

**beyond  
the flaws  
of GWP  
metrics.**

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## BEYOND THE FLAWS OF GWP METRICS

### ***The Chemical Isn't the Problem – It's how we measure them.***

The Global Warming Potential (GWP) metric is intended to stand as a beacon, guiding our understanding of how greenhouse gases contribute to the threatening reality of a warming earth. Embedded within this metric lies the foundation of refrigerant rating systems, serving as the primary determinant of a refrigeration system's environmental impact. Yet, beneath this widely accepted framework lies a labyrinth of limitations and omissions that weakens its credibility as a reliable measure.

At its core, the GWP value is intended to quantify the effectiveness of a gas in trapping heat in the atmosphere, offering insights about our products and their role in driving climate change. For industries reliant on refrigeration, this metric takes center stage, dictating the selection and classification of refrigerants based on their perceived environmental impact. However, what if the basis of our decision-making process is inherently flawed? What if, by fixating solely on the chemical, we overlook crucial attributes with even more significant environmental impacts?

While well-meaning in its intent, the GWP metric lacks a holistic assessment of a chemical's environmental footprint. It confines its evaluation to a narrow scope, focusing solely on the direct emissions of greenhouse gases over a predetermined timeframe. Yet, the impact of a chemical extends far beyond its potential atmospheric discharge and includes its entire lifecycle. From its manufacturing process, the mechanics and architecture surrounding it during its use, to its potential for recovery and reuse, the true environmental impact of a refrigerant remains shrouded in obscurity.

### **Biased Beginnings**

GWP is measured in tons of CO<sub>2</sub> over a specified number of years – CO<sub>2</sub> equivalent (CO<sub>2</sub>e). It represents the heat that a chemical will trap in the atmosphere compared to the same amount of CO<sub>2</sub> (which has been given a value of 1). While CO<sub>2</sub> serves as the benchmark against which other greenhouse gases are measured, it is misrepresented when referring to refrigerants. While some naturally occurring gases (like CO<sub>2</sub> and ammonia) are often referred to interchangeably with industrially manufactured gases, failing to distinguish between them can create the false impression that certain refrigerants are entirely natural with a negligible environmental impact. All refrigerant-grade gases require rigorous industrial processes to meet purity and performance standards and involve energy consumption, feedstock, and purification processes. They are manufactured products, not simply extracted from nature in usable form.

Due to the omission of industrial manufacturing impacts, incomplete data exposes inherent distortions of the metric. For example, the production methods responsible for refrigerant-grade CO<sub>2</sub> and Ammonia production, such as the energy-intensive Haber-Bosch synthesis process, remain conspicuously absent from its impact assessment. Likewise, the mining/manufacturing processes for elements like fluorine (found in some synthetic refrigerants) are omitted from quantifying environmental impact. Consequently, comparing chemicals based solely on their GWP values yields a faulty narrative.

## Categorizing Greenhouse Gas Emissions

To address pertinent exclusions, greenhouse gases are categorized into Scope 1, 2, and 3 emissions, creating a more comprehensive emissions inventory. Scope 1 emissions, which represent direct emissions, encompass the immediate release of refrigerants into the atmosphere, often due to leaks (throughout operating life or catastrophic release), equipment maintenance, or end-of-life disposal. These emissions are the primary concern of the GWP metric, but they are only the tip of the iceberg and fail to account for the environmental impact of the equipment or its operation.

Power generation is carbon-intensive, and its emissions fall under Scope 2, which includes the indirect emissions from the energy used to power refrigeration systems throughout their lifecycle. Even if refrigerants have a low GWP, the overall carbon footprint may still be substantial, driven by the energy performance of the equipment. Factors such as non-renewable energy sources, refrigerant properties, and system design all influence energy consumption. Therefore, assessing the carbon intensity of the energy powering refrigeration systems is crucial to understanding their full environmental impact.

Scope 3 emissions encompass the broadest range of factors by including all indirect emissions throughout a refrigeration system's lifecycle that are not covered by Scope 2. This extensive category, often overlooked yet critical, can account for 85-90% of total emissions. From production and transportation to distribution, disposal, or recycling, the environmental costs associated with manufacturing refrigerants, equipment, and managing their end-of-life are significant contributors to Scope 3 emissions. These also include emissions generated by suppliers and third-party logistics. Addressing them requires collaboration with supply chain partners, selecting lower-emission materials, and adopting best practices for refrigerant management to minimize environmental impact.

## Alternative Metrics

Understanding the full spectrum of emissions is essential to gain an accurate view of a refrigerant's footprint. The GWP, providing only a partial view of the actual environmental impact, prompted the introduction of alternative metrics like Total Equivalent Warming Impact (TEWI) and Life Cycle Climate Performance (LCCP). These evaluations consider the different categories of GHGs. TEWI is a combination of scope 