their role as sustainable alternatives to traditional cooling methods. While cooling technologies drive energy consumption and emissions, the carbon impact of HVAC systems remains underexplored. This study aims to bridge this gap by modeling energy use, emissions, and sustainability trends. HVAC systems are essential for indoor comfort, especially as global heat events increase, worsened by urban heat islands and greenhouse gas emissions. These systems consume significant amounts of electricity and water, particularly in offices and hospitals, contributing to 20–40% of building energy use in the EU and U.S. Water-efficient systems, such as hygroscopic cooling, are crucial amid rising water scarcity, and hybrid systems show promise in reducing water use by up to 20%. The study also evaluates HVAC integration with renewable energy for improved efficiency and cost-effectiveness.

Globally, temperatures have reached record highs due to human-induced greenhouse gas (GHG) emissions, with emissions from the RACHP (Refrigeration, Air Conditioning, and Heat Pumps) sector expected to rise sharply. In 2014, RACHP systems accounted for 7.8% of global CO2-equivalent emissions, contributing to 12% of global radiative forcing [18].

The 2015 global agreement to limit the temperature rise to below 2°C has pressured the sector to adopt sustainable systems. RACHP emissions include direct refrigerant leaks and indirect emissions from fossil fuel electricity use. The Kigali Amendment targets direct emissions by phasing out harmful refrigerants, but indirect emissions, which comprise over 80% of

---

*Corresponding author e-mail: aqasem880@gmail.com ; (Ahmed Qasem Abdelhamid).

Receive Date: 03 December 2024, Revise Date: 03 January 2025, Accept Date: 23 January 2025

DOI: 10.21608/ejchem.2025.340946.10924

©2025 National Information and Documentation Center (NIDOC)

the impact, require advanced system efficiency. However, measuring these improvements remains complex due to the lack of standardized metrics [1].

Despite progress, cooling technologies continue to drive global electricity production and emissions, necessitating further innovations. Trends in refrigeration focus on natural refrigerants and green technologies, such as waste-heat-driven systems, which offer environmental benefits but may require additional energy. Efficient humidity control, particularly in humid regions, could further reduce air conditioning energy use and emissions.

In this context, while many studies have assessed the carbon footprint of HVAC systems in other countries, the carbon and water footprints of HVAC systems in Egypt have not been studied in detail. This research is unique in calculating both the carbon and water footprints of HVAC systems in Egypt, taking into account local emission factors. Furthermore, it compares two different types of HVAC systems to understand their relative environmental impacts, offering valuable insights into the sustainability of HVAC solutions in a regional context [27].

Boundaries will define what aspects of the HVAC systems are included in the study (operation)

Scopes will determine whether you are looking at direct emissions (scope 1), indirect emissions from energy use (scope 2), or other indirect emissions from the supply chain (scope 3).

2. Climate change

2.1 Overview

Overview

Climate change refers to the long-term changes in average weather patterns that define various climates at local, regional, and global levels. Since the mid-20th century, these shifts have been largely driven by human activities, especially fossil fuel combustion, which increases greenhouse gases in the atmosphere and raises Earth's surface temperature. While natural processes like ocean cycles and volcanic eruptions can influence climate, their effects are overshadowed by human-induced factors. Scientists use ground, aerial, and satellite observations, along with computer models, to monitor climate change and analyze climate data. This data reveals key indicators such as rising temperatures, increasing sea levels, melting ice, and changes in extreme weather events. Global warming specifically refers to the long-term rise in Earth's surface temperature since the pre-industrial era, primarily due to human activities. It is essential to note that "global warming" is not synonymous with "climate change.

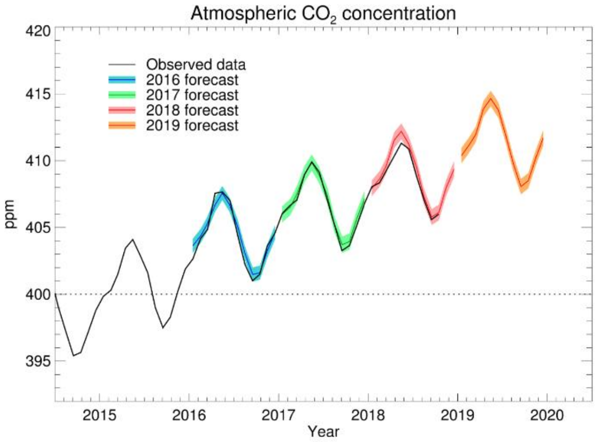


Figure 1: Atmospheric carbon dioxide concentration

2.2 Weather vs. Climate

Weather refers to short-term atmospheric conditions in specific locations, such as rain, snow, and storms. In contrast, climate represents long-term averages of temperature and precipitation over at least 30 years at regional or global levels. Since the pre-industrial period, human activities have raised Earth’s average temperature by about 1 degree Celsius (1.8 degrees Fahrenheit), with an increase of over 0.2 degrees Celsius (0.36 degrees Fahrenheit) per decade. This warming is predominantly due to human actions since the 1950s and is occurring at an unprecedented rate.

"Climate change" and "global warming" are often used interchangeably but denote different concepts. The ongoing increase in average global temperature affects the Earth's climate system, resulting in extreme weather events, heat waves, and biodiversity loss. The burning of fossil fuels, deforestation, and certain agricultural practices significantly contribute to greenhouse gas emissions, particularly methane and carbon dioxide, intensifying global warming.

The environment is increasingly impacted by climate change, leading to rising sea levels, melting ice, and changing weather patterns. These shifts cause threats such as flooding, heat waves, food and water shortages, and increased diseases. Vulnerable populations, especially those contributing minimally to emissions, are the most affected. Recent records indicate that 2023 was the warmest year since monitoring began in 1850, with a global temperature rise of +1.48 °C (2.66 °F).

To mitigate global warming, countries aim to limit temperature increases to below 2 °C (3.6 °F), as outlined in the 2015 Paris Agreement. Achieving this goal requires halving emissions by 2030 and reaching net-zero by 2050. Potential solutions include transitioning to renewable energy sources like solar, wind, and nuclear power, improving energy efficiency, and enhancing carbon sequestration through practices such as afforestation.

Global warming, largely driven by human activities, poses a significant threat to ecosystems and human societies. It results from greenhouse gas emissions, deforestation, and the burning of fossil fuels. The greenhouse effect, essential for maintaining the Earth's temperature, occurs when greenhouse gases trap heat in the atmosphere. Without this effect, life as we know it would be impossible. The balance of greenhouse gases, including carbon dioxide, methane, and nitrous oxide, is crucial in regulating Earth's climate and supporting life

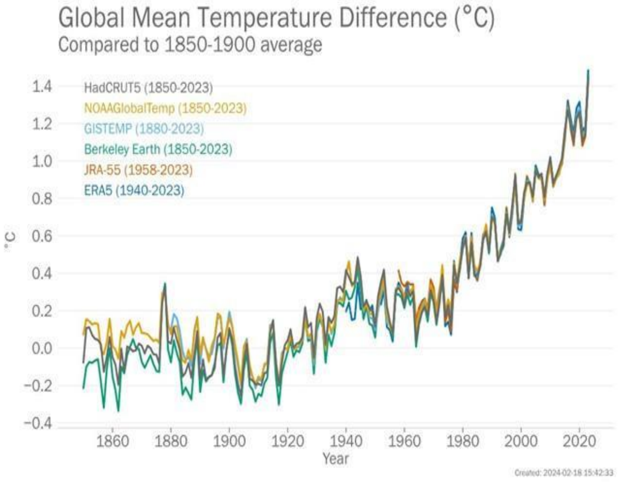


Figure 2: Global mean temperature difference

2.3 Greenhouse gas

The greenhouse effect, crucial for regulating Earth's temperature, has existed for millions of years. Joseph Fourier identified it in 1827, with experimental confirmation by John Tyndall in 1861 and quantification by Svante Arrhenius in 1896. Arrhenius highlighted the urgent need to address anthropogenic greenhouse gas emissions due to their role in climate change. The study focuses on greenhouse gases (GHGs) like carbon dioxide (CO_2), methane (CH_4), and nitrous oxide (N_2O), which are primarily influenced by human activities. Monitoring these emissions is vital for understanding their contributions to global warming.

The World Resources Institute’s Climate Analysis Indicators Tool (CAIT) compiles greenhouse gas data from various sources. GHGs are expressed in carbon dioxide equivalents (CO_2e) to facilitate comparisons, with methane being significantly more potent in terms of warming potential. Human activities since the Industrial Revolution have drastically increased CO_2 and CH_4 levels, impacting the natural carbon cycle and potentially leading to a global temperature rise exceeding 2.0 °C by 2070.

Electromagnetic radiation plays a key role in the greenhouse effect, with gases like CO_2 and methane effectively trapping heat. Recent studies underscore the importance of atmospheric chemistry in regulating GHGs, highlighting the rise of tropospheric ozone (O_3) and the influence of emissions from various sources. While some gases like CFCs are declining due to regulations, others like hydrofluorocarbons (HFCs) are increasing [11].

Projected changes in greenhouse gas concentrations and emissions may significantly impact climate and air quality. For instance, SRES scenarios predict substantial increases in tropospheric ozone, potentially harming agricultural productivity. A comprehensive assessment of human impacts on GHGs requires understanding the sources and interactions within the climate system, as indirect effects must also be considered in evaluating overall contributions to climate change.

Table 1: GWPs of Common Greenhouse Gases and Refrigerants

Refrigerant	GWP
R 1233zd	79
R 401 A	18
R 401 B	15
R 401 C	21
R 402 A	1680
R 402 B	1064
R 403 A	1400
R 403 B	2730
R 404 A	3260
R 406 A	0
R 407 A	1770
R 407 B	2285
R 407 C	1528
R 407 D	1428
R 407 E	1363
R 408 A	1944
R 409 A	0
R 409 B	0
R 410 A	1725
R 410 B	1833
R 411 A	15
R 411 B	4
R 412 A	350
R 413 A	1774
R 414 A	0
R 414 B	0
R 415 A	25
R 415 B	105
R 416	767
R 417	1955

Table 1 Cont.: GWPs of Common Greenhouse Gases and Refrigerants

R 418	4
R 419	2403
R 420	1144
R 500	37
R 501	0
R 502	0
R 503	4692
R 504	313
R 505	0
R 506	0
R 507	3300
R 508 A	10175
R 508 B	10350
R 509	3920

Table 2: Global Warming Potential

Common Name	Formula	GWP
Carbon dioxide	CO_2	1
Methane	CH_4	25
Nitrous Oxide	N_2O	298
Sulfur Hexafluoride	SF_6	22800
Nitrogen Trifluoride	NF6	17200
HFC-23	CHF_3	14800
HFC-32	CH_2F_2	675
HFC-41	CH_3F	92
HFC-125	C_2HF_5	3500
HFC-134	CHF_2CHF_2	1100
HFC-134a	$C_2H_2F_4$	1430
HFC-143	CH_2FCHF_2	353
HFC-143a	$C_2H_2F_3$	4470
HFC-152	CH_2FCH_2F	53
HFC-152a	$C_2H_4F_2$	124

Table 2 Cont.: Global Warming Potential

HFC-161	CH_3CH_2F	12
HFC227ea	C_2HF_7	3220
HFC-236cb	$CH_2FCF_2CF_2$	1340
HFC-236ea	CHF_2CHFCF_3	1370
HFC-236fa	$C_2H_2F_6$	9810
HFC-245-ca	$CH_2FCF_2CHF_2$	693
HFC-245fa	$CHF_2CH_2F_3$	1030
HFC-365mfc	$CH_2CF_2CH_2CF_2$	794
HFC-43-10-mee	$CF_3CHFCHFCF_2CF_3$	1640
PFC-14	CF_4	7390
PEC-116	C_2F_6	12200
PEC-218	C_2F_8	8830
PEC-318	c-C_4F_8	10300
PEC-3-1-10	C_4F_{10}	8860
PEC-3-1-12	C_5H_{12}	9160
PEC-4-1-14	C_6H_{14}	9300
PEC-9-1-118	$C_{10}H_{18}$	>7500

3. Carbon and water footprint

3.1 Carbon Footprint

The term "carbon footprint" has gained prominence in the UK, driven by growing climate change concerns. Despite its widespread use, there is no precise academic definition, leading to disparities between public and scholarly understandings. A carbon footprint quantifies total greenhouse gas emissions linked to activities, products, or organizations, typically expressed in tons of CO_2-equivalent (CO_2e). This measurement includes direct and indirect emissions, adhering to the Greenhouse Gas Protocol's classifications (Scopes 1, 2, and 3).

Methods for calculating carbon footprints vary, with life cycle assessments (LCA) considering emissions throughout a product's lifecycle, and input-output analyses focusing on economic interactions. Nations use consumption-based accounting for comprehensive emissions assessments, addressing gaps in production-based methods. Reducing carbon footprints involves lifestyle changes, such as dietary adjustments and sustainable transportation choices, while businesses must implement emission-reduction strategies to comply with regulations and engage stakeholders.

Sustainability science studies human interactions with Earth's systems, emphasizing the need for actionable steps towards sustainable consumption. Water sustainability is crucial, as highlighted in the European Communication "A Blueprint to Safeguard Europe's Water Resources." Comprehensive assessments of water use and consumption patterns are essential for effective policy applications, necessitating harmonized methodologies.

Current efforts to mitigate greenhouse gas emissions are insufficient to limit global temperature rise to 1.5˚C. An analysis of U.S. household income and emissions reveals significant inequalities, with the top earners contributing a disproportionate share of emissions. This highlights the potential for an income-based carbon tax focused on investments as a more equitable approach to decarbonization and climate finance. overall, a carbon footprint encompasses total GHG emissions from a product or individual, calculated across its lifecycle and expressed in CO_2e for comparability. Different gases, such as methane and nitrous oxide, are included based on their global warming potential, emphasizing the need for comprehensive emissions

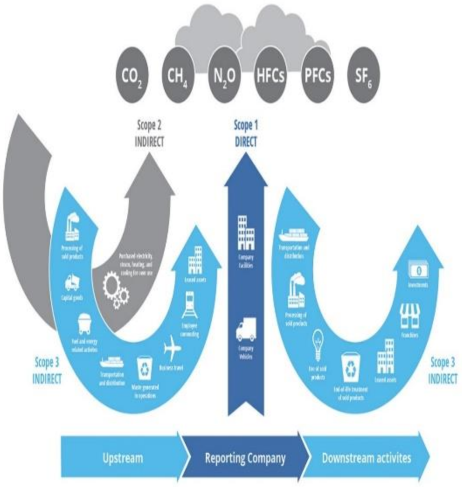


Figure 3: Greenhouse gases scopes assessments

3.2 Water Footprint

Water is crucial for sustaining civilizations, driving economic growth, and, most importantly, supporting agriculture. As the largest consumer of freshwater, agriculture accounts for approximately 99% of the global consumptive water footprint. It is projected that consumptive water usage for food and fodder crop production will increase by 0.7% annually, rising from an estimated 6,400 Gm^3/year in 2000 to 9,060 Gm^3/year by 2050 to adequately nourish the anticipated global population of 9.2 billion. Although water is abundant in certain regions, many river basins, especially in arid and semi-arid areas, are facing water scarcity and deteriorating water quality due to population growth and increased water demand.

Effective water resource planning and management at the river basin level aim to enhance water availability, improve water quality, and sustain environmental flows to support riparian ecosystems. Assessing water resource use and availability has become a key focus of global research, often involving comparisons of water use and availability to evaluate scarcity in specific regions. Traditionally, total water withdrawal across various sectors (agricultural, domestic, and industrial) has been used as an indicator of freshwater use. However, this total withdrawal may not accurately represent water use at the catchment level since a portion of the withdrawn water is returned to the catchment.

New paradigms and methods, such as virtual water content (VWC) and water footprint (WF), have gained traction in the scientific community to promote sustainable and efficient water usage in planning and management. Introduced in 2002 by Arjen Hoekstra during the International Expert Meeting on Virtual Water Trade in Delft, the water footprint serves as a consumption-based indicator of water usage, encompassing all freshwater use (including consumption and pollution) associated with the production of goods and services consumed by individuals in a particular region.

The water footprint of production includes both direct and indirect water use of domestic resources, while the WF of consumption accounts for direct and indirect water use from both domestic and foreign sources utilized for local consumption. The water footprint can be categorized into blue, green, and grey components: the green WF quantifies the volume of rainwater consumed during the crop's growing period; the blue WF measures surface and groundwater usage; and the grey WF indicates the amount of freshwater needed to assimilate nutrients and pesticides leaching from fields, based on natural background concentrations and current water quality standards. Thus, the water footprint provides a quantifiable measure of water consumption per crop unit, along with the associated volume of water pollution, making it a comprehensive indicator of freshwater usage [22] [33] [34].

A water footprint reflects the amount of water used in relation to human and industrial consumption. It encompasses all fresh water required to produce the goods and services consumed by an individual, community, or organization. Water use is defined as the volume of water consumed, evaporated, or contaminated within a specific timeframe. Water footprints can be determined for any clearly defined group of producers (like government agencies or corporations) or consumers (such as individuals, families, cities, or nations) and can apply to various goods or services, including specific activities like rice cultivation.

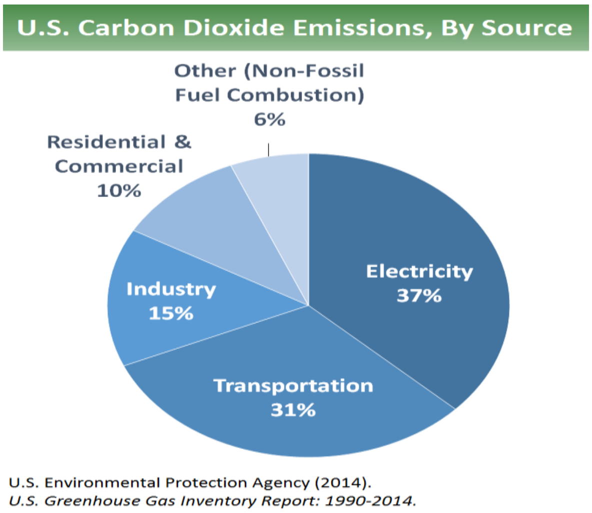
When assessing water usage from a production perspective, three categories of water consumption are typically measured: water withdrawals in residential, commercial, and agricultural sectors. Although this information is valuable, it offers a limited perspective in a global context where products are often not consumed in their country of origin. International trade in agricultural and industrial commodities generates a global flow of virtual water, or embodied water, paralleling the concept of embodied energy.

The water footprint concept, developed in 2002, provides a consumption-based indication of water usage, enhancing the traditional production-sector-based indicators. It resembles the ecological footprint concept introduced in the 1990s. The water footprint serves as a spatially explicit indicator displaying the locations and volumes of pollution and water use. The global significance of the water footprint emphasizes the need for sustainable and equitable resource management, addressing ecological challenges, water scarcity, and climate change. It offers comprehensive insights for equitable and adequate water resource management, advocating for a sustainable and fair approach to water use to tackle global concerns. This approach is essential for ensuring responsible and equitable water resource management worldwide, illustrating how economic processes and decisions affect global ecological realities, such as the availability of water resources.

Human activities significantly influence water resources through both consumption and pollution. Globally, agricultural production represents the largest share of water use, with substantial consumption and pollution also occurring in industrial and domestic sectors (WWAP, 2009). Specific activities—such as irrigation, bathing, washing, cooling, and processing—contribute to total water consumption and pollution. Generally, total water use is viewed as the cumulative effect of various independent activities that demand and contaminate water. However, there has been insufficient focus on the relationship between total water consumption and pollution and community consumption patterns and the global economy's structure that produces various goods and services.

Historically, water management practices have not adequately addressed consumption and pollution associated with entire production and supply chains. This gap has limited awareness of how the organization and characteristics of these chains significantly influence the volumes and distribution of water consumption and pollution linked to final consumer products. Hoekstra and Chapagain (2008) noted that visualizing the hidden water usage behind products can enhance understanding of global freshwater challenges and quantify the impacts of consumption and trade on water resources, providing a foundation for more effective freshwater resource management.

Freshwater is increasingly recognized as a global resource due to the rising international trade in water-intensive commodities. There are global markets for products that require substantial water, including crops, livestock, natural fibers, and bio-energy. Consequently, the utilization of water resources has become geographically disconnected from consumers. For example, while Malaysia does not cultivate cotton, it imports raw cotton from countries like China, India, and Pakistan for processing in its textile industry, subsequently exporting cotton garments to Europe. Thus, understanding the water resource implications of consuming a cotton product requires examining the supply chain and tracing the product's origins. Identifying these hidden connections between consumption and water use can inform new water governance strategies, recognizing new triggers for change. Traditionally overlooked, final consumers, retailers, food industries, and traders in water-intensive products can now be seen as potential change agents, influencing water management through both direct usage and indirect consumption.



U.S. Environmental Protection Agency (2014).
U.S. Greenhouse Gas Inventory Report: 1990-2014.

Figure 4: U.S. Carbon dioxide emission

4. HVAC technologies

4.1 Overview

District cooling functions as the cooling counterpart to district heating. It operates on similar principles, supplying chilled water to buildings such as offices and factories. In winter, seawater can often serve as a cost-effective cooling source, reducing the need for electricity to power compressors for cooling. Alternatively, district cooling can be implemented through a Heat Sharing Network, allowing each building in the network to use a heat pump to transfer heat to an ambient ground temperature circuit.

Additionally, there are 5th generation district heating and cooling systems, known as cold district heating networks, which can provide both heating and cooling at the same time. These systems recycle waste heat from chillers for use in space heating or hot water production.

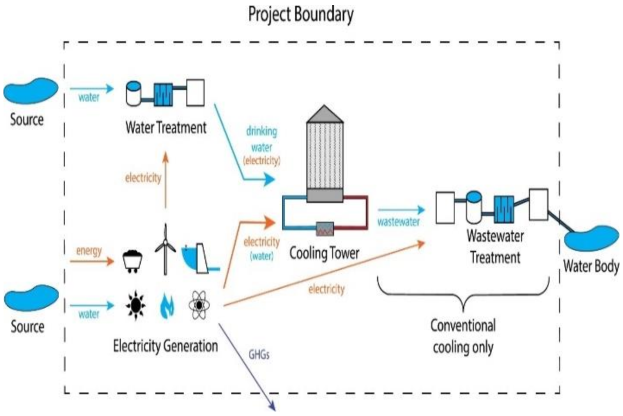


Figure 5: Cooling tower boundary

This document introduces HVAC (Heating, Ventilation, and Air Conditioning) systems, aimed at engineers, architects, and construction professionals seeking a foundational understanding of HVAC concepts, principles, systems, and equipment. While it is not a design manual, it enhances comprehension of HVAC technologies, presenting design information in a manual format to illustrate fundamental principles.

Cooling Cycle (Chilled Water System)

In a chilled water system, supply air exits the cooling coil at approximately 20°F cooler than the conditioned space, flows through ductwork, and enters the area. This cool air absorbs heat and returns warmer air through the return duct to the air handling unit. The return air mixes with outside air in the mixing chamber, passes through filters, and cools again in the coil, releasing heat into the chilled water.

Chilled water, after absorbing heat, travels through the chilled water return (CHWR) pipe to the chiller's evaporator, where it releases heat. The refrigerant evaporates, absorbing heat and transporting it to the compressor and condenser, which transfers heat to the cooling tower.

Key Components of a Chilled Water System:

- Refrigeration compressor (reciprocating, scroll, screw, or centrifugal)
- Shell and tube heat exchanger (evaporator)
- Shell and tube heat exchanger (condenser)
- Cooling tower
- Expansion valve between condenser and evaporator

A chilled water system can connect multiple cooling coils throughout large buildings, centralizing refrigeration equipment.

Importance of Cooling

Cooling not only enhances thermal comfort but also protects vulnerable populations from heat stress, ensures vaccine viability, preserves food, and maintains workforce productivity. However, traditional cooling systems contribute significantly to pollution and energy consumption, accounting for approximately 7% of global greenhouse gas emissions. Increasing cooling energy demand, often generated from coal, poses challenges to achieving a zero-emission grid. Many companies advocate for sustainable practices in the district cooling sector to minimize consumption and assist with HVAC system maintenance.

4.2 District Cooling Overview

A district cooling (DC) system generates and distributes chilled water from a central plant to multiple buildings, maximizing efficiency and sustainability. While individual air conditioners have lower capital costs, their operational costs are higher due to lower efficiency. In contrast, district cooling systems, despite higher initial costs, provide better energy efficiency, particularly in densely populated areas [45].

A district cooling (DC) system is a centralized air-conditioning approach that produces and distributes chilled water from a central plant to various buildings, enhancing efficiency and economies of scale. Compared to individual air conditioning units, district cooling offers a more reliable and environmentally friendly solution for delivering chilled water to residential, commercial, and industrial consumers. While individual room air conditioners generate cooling on-site, district cooling systems centralize this process, using a network of pipes to serve multiple buildings.

Although initial investments in district cooling systems are higher, they provide better energy efficiency and lower long-term operational costs, particularly in densely populated areas where cooling demand is high. The decision to implement district cooling versus individual air conditioning often depends on the density of cooling needs. While district cooling may not be the best choice for every building, it is advantageous in urban environments.

When connected to a district cooling system, buildings may require additional components such as control systems, pumps, heat exchangers, and energy metering systems. The energy efficiency of district cooling systems is crucial in regions with energy supply concerns, and they significantly reduce carbon dioxide emissions compared to individual units. This technology has expanded rapidly in developing countries, particularly in the Middle East, where the Gulf region has the highest installed air conditioning capacity in the world.

Applications of District Cooling

- Canada: Enwave Energy Corporation's Deep Lake Water Cooling (DLWC) system in Toronto provides over 40,000 tons of cooling capacity using Lake Ontario water.
- France: Paris’s "Cold Network" has operated since 1991, supplying cooling to 500 clients with a capacity of 400 MW.
- Finland: Helsinki utilizes waste heat from summer CHP power generation for cooling, reducing electricity consumption significantly.
- Germany: Munich's district cooling system has rapidly expanded since 2011, serving 16 organizations.
- India: GIFT City operates India's first district cooling system, with plans for expansion.
- Kuwait: A project for Sabah Al-Salem University City can handle a cooling load of 72,000 TR.
- United States: Cornell University uses Cayuga Lake for its Lake Source Cooling System, providing 14,500 tons of cooling.

Benefits of District Cooling Systems

District Cooling Systems (DCS) consume 20-35% less electricity than traditional systems and offer numerous advantages:

- Lower Initial Capital Costs: Eliminates the need for individual chiller plants in buildings.
- Design Flexibility: Simplifies building designs by reducing equipment requirements.
- Mitigation of Urban Heat Islands: Reduces heat island effects and noise from HVAC equipment.
- Adaptability: Easily adjusts to varying demand with added capacity without extensive modifications

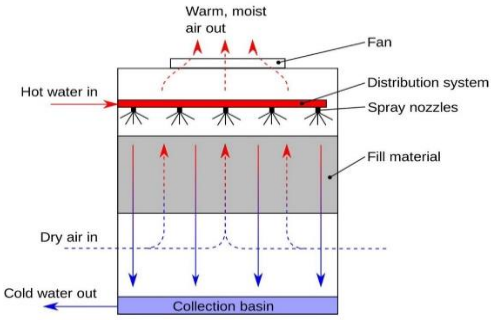


Figure 6: Cooling Tower

4.3 Vapor-Compression Refrigeration

Vapor-compression refrigeration (VCR) is the most common method for cooling buildings and vehicles. It operates by transferring heat from a designated area to lower its temperature and is widely used in various applications, from household refrigerators to industrial processes. VCR systems consist of four main components: a compressor, a condenser, an expansion valve, and an evaporator.

The cycle begins when the refrigerant is compressed, increasing its pressure and temperature. It then passes through the condenser, where it cools and condenses into a liquid. This liquid refrigerant expands through the expansion valve, causing a drop in pressure and temperature. As it flows through the evaporator, it absorbs heat from the surroundings, evaporating back into a gas and completing the cycle.

Choosing the right refrigerant is vital for the efficiency of refrigeration systems. While CFCs, such as R-11 and R-12, were widely used due to their stability, they have been phased out due to their negative impact on the ozone layer. HFCs and HCFCs are now common, but they also contribute to global warming. Research is ongoing to find safer alternatives like supercritical carbon dioxide (R-744) and hydrocarbons, although safety concerns limit their use. The system is increasingly focused on refrigerants with lower global warming potential (GWP) to meet environmental regulations.

Gas compressors types:

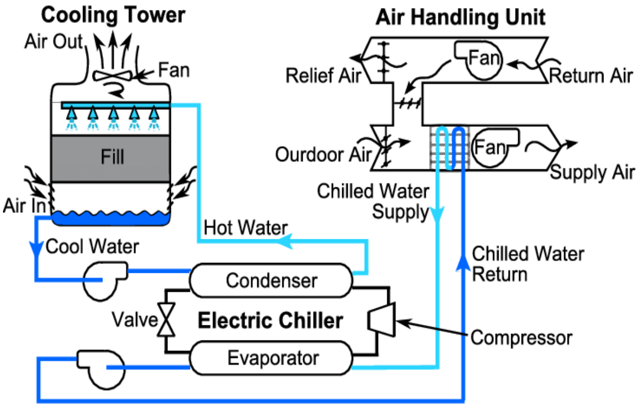


Figure 7: Vapor compression refrigeration cycle

Gas Compressors

In refrigeration, reciprocating and scroll compressors are the most commonly used types, although centrifugal and rotary screw compressors are occasionally employed in industrial applications and large chillers. The selection of compressor type depends on pressure, size, noise, and efficiency, with specific applications favoring particular designs. Compressors can be classified as open, hermetic, or semi-hermetic based on their configurations:

Hermetic Compressor with a Hermetic Motor

Semi-Hermetic Compressor with a Hermetic Motor

Hermetic Compressor Driven by an Open Motor (belt-driven or tightly coupled)

Semi-Hermetic Compressor with an Open Motor (close-coupled or belt-driven)

In hermetic and semi-hermetic compressors, the motor is integrated into the refrigerant system and cooled by the refrigerant. However, if the motor fails, it necessitates complete removal of the compressor, and burnt windings can contaminate the refrigerant system.

Open compressors, on the other hand, feature an external motor that can be easily repaired without depressurizing the system. While they are generally more reliable and simpler in design, they can leak refrigerant if shaft seals fail. Liquid injection is sometimes used in hermetic compressors to mitigate cooling issues.

Types of Compressors

- Reciprocating Compressors: These positive displacement compressors use a piston design to compress refrigerant.
- Rotary Screw Compressors: Another type of positive displacement compressor, these capture refrigerant vapor using two interlocking rotors, compressing it as it moves to the discharge point. Larger units are efficient, while smaller ones may face back leakage issues.
- Centrifugal Compressors: Dynamic compressors that increase refrigerant pressure by converting velocity into pressure energy through a rotating impeller. They feature a "Centrifugal Compressor Map," indicating operational parameters like the surge line and choke line. Larger, lower-speed compressors typically experience fewer surge conditions than smaller, higher-speed models.
- Scroll Compressors: Also positive displacement devices, they use a rotating spiral around a stationary spiral to compress refrigerant, creating progressively smaller pockets until the desired pressure is achieved.

4.4 Absorption chillers

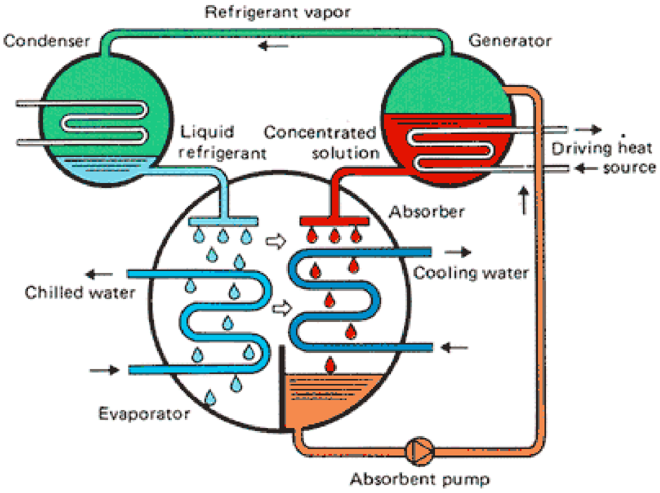


Figure 8: Gas absorption refrigeration cycle

Absorption Chillers

Absorption chillers utilize waste heat from various processes to power thermodynamic cycles for cooling water used in HVAC systems. Unlike mechanical compressors, these chillers use an absorption refrigeration cycle and range in size from 20 to 1,500 tons. The key components remain similar to those in vapor-compression systems, but absorption chillers include an absorber, pump, and generator instead of a compressor.

Absorption Cycle Overview:

A high-temperature energy source (typically steam or hot water) heats the refrigerant in the generator, causing it to evaporate.

The refrigerant vapor moves to the condenser, while the concentrated solution returns to the absorber.

In the absorber, the vapor is absorbed by the solution, releasing heat and condensing into a liquid.

Types of Absorption Chillers:

1. **Single-Effect Absorption Chillers:**

The refrigerant cools the water once as it passes through the evaporator.

The generator heats the diluted solution to regenerate the refrigerant, which is then cycled back into the system.

2. **Double-Effect Absorption Chillers:**

Similar components to single-effect chillers but include an additional generator and heat exchanger.

Operates through two cycles, allowing the refrigerant to cool the water twice, enhancing efficiency and heat absorption.

3. **Direct-Fired Absorption Chillers:**

Function like single-effect chillers but use a gas flame to heat the absorption solution instead of hot water.

Advantages of Absorption Chillers

- Ideal for Tri-Generation: Effectively integrates with cogeneration systems to reduce costs related to electricity, hot water, heating, and cooling.
- Long Service Life: Can operate for up to 20 years with minimal overhauls.
- Low Cold Production Cost: Generates cooling at a low cost.
- Reduced Noise and Vibration: Quieter operation due to the absence of electric motor-driven compressors.
- Cost Savings: Using gas generators can lower initial costs compared to traditional systems.
- Energy Savings During Peak Demand: Produces cold/heat without consuming electricity, preventing overload during peak periods.
- Compatibility with District Steam Systems: Integrates efficiently with district steam systems.
- Load Balancing: Handles critical cooling loads with minimal power consumption.

- Emergency Generator Compatibility: Lower energy usage allows for emergency generator operation.
- Environmental Safety: Uses refrigerants that do not deplete the ozone layer.
- Reduced Environmental Impact: Lowers greenhouse gas emissions by minimizing electricity use.

Disadvantages of Absorption Chillers

- High Initial Capital Cost: Upfront investment is significantly higher than vapor-compression systems.
- Corrosive Nature of Lithium Bromide: Corrosive solutions can shorten system lifespan; ammonia systems are also corrosive to copper.
- Low Working Pressures: Operate at low pressures, requiring tight seals to prevent gas entry, which is critical for system integrity.
- Lower Coefficient of Performance (COP): COP is significantly lower than vapor-compression systems, making them competitive mainly when electricity-to-fuel ratios are favorable.
- Higher Heat Rejection Requirements: Require more extensive heat rejection and larger cooling towers, increasing operational costs.

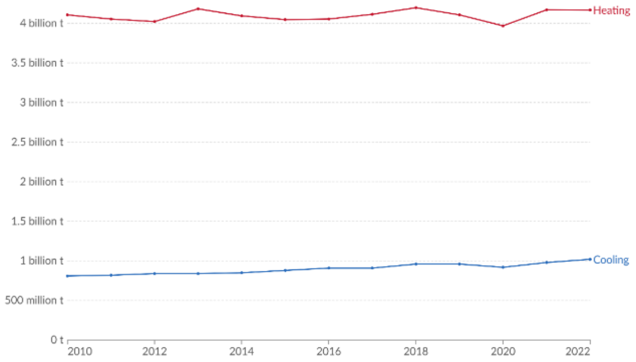


Figure (9) CO_2 Emissions from Heating and Cooling Systems Globally

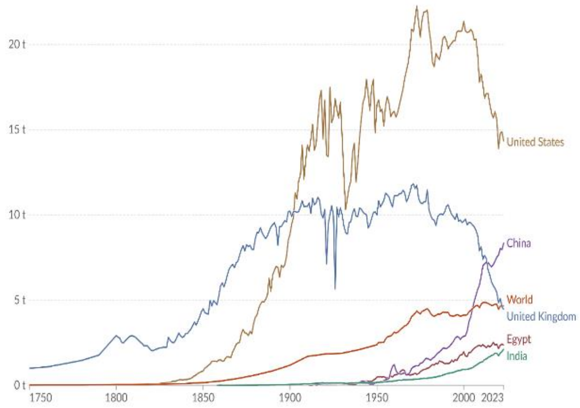


Figure (10) CO_2 emissions from Fossil Fuel and Industry

5. Materials and methods

5.1 Materials

Large organizations typically generate emissions from refrigeration and air conditioning equipment, though the potential sources of these emissions and the availability of data can vary significantly. For example, a supermarket chain with extensive refrigeration systems may have on-site refrigerant storage and keep detailed records of refrigerant usage. In contrast, an industrial firm might only use air conditioning in its office space and lack comprehensive data on refrigerant consumption. Often, organizations that do not consider refrigeration a core business activity exclude related GHG emissions from their inventories, deeming them immaterial. However, the materiality of any emissions source can only be accurately determined after assessment. This assessment need not involve rigorous quantification of all sources; at the very least, organizations should develop an estimate based on the data they have available for all emission sources.

To aid in calculating GHG emissions, this guidance outlines four methods, each requiring different levels of accuracy and data collection. Organizations can estimate fugitive GHG emissions from refrigeration and air conditioning systems, fire suppression systems, or purchased industrial gases using one of the following approaches:

Section 2.1 details a Preliminary Screening Method to estimate emissions from refrigeration, air conditioning, and fire suppression equipment. This approach relies on the type of equipment used and associated emission factors, requiring minimal data collection. However, it is not suitable for quantifying emissions from purchased gases. This method is intended solely as a screening tool because the emission factors employed are highly uncertain. These factors can vary not only between individual equipment pieces but also change over time. Even with precise tracking of the refrigerant added to equipment—allowing for the establishment of a prior leak rate—this rate can fluctuate after leaks are repaired or as the equipment ages. If emissions from this equipment are deemed significant relative to other emission sources within the organization (such as stationary combustion or mobile sources), then one of the other methods should be used for more accurate emissions calculation.

Section 2.2 introduces a Method for Purchased Gases, which is applicable to organizations that purchase, utilize, and emit industrial gases. For those organizations that maintain an inventory of industrial gases or use equipment that maintains a charge of an industrial gas—similar to how refrigerants are used in air conditioning—applying one of the material balance methods is recommended.

Section 2.3 explains a Material Balance Method for calculating emissions related to the installation, operation, and disposal of refrigeration and air conditioning equipment. This method is particularly suitable for organizations that manage their own equipment and requires data on the total refrigerant inventory at both the beginning and end of the reporting period, any purchases made during that time, and changes in the overall refrigerant capacity of the equipment. This method can also be used to calculate emissions from fire suppression systems.

Section 2.4 outlines a Simplified Material Balance Method, which is suitable for organizations that do not keep or track a stock of refrigerants and have not modified their equipment to utilize a different refrigerant during the reporting period. This method is particularly recommended for organizations that rely on contractors to service their refrigerant-containing equipment. It facilitates the tracking of emissions associated with the installation, operation, and disposal of the equipment.

To implement this method, organizations need to gather data on the quantity of refrigerant in three key areas: (a) the amount used to charge new equipment during installation, (b) the quantity used for servicing existing equipment, and (c) the refrigerant recovered from equipment that is being retired. Additionally, organizations must also know the total refrigerant capacities for both new and retiring equipment. Service contractors, if informed in advance about the need for this information, should be able to provide the necessary data [43].

Refrigeration systems, domestic air conditioning, heat pumps, mobile air conditioning, chillers, retail food refrigeration, cold storage warehouses, refrigerated transport, industrial process refrigeration, and commercial unitary air conditioning systems collectively contribute to emissions in this sector. Traditionally, various ozone-depleting substances (ODS), such as CFCs and HCFCs, have been utilized as refrigerants, but these substances are currently being phased out under the Montreal Protocol in favor of HFCs.

HFC emissions arise from the manufacturing process, equipment leakage throughout its operational life, and disposal at the end of its lifespan. These gases possess 100-year global warming potentials (GWP) ranging from 140 to 11,700 times that of carbon dioxide, indicating their significant potential impact on climate change. Consequently, reducing these emissions can yield substantial environmental benefits.

This protocol addresses emissions generated during the manufacturing, operational, and disposal phases of refrigeration and air-conditioning systems.

Activity Data and Emission Factors

Estimates of HFC emissions can be made using data readily accessible to manufacturers and users of refrigeration and air-conditioning equipment. This guideline includes a screening method to evaluate the significance of HFC emissions, alongside two quantification approaches. Organizations can select a quantification method based on data availability, the purpose of the assessment, and the desired accuracy level.

For equipment manufacturers and users who maintain their own equipment, the preferred method is to estimate HFC emissions based on the quantity of refrigerant purchased and utilized. This Sales-Based Approach relies on data from purchase and service records and accounts for emissions arising from equipment manufacturing (for producers) or installation (for users), as well as operation, servicing, and disposal.

For equipment users who employ contractors for maintenance, the Lifecycle Stage Approach is recommended. This method tracks emissions across the equipment's lifecycle, requiring data on the amount of refrigerant used to charge new equipment during installation, the quantity used for servicing, and the amount recovered from retiring equipment, alongside the full charges for both new and retiring systems. Contractors, when informed in advance, should be able to provide this information.

A screening method is also available for companies needing to determine whether their emissions from refrigeration and air conditioning (RAC) equipment are significant compared to other emission sources. This screening can utilize default equipment emission factors or leak rates but should not replace the more accurate quantification methods provided in this tool. Given the uncertainty of leak rates, if a company determines that its RAC emissions are significant, it should use one of the quantification methods for estimating HFC emissions.

HFC Emissions from Refrigeration and Air-Conditioning

A. Approach Description Direct emissions refer to those produced from owned or controlled sources. In this context, direct HFC emissions stem from the manufacturing, servicing, or disposal of controlled refrigeration and air-conditioning equipment. A screening method is available to assess whether emissions from RAC equipment are significant, with two quantification approaches provided, ordered by increasing certainty. Equipment manufacturers and users maintaining their own equipment will likely find the Sales-Based Approach easiest to use, while those using contractors for maintenance may prefer the Lifecycle Stage Approach.

Environmental Impact Assessment of Refrigeration Systems

Historically, technical-economy analyses have been employed to evaluate new power-intensive equipment or technologies. Recently, researchers have begun using various life cycle assessment (LCA) methodologies for evaluating technologies or products, including refrigeration systems. The environmental impact of different refrigeration equipment types has been assessed primarily over the past few decades, employing various methodologies and indices.

One of the earliest environmental assessment methods was the Total Equivalent Warming Impact (TEWI), which helps evaluate the suitability of alternative refrigerants. However, TEWI has limitations, such as its dependency on equipment cooling capacity and its omission of energy resources used during manufacturing and disposal. Despite these shortcomings, TEWI remains a recommended method for assessing the environmental impact of refrigeration systems, particularly in Part I of Standard EN 378, which suggests TEWI as a criterion for overall environmental impact assessment. This approach assumes that GHG emissions associated with component production processes are negligible during the refrigerator's lifetime. However, emissions related to equipment creation, particularly for smaller units, can be significant.

Danfoss has utilized the TEWI concept to demonstrate the relationship between direct (refrigerant leakage) and indirect (electricity consumption) impacts on GHG emissions from refrigerators. Recent publications validating refrigerant selection have also employed the TEWI concept. For example, the TEWI analysis indicated that R744 could be a next-generation refrigerant in terms of TEWI, cost, and safety according to ASHRAE. Nevertheless, this conclusion has faced criticism, as it does not adequately account for the higher manufacturing costs associated with R744 systems compared to other refrigerants. Studies analyzing TEWI and total cost for refrigerants in Italy, Germany, and France suggest that both indicators should be combined into a comprehensive criterion to avoid contradictory results in refrigerant selection.

The TEWI methodology has since evolved into the Life Cycle Carbon Footprint (LCCP) concept, which incorporates TEWI while also including direct and indirect GHG emissions from component manufacturing and working fluid production. LCCP assessments have included emissions associated with refrigerant production and the extraction of materials for refrigeration systems, making it a widely used approach for analyzing refrigeration equipment. Both LCCP and TEWI are recommended for evaluating GHG emissions related to air conditioning and refrigeration systems.

In the context of power-intensive equipment, Carbon Footprint Assessment (CFA) has become increasingly common. CFA evaluates the complete lifecycle but focuses solely on the environmental burden of global warming. It is a standardized methodology (ISO 14067:2018) and can be viewed as a simplified version of LCA, concentrating on GHG emissions related to climate change potential.

The Environmental Life Cycle Assessment (LCA) methodology is widely employed to analyze various products, including refrigeration systems. LCA is a standardized methodology (ISO 14044:2006) that evaluates multiple environmental indicators, including global warming potential, acidification potential, and ozone depletion potential. However, accurately combining all indicators into a single measure proves challenging, hindering the selection of equipment with the least environmental impact. Additionally, the LCA methodology often requires extensive initial data, complicating comprehensive analysis.

Several authors have proposed alternative approaches for analyzing refrigeration equipment, such as modified LCCP, simplified GHG emission evaluations, and exergy economic and environmental analyses. Some studies have simultaneously utilized multiple criteria to assess equipment or technology, showcasing comprehensive thermal-economic-environmental evaluations across different refrigerants.

Limitations and Uncertainties of the Study

Despite providing a comprehensive analysis of the water and carbon footprints of various HVAC systems (vapor compression and gas absorption), there are several limitations and uncertainties that should be considered:

Assumptions Related to Technology:

The study assumes that all HVAC systems operate under ideal conditions, which might not always reflect real-world scenarios. Uncertainties arise from variations in operating conditions, such as fluctuating thermal loads, ambient temperatures, and system performance over time, which can affect the generalizability of the results.

Energy Source Variability:
A key uncertainty in estimating the carbon footprint lies in the energy sources used to power the systems. The study assumes a uniform energy mix, but in practice, this varies by region and over time. Different energy sources (e.g., coal, natural gas, renewable energy) have distinct carbon intensities, and future shifts in energy generation can introduce uncertainty into the carbon footprint estimates.

Data Uncertainties:
There is inherent uncertainty in the data used for estimating the water and carbon footprints of HVAC systems. Variability in measurement techniques, equipment specifications, and operational conditions across studies may result in discrepancies in the data. Moreover, the lack of standardized methodologies for assessing environmental impacts across HVAC systems further contributes to this uncertainty.

Geographical Variability:
The study assumes certain geographical conditions, such as climate, which may not hold true in all locations. Different regions exhibit unique environmental factors that can influence the efficiency and environmental impact of HVAC systems. This introduces uncertainty in applying the study's findings to different geographical contexts.

Uncertainties in Environmental Impact:
While the study focuses on water and carbon footprints, there are additional environmental impacts, such as the use of refrigerants with high global warming potential or the environmental burden of manufacturing HVAC components. These factors introduce uncertainty, as their influence on the overall environmental footprint may vary depending on the type of HVAC system and local regulations.

Table 3: System Boundaries

Equipment	Input	Output	Boundaries
Chillers	**Electricity** **water from cooling tower** **chilled water Supply** **Fuel & Chemicals** **refrigerant**	**Cooled water for distribution to the end-use system** **waste heat sent to cooling tower**	**Refrigeration cycle** **H E with chilled water and condenser water**
Cooling Towers	**Water & Electricity**	**Blowdown Water** **Cold Water**	**H E between water and air** **Pumping of water**
Pumps	**Electricity & Water**	**Pressurized water**	**Mechanical energy transfer from the pump to the water** **Circulation of water**

5.2 Methods:

Calculation Carbon Footprint

Integrating human labor emissions (emh.l) into lifecycle assessments represents an innovative step towards broader comprehensiveness in environmental impact analysis. This integration relies on national indicators such as the carbon intensity of GDP (emGDP) and average national wages. Although this methodology faces challenges related to data availability and accuracy, it offers a reliable means to estimate the carbon footprint associated with human activities during manufacturing and maintenance phases. Notably, this approach highlights significant disparities between high-income and low-income countries, as labor-related emissions tend to be higher in nations with elevated income levels, reflecting the direct correlation between economic activity and environmental impact.

A novel approach is proposed for calculating Total Equivalent Greenhouse Gas Emissions (TEGHGE). This modified eco-energy analysis of refrigeration systems aims to select rational schematic solutions with minimal specific lifecycle CO2 emissions per kWh of cooling energy. Key contributions to GHG emissions considered in this approach include:

- Indirect CO2 emissions from electricity consumption.
- Indirect CO2 emissions associated with manufacturing, maintenance, repair, and disposal of refrigeration systems.
- Indirect CO2 emissions related to human labor (in maintaining refrigeration systems) that meet societal needs.
- Direct CO2 emissions from fuel combustion for heat production.
- Direct GHG emissions from refrigerant leakage.

The distinctive features of the TEGHGE approach compared to TEWI, LCCP, LCA, and CFA include:

- Consideration of all equipment lifecycle stages (unlike TEWI).
- Availability of initial data for TEGHGE calculations (unlike LCA).
- Inclusion of CO2 emissions associated with human labor in the production and maintenance of the analyzed system (unlike LCCP and CFA).
- Input Data Collection

National environmental and energy indicators relevant for TEGHGE calculations include:

- Electricity emission factor (β).
- CO2 emissions due to human labor (emh.l).

- National carbon intensity of GDP (emGDP).

Boundaries:

System Boundaries: Define which components of the HVAC systems will be included in your analysis. For example:

- Vapor Compression Systems: Include the compressor, evaporator, condenser, and expansion valve, as well as refrigerants.
- Gas Absorption Systems: Include the absorber, generator, and evaporator, and the use of absorbent materials.

Scopes of Emissions:

1. **Scope 1 (Direct Emissions):**

Vapor Compression: Include refrigerant leakage and emissions from any direct combustion of fuels.

Gas Absorption: Focus on direct emissions from the absorption process, where refrigerant or absorbent leakage might occur.

2. **Scope 2 (Indirect Emissions from Energy Use):**

Both systems will likely consume electricity or heat energy. Estimate the carbon emissions from the energy consumption for each system, considering the energy mix of the region where the HVAC systems are used.

3. **Scope 3 (Other Indirect Emissions):**

Include emissions from the manufacturing and transportation of HVAC components, refrigerants, and materials used in both systems.

For instance, emissions from the supply chain of refrigerants or absorbents should be taken into account, as well as the embodied energy in materials used for construction.

You may also mention how the water footprint is determined in parallel, including water usage for cooling and system maintenance.

The TEGHGE values and refrigerant emissions (emrefr) for analyzed chillers, manufactured and operated in various countries, will vary. Consequently, environmental and energy indicators were used in further analysis to assess whether the effectiveness of heat-driven refrigeration machines is country-dependent.

The national electricity CO2 emission factor (β) quantifies emissions during electricity generation. Accurately determining this factor is crucial at the initial stage of data collection, as it depends on the energy generation structure of the country where the systems are located. It's essential to note that electricity generation, even without combustion, contributes to GHG emissions.

Information regarding the electricity CO2 emission factor (β) for European countries from 2009 is available from the European Environment Agency, while global data from 2011 exists. For the selected countries, data on consumed and generated electricity were utilized. The authors note the lack of recent, accessible data on the electricity CO2 emission factor for all countries. The obtained values raised concerns about the high β for certain nations (e.g., India at 1.8 kg CO2 per kWh), as this average exceeds typical values for lignite combustion.

The CO2 emissions related to human labor must also be considered in lifecycle GHG emission assessments. Quantitative evaluation of labor's environmental impact remains a contentious issue in LCA and Industrial Ecology. Currently, no unified approach exists for estimating this value. One hour of labor from a highly skilled worker (HL-1) results in greater environmental impacts compared to technician labor (HL-2) and manual worker labor (HL-3). Specifically, one hour of HL-1 labor produces 0.52 kg CO2, while HL-2 and HL-3 workers generate 0.46 kg CO2 and 0.41 kg CO2, respectively. Generally, higher-income countries have greater emissions associated with labor than lower-income nations.

The minimum value of emh.l is determined by the worker's living wage. To facilitate comparative analysis, the authors suggest calculating emh.l using average national indicators, including specific nominal wages and national carbon intensity of GDP. This approach posits that worker emissions are proportional to national GDP and, ultimately, are assessed in kg CO2 per hour. This methodology suggests that higher-income countries will show increased labor emissions.

In this study, saturated water steam at 100 °C was evaluated as an energy source for energy storage (ES) and absorption systems (AS). Three distinct scenarios for generating heat in the form of steam for AS and ES were analyzed:

- Scenario 1: Waste heat is treated as a cost-free energy source, implying that its use does not result in CO2 emissions.
- Scenario 2: Steam is produced using a natural gas steam generator. The greenhouse gas (GHG) emissions associated with generating 1 kJ of steam were tentatively estimated at 62×10−662 \times 10^{-6}62×10−6 kg CO2 per kJ. This estimation is based on the calorific value of natural gas (assumed to be 34.4 MJ/m^3), its density at standard conditions (0.719 kg/m^3), an emission factor of 0.0559 kg CO2/MJ, and a steam generator efficiency of 0.9.
- Scenario 3: Waste heat at temperatures of 100 °C and above possesses relatively high quality and is commonly utilized in various processes. The study explores the potential of enhancing the value of waste heat at 55 °C through different technologies. It was found that the lowest CO2 emissions can be achieved through direct low-pressure water evaporation followed by steam compression when utilizing waste heat at 55 °C. The technology for increasing the potential of hot water was deemed the most economically viable. Consequently, CO2 emissions were calculated for producing 1 kJ of steam from waste heat at 55 °C across different countries. The calculations for emissions from steam production (emstem_{st}emst) assumed that the electricity required for producing 1 kg of steam via this technology is 661 kJ, while the heat of vaporization of water at 100 °C is 2256 kJ/kg, along with the national electricity CO2 emissions [27].

Calculation water footprint

The water footprint of a product can be calculated in two alternative ways: with the chain-summation approach or the stepwise accumulative approach. The former can be applied for particular cases only; the latter is the generic approach.

The chain-summation approach This approach is simpler than the one that will be discussed next, but can be applied only in the case where a production system produces one output product. In this particular case, the water footprints that can be associated with the various process steps in the production system can all be fully attributed to the product that results from the system. In this simple production system, the water footprint of product p (volume/ mass) is equal to the sum of the relevant process water footprints divided by the production quantity of product p: [volume/mass]

$$WF_{prod}[p] = \frac{\sum_{s=1}^{k} WF_{proc}[s]}{P[p]} \qquad \text{[volume/mass]}$$

In this context, WFproc[s]WF_{\text{proc}}[s]WFproc[s] represents the process water footprint for process step sss (measured in volume/time), while P[p]P[p]P[p] indicates the production quantity of product ppp (measured in mass/time). In reality, straightforward production systems that yield a single output product are quite rare; hence, a more comprehensive accounting method is required. This method must effectively allocate the water usage across various output products from a production system while avoiding any double counting.

The Stepwise Accumulative Approach

This approach offers a versatile framework for calculating a product's water footprint, relying on the water footprints of the input products involved in the final processing step and the process water footprint of that specific step. In scenarios where multiple input products contribute to the production of a single output product, the water footprint of the output can be derived by summing the water footprints of the input products and adding the process water footprint.

Conversely, in cases where a single input product leads to multiple output products, the water footprint of the input must be allocated among the individual output products. This allocation can be achieved proportionally based on the value of the output products. While a distribution based on the weight of the products is also possible, it may be less meaningful.

We want to calculate the water footprint of a product p, which is being processed from y input products. The input products are numbered from i=1 to y. Suppose that processing of the y input products results in z output products. We number the output products from p=1 to z.

If there is some water use involved during processing, the process water footprint is added to the water footprints of the input products before the total is distributed over the various output products. The water footprint of output product p is calculated as:

$$WF_{prod}[p] = \left(WF_{proc}[p] + \sum_{i=1}^{y} \frac{WF_{prod}[i]}{f_p[p,i]} \right) \times f_v[p] \qquad \text{[volume/mass]}$$

The parameter fp[p,i]f_{p}[p,i]fp[p,i] is known as the 'product fraction', and fv[p]f_{v}[p]fv[p] is referred to as the 'value fraction'; both of these parameters will be defined further below. It is important to note that when utilizing the equation, the process water footprint should be considered in terms of water volume per unit of processed product. If the process water footprint is specified per unit of a particular input product, the corresponding volume must be divided by the product fraction for that input product [7].

6. Results and discussions

6.1 Results

The study evaluated the greenhouse gas (GHG) emissions from the use of water and electricity in cooling towers at two locations—DCMB and Fort Irwin—both with a capacity of 60 refrigeration tons (RT). The primary source of monthly GHG emissions was found to be direct electricity consumption. A detailed breakdown of emissions from electricity use, water evaporation, and wastewater discharge can be found in Sections 8 to 16 of the Supporting Information. Notably, GHG emissions were higher for hygroscopic cooling towers compared to traditional evaporative systems due to increased electricity demand.

For DCMB, the "hygroscopic high" scenario resulted in the highest emissions, while the "hygroscopic low" scenario produced emissions similar to conventional systems. The "hygroscopic composite" scenario had a distinct emission profile. At Fort Irwin, the "hygroscopic high" mode also led to the highest emissions, while the other scenarios aligned more closely with traditional systems. The results indicate that the "hygroscopic composite" mode was more effective in arid climates like Fort Irwin's than in moderate coastal climates such as Monterey Bay. Fort Irwin's greater temperature fluctuations and the energy-intensive process of obtaining water in Southern California contributed to higher GHG emissions compared to Monterey.

To assess the trade-off between water savings and GHG emissions, the study calculated the increase in emissions per gallon of water saved. The "hygroscopic low" mode exhibited the smallest trade-off, while "hygroscopic high" and "hygroscopic composite" modes involved higher emissions. In regions like Fort Irwin, the most aggressive water-saving strategies, such as "hygroscopic high," required significant trade-offs due to increased electricity consumption in the hot, dry climate. Operational scenarios should be chosen based on objectives for water and energy savings, local climate, and regulatory factors. For balancing water conservation and GHG emissions, the "low" mode is generally recommended, except in extremely water-scarce regions, where "high" or "composite" modes might be necessary.

The study also explored water energy intensity, noting that GHG emissions from electricity use far exceeded those from water transportation and treatment. It is unlikely that the use of hygroscopic systems could achieve zero emissions in California’s energy sector due to the current fuel mix. California’s energy grid, however, ranks among the lowest in emissions compared to other U.S. regions. Significant reductions in GHG emissions would require transitioning to low-carbon energy sources.

The analysis also compared direct water usage (evaporation from the HVAC tower) with indirect water consumption (used for electricity generation). Direct water consumption was significantly higher than indirect consumption, but overall, the hygroscopic technology reduced total water use in most cases. However, at Fort Irwin, the technology's water use increased during peak operational months due to high evaporative losses.

The findings underscore the complexity of balancing water savings and GHG emissions, particularly in regions with water shortages.

In Egypt, the analysis of emission factors for electricity generation and natural gas utilization highlights the significant variations in the environmental impacts of different chillers. Each chiller model operates with its own specific emission factor, which ultimately contributes to diverse carbon and water footprints. This diversity is essential for comprehensively understanding how various energy sources affect environmental sustainability. Among the different options available, chillers powered by natural gas exhibit markedly lower carbon and water footprints compared to those using electricity. This difference is particularly relevant when evaluating the ecological consequences of cooling technologies in the region. For each ton of cooling capacity produced, the choice of energy source profoundly influences overall emissions and resource consumption.

The implications of scopes: Consider how focusing only on operational emissions (scope 2) versus considering embodied emissions (scope 3) changes the overall environmental impact. For instance, if your study focuses only on operational energy use, it may underrepresent the impact of refrigerants or the embodied energy in the materials used.

Comparison of GHG emissions from electricity consumption:

The GHG emissions from electricity consumption were evaluated against benchmark values specific to Egypt's energy mix. The results indicate that electricity-related emissions significantly exceed those from water transport and treatment, consistent with the characteristics of Egypt's electricity generation system.

Efficiency analysis of cooling systems:

The findings show that hygroscopic cooling systems require higher energy consumption compared to traditional systems, leading to increased GHG emissions. This aligns with similar studies on the environmental impacts of advanced cooling technologies in Egypt.

Effect of local climate conditions:

The analysis highlights how Egypt's climate, particularly during peak summer months, influences the operational efficiency of cooling systems. Hygroscopic systems showed variable performance depending on water availability and energy consumption.

Recommendations for Future Research:

To overcome these limitations, future studies should consider a broader range of operating conditions, incorporate real-world data from various geographic locations, and explore the inclusion of additional environmental impacts, such as refrigerant management and lifecycle assessments. A more detailed and diverse approach would improve the accuracy and applicability of the findings across different regions and HVAC system types.

Comparison of direct and indirect water consumption:

Direct water consumption (evaporation) was compared to indirect consumption (related to electricity generation), confirming that hygroscopic systems reduce overall water use under most scenarios, aligning with national water conservation benchmarks in Egypt.

Regional factors influencing results:

The study emphasizes the importance of considering Egypt's specific energy mix and water scarcity challenges when evaluating cooling technologies, as these factors significantly influence GHG emissions and water use.

This version tailors the discussion to Egypt, ensuring the focus remains on local conditions and benchmarks.

Below is the carbon and water footprint calculation for gas absorption chiller (1250 RT) and vapor compression chiller (3300 RT)

Table 4: Vapor Compression Chiller Water and Carbon Footprint Calculations:

Vapor Compression								
Scopes	CFP							WFP
	Chiller				Cooling Tower			29.5 m3/hr
	Category	Used	Factor	MT CO2 e	Used	Factor	MT CO2 e	
Scope 1	stationary Freon	2972 kg	79	234788	110	0.425	46.6	
Scope 2	electricity	2154+200+90+315	0.425	1172.6				
Scope 3								
Total	236007							

Table 5: Gas Absorption Chiller Water and Carbon Footprint Calculation:

Gas Absorption								
Scopes	CFP							WFP
	Chiller				Cooling Tower			12.2 m3/hr
	Category	Used	Factor	MT CO2 e	Used	Factor	MT CO2 e	
Scope 1	stationary				55	0.425	23.4	
Scope 2	electricity	157.5+75+110+12	0.425	150.7				
Scope 3	Chemical	7500 kg	3	22500				
	Fuel	283.3 m3/hr	2.04	577.9				
Total 23252								

The graph below illustrates these emission differences, providing a clear visual representation of the distinct profiles associated with each chiller type. By examining this data, we can identify the potential benefits of adopting more sustainable cooling solutions that prioritize lower emissions. Additionally, understanding these differences can guide policymakers and industries toward making informed decisions regarding energy consumption and environmental protection. As Egypt continues to develop its infrastructure and energy policies, the transition to more environmentally friendly technologies will be crucial in mitigating climate change impacts and preserving valuable water resources. Ultimately, the findings emphasize the importance of selecting energy-efficient cooling options that minimize the ecological footprint while meeting the growing demands for cooling in various sectors.

Table 6: Comparison of carbon footprint for Vapor Pressure and Gas Absorption Chillers (1-ton refrigeration)

Chiller	CO_2-eq (kg/hr)
Vapor Pressure	71.5
Gas Absorption	18.6

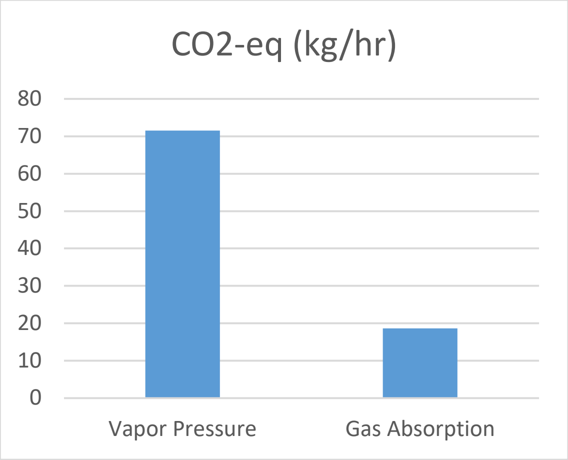


Figure 11: Comparison of carbon footprint for Vapor Pressure and Gas Absorption Chillers (1-ton refrigeration)

Table 7: Comparison of Water footprint for Vapor Pressure and Gas Absorption Chillers (1-ton refrigeration)

Chiller	WF (m3/hr)
Vapor Pressure	29.5
Gas Absorption	12.2

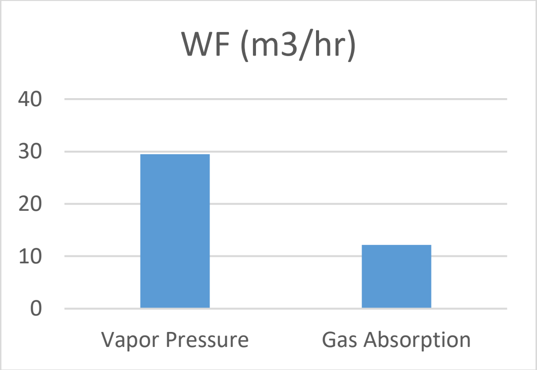


Figure 12: Comparison of Water footprint for Vapor Pressure and Gas Absorption Chillers (1-ton refrigeration)

6.2 Discussions

The energy efficiency of refrigeration systems is the key factor influencing their environmental impact, particularly through the indirect effects associated with energy production. While opting for renewable energy sources can reduce the environmental impact under conditions of similar system energy efficiency, this option remains limited due to the predominant reliance on fossil fuels in the global energy mix (IEA, 2013). For the short to medium term, further technological advancements are necessary to minimize refrigerant leakage, which can be exacerbated by vibrations and the deterioration of piping. A leakage rate of 10% can contribute up to 27% of the life cycle carbon footprint (CF) of a refrigeration system. For example, reducing this leakage rate for R-404A by half could lower the life cycle CF by approximately 21%. Retrofitting the existing R-404A refrigerant in both medium-temperature (MT) and low-temperature (LT) systems could lead to substantial environmental benefits. Specifically, replacing R-404A with R-407F in the analyzed LT system may result in an average increase of 36% in the coefficient of performance (COP) and a reduction of about 14% in $CO2$ equivalent emissions. In the MT system, switching from R-404A to R-410A could yield a 15% increase in average COP and a 23% decrease in emissions. While R-407F is slightly more demanding in terms of environmental conditions related to high leakage rates and set point temperatures, it may be a more viable option compared to R-410A in the MT system. Using the proposed methodology, it has been possible to determine optimal system configurations that would facilitate these environmental improvements without significant changes to the refrigeration plants being analyzed, no additional redesign costs, and the potential for reduced energy consumption and economic savings for end users. International regulations are motivating industry investments in development and driving changes in plant design, alongside the creation of new refrigerants, which are essential for a long-term strategy to mitigate greenhouse gas emissions. However, following the methodology outlined in this study allows original equipment manufacturers (OEMs) to achieve significant technological and environmental enhancements with minimal effort and rapid results. Focusing exclusively on energy efficiency and technical capabilities, or solely on direct emissions and the global warming potential (GWP) of refrigerants, can lead to biased and incomplete evaluations. This study's comprehensive analysis of various life cycle scenarios, along with considerations of refrigerants and devices, provides a holistic view of the environmental impact of refrigeration systems and highlights design and life cycle hotspots. While the findings presented are particularly relevant to small- and medium-sized walk-in refrigeration units, the methodology can be adapted to a range of refrigeration systems and serves as a basis for further comparisons with related equipment.

7. Conclusions

For years, the environmental impact of RACHP systems has been studied, involving diverse stakeholders like suppliers, governments, and manufacturers. Efforts focus on reducing GHG emissions through energy-efficient technologies and low-GWP refrigerants. New regulations aim to accelerate innovation. This study evaluates industry methods like TEWI and LCCP metrics, showing the significant influence of factors such as β (emission factor) and Lannual (annual leakage rate) on outcomes. Despite progress, environmental benefit measurement remains non-standardized.

Global urbanization, rising incomes, and climate change are driving expansion in cooling and refrigeration, especially in developing countries. Cooling services are vital for comfort, vaccine distribution, food waste reduction, and economic productivity, aligning with SDG 7 goals. However, emissions from energy use and refrigerant leaks must be addressed to meet climate targets. Innovative solutions include AI and natural refrigerants, requiring collaboration across sectors to ensure sustainable and equitable cooling access.

Refrigeration has contributed significantly to GHG emissions, but regulations now promote low-GWP fluids and energy-efficient devices. While switching to low-GWP refrigerants can reduce direct emissions, poor system performance may increase indirect emissions. Comprehensive life cycle analyses are necessary to balance these factors. Carbon Footprint Analysis (CFA) evaluates refrigerant-device configurations, revealing energy efficiency as the primary determinant of sustainability, followed by gas leakage and production impacts. Fluorinated gases, when selected carefully, can provide cost-effective medium-term solutions.

Refrigerant evolution—from hydrocarbons to HFOs—highlights ongoing efforts to reduce direct emissions. Yet, enhancing system efficiency with environmentally friendly fluids remains essential. Minimal system modifications can yield significant sustainability gains. In Egypt, natural gas-powered chillers have lower carbon and water footprints than electric ones, emphasizing the importance of energy sources. Further research is crucial for long-term strategies and improving refrigeration efficiency.

Table 8: Comparison of carbon footprint for Vapor Pressure and Gas Absorption Chillers with (3000 ton)

Chiller	CO_2-eq (kg/yr)
Vapor Pressure	214500
Gas Absorption	55800

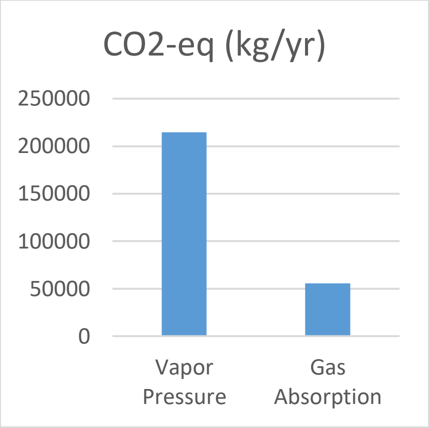


Figure 13: Comparison of carbon footprint for Vapor Pressure and Gas Absorption Chillers with (3000 ton)

Table 9: Comparison of Water footprint for Vapor Pressure and Gas Absorption Chillers (3000 ton)

Chiller	WF (m3/yr)
Vapor Pressure	88500
Gas Absorption	36600

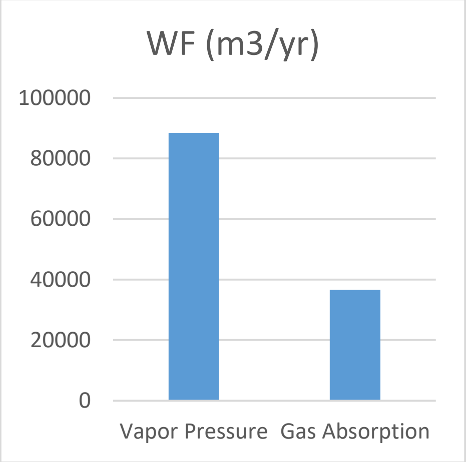


Figure 14: Comparison of Water footprint for Vapor Pressure and Gas Absorption Chillers (3000 ton)

8. Conflicts of interest

I, Ahmad Qasem Abdelhamid Abdelkhalik, a student in the Master of Environmental Engineering Sciences program at Ain Shams University, declare that there are no conflicts of interest related to the research presented in this master's thesis titled "water and carbon footprint for different technologies of HVAC systems (vapor compression and gas absorption)"

I confirm that I have not engaged in any activities or maintained any personal or professional relationships that could affect the objectivity of this research. I have not received any funding or support from any entity that has an interest in the outcomes of this study. Furthermore, I do not have any financial, commercial, or personal relationships with any individual or organization that could influence the integrity of this research.

I am committed to upholding the highest standards of integrity and objectivity in conducting this research and aim to present accurate and reliable results that contribute to the advancement of knowledge in this field.

By signing this statement, I affirm the accuracy of the information provided and confirm that there are no conflicts of interest.

9. Acknowledgments

I want to sincerely thank and appreciate my Supervisors. I have had the privilege of studying under their direction and receiving instruction in a manner that upholds my dignity and humanity. I would also like to express my gratitude to Gas Cool Staff for their unwavering assistance during this research project.

10. References

[1] Adrian Mota-Babiloni, Jader R. Barbosa Jr., Pavel Makhnatch, Jaime A. Lozano, (2020): Assessment of the utilization of equivalent warming impact metrics in refrigeration, air conditioning and heat pump systems, https://http//www.elsevier.com/locate/rser
[2] Aik Jong Tan, Darin W. Nutter, (2011): CO2e emissions from HVAC equipment and lifetime operation for common U.S. building types, www.IJEE.IEEFoundation.org
[3] Alessandro Cascini, Mauro Gamberi, Cristina Mora, Michele Rosano, Marco Bortolini, (2016): Comparative Carbon Footprint Assessment of commercial walk-in refrigeration systems under different use configurations, https://www.elsevier.com/locate/jclepro
[4] Ali Habib, (2022): Electricity Sector's Emissions: Problems and Potential Solutions, https://aps.aucegypt.edu/en
[5] American Petroleum Institute- API, (2021): Compendium of Greenhouse Gas Emissions Methodologies for the Natural Gas and Oil Industry
[6] Andr´es Rodríguez-Toscano, Carlos Amaris, Alexis Sagastume-Guti´errez, Mahmoud Bourouis, (2022): Technical, environmental, and economic evaluation of a solar/gas driven absorption chiller for shopping malls in the Caribbean region of Colombia, https://www.elsevier.com/locate/csite

[7] Arjen Y. Hoekstra, Ashok K. Chapagain, Maite M. Aldaya and Mesfin M. Mekonnen, (2011): The Water Footprint Assessment Manual

[8] Benjamin Mitterrutzner, Claudio Zandonella Callegher, Riccardo Fraboni, Eric Wilczynski, Simon Pezzutto, (2023): Review of heating and cooling technologies for buildings: A techno-economic case study of eleven European countries, http://www.elsevier.com/locate/energy

[9] Chima Cyril Hampo , Hamdan Haji Ya, Mohd Amin Abd Majid, Ainul Akmar Mokhtar, Ambagaha Hewage Dona Kalpani Rasangika and Musa Muhammed, (2021): Life Cycle Assessment of a Vapor Compression Cooling System Integrated within a District Cooling Plant, https://www.mdpi.com/2071-1050/13/21/11940

[10] Christina Kiamili, Alexander Hollberg and Guillaume Habert, (2020): Detailed Assessment of Embodied Carbon of HVAC Systems for a New Office Building Based on BIM, https://www.mdpi.com/journal/sustainability

[11] Darkwah Williams Kweku1,2*, Odum Bismark3, Addae Maxwell4, Koomson Ato Desmond2, Kwakye Benjamin Danso5, Ewurabena Asante Oti-Mensah4, Asenso Theophilus Quachie5 and Buanya Beryl Adormaa, (2018): Greenhouse Effect: Greenhouse Gases and Their Impact on Global Warming

[12] Department for Energy Security & Net Zero and Department for Environment Food & Rural Affairs, (2022): UK Government GHG Conversion Factors for Company Reporting

[13] Environmental management — Life cycle assessment — Principles and framework, (2006): ISO 14040

[14] Environmental management — Life cycle assessment — Requirements and guidelines, (2006): ISO 14044

[15] Greenhouse gases Carbon footprint of products Requirements and guidelines for quantification, (2018): ISO 14067

[16] Jaafar Younes, Minzhou Chen, Kamel Ghali, Risto Kosonen, Arsen Krikor Melikov, Azin Velashjerdi Farahani, Simo Kilpeläinen, Nesreen Ghaddar, (2023): Enhancing sustainability and resilience of elderly dwellings: Optimized refurbishing parameters and air conditioning operation, http://www.elsevier.com/locate/enb

[17] Jason Woods, Nelson James, Eric Kozubal, Eric Bonnema, Kristin Brief, Liz Voeller, and Jessy Rivest, (2022): Humidity's impact on greenhouse gas emissions from air conditioning, https://doi.org/10.1016/j.joule.2022.02.013

[18] Jenni Nugent, Scott M. Lux, Christopher Martin, Ashlynn S. Stillwell, (2022): A water and greenhouse gas inventory for hygroscopic building-scale cooling tower operations, www.elsevier.com/locate/buildenv

[19] Junzhang Wu, Guanghai Liu, Alessandro Marson, Andrea Fedele, Antonio Scipioni, Alessandro Manzardo, (2022): Mitigating environmental burden of the refrigerated transportation sector: Carbon footprint comparisons of commonly used refrigeration systems and alternative cold storage systems

[20] Justo García-Sanz-Calcedo, Nuno de Sousa Neves, Jo~ao Paulo Almeida Fernandes, (2021): Measurement of embodied carbon and energy of HVAC facilities in healthcare centers, https://www.elsevier.com/locate/jclepro

[21] LG, (2020): Absorption Chiller Manual, http://www.lgeaircon.com/

[22] M.M. Mekonnen A.Y. Hoekstra, (2010): The green, blue and grey water footprint of crops and derived crop products

[23] Manuel C. Felgueiras, Rute Santos, Luís M. Fonseca, and Nídia S. Caetano, (2016): Buildings Sustainability: The HVAC Contribution,

[24] MARIA HEIN, (2020): The carbon footprint caused by the oversizing of building service systems

[25] Maurizio Santin, Damiana Chinese, Onorio Saro, Alessandra De Angelis and Alberto Zugliano, (2019), Carbon and Water Footprint of Energy Saving Options for the Air Conditioning of Electric Cabins at Industrial Sites, https://www.mdpi.com/journal/energies

[26] Mona Mohamed Abd Elhamid, Monika Heckova, Marina Stramarko, (2022): Assessment of embodied carbon of ventilation systems and their components in educational and office buildings

[27] Nader R. Ammara, Ibrahim S. Seddiek, (2018): Thermodynamic, environmental and economic analysis of absorption air conditioning unit for emissions reduction onboard passenger ships, https://www.elsevier.com/locate/trd

[28] Nilofar Asim, Marzieh Badiei, Masita Mohammad, Halim Razali, Armin Rajabi, Lim Chin Haw and Mariyam Jameelah Ghazali, (2021): Sustainability of Heating, Ventilation and Air-Conditioning (HVAC) Systems in Buildings—An Overview, https://doi.org/10.3390/ijerph19021016

[29] Olga Khliyeva, Kostyantyn Shestopalov, Volodymyr Ierin, Vitaly Zhelezny, Guangming Chen, Gao Neng, (2023): Environmental and energy comparative analysis of expediency of heat-driven and electrically-driven refrigerators for air conditioning application, https://www.elsevier.com/locate/apthermeng

[30] Optimized Thermal Systems, Inc, (2020): Estimation of Lifetime CO2 Emissions of Commercial HVAC Equipment through Building Energy Modeling

[31] Rajeanderan Revichandran, Jaffar Syed Mohamed Ali, Moumen Idres, A. K. M. Mohiuddin, (2022): A Review of HVAC System Optimization and Its Effects on Saving Total Energy Utilization of a Building

[32] Rami Mansouri, Baby-Jean Robert Mungyeko Bisulandu and Adrian Ilinca, (2023): Assessing Energy Performance and Environmental Impact of Low GWP Vapor Compression Chilled Water Systems, https://doi.org/10.3390/en16124751

[33] Santosh S. Mali, D.K. Singh, (2019): The water footprint: concept, applications and assessments

[34] Serenella Sala, Alessandra Bianchi, Jean-Christophe Bligny, Faycal Bouraoui, Valentina Castellani, Camillo De Camillis, Sarah Mubareka, Ine Vandecasteele, Marc-Andree Wolf, (2013): Water footprint in the context of sustainability assessment

[35] Sheng Zhang, Paweł Ocło´n, Jiˇrí Jaromír Klemeˇs, Piotr Michorczyk, Kinga Pielichowska, Krzysztof Pielichowski, (2022): Renewable energy systems for building heating, cooling and electricity production with thermal energy storage, https://www.elsevier.com/locate/rser

[36] Specification with guidance at the organization level for quantification and reporting of greenhouse gas emissions and removals, (2018): ISO 14064-1

[37] Specification with guidance at the project level for quantification, monitoring and reporting of greenhouse gas emission reductions or removal enhancements, (2019): ISO 14064-2
[38] Specification with guidance for the verification and validation of greenhouse gas statements, (2019): ISO 14064-3
[39] Thomas Wiedmann, Jan Minx, (2008): A Definition of 'Carbon Footprint'
[40] Trane, (2015): Water Cooled Chiller Manual, https://www.trane.com/index.html
[41] U.S. Environmental Protection Agency-EPA, (2014): EPA Simplified GHG Emissions Calculator, http://www.epa.gov/climateleadership/documents/resources/lowemitter_guidance.pdf
[42] U.S. Environmental Protection Agency-EPA, (2023): Emission Factors for Greenhouse Gas Inventories
[43] United Nations Framework Convention on Climate Change-UNFCCC, (2021): Greenhouse Gas Emissions Calculator
[44] United States Environmental Protection Agency- EPA, (2020): Direct Fugitive Emissions from Refrigeration, Air Conditioning, Fire Suppression, and Industrial Gases, https://www.epa.gov/climateleadership
[45] Valerie Eveloy and Dereje S. Ayou, (2019): Sustainable District Cooling Systems: Status, Challenges, and Future Opportunities, with Emphasis on Cooling-Dominated Regions, https://www.mdpi.com/1996-1073/12/2/235
[46] Yabin Dong, Marney Coleman, and Shelie A. Miller, (2021): Greenhouse Gas Emissions from Air Conditioning and Refrigeration Service Expansion in Developing Countries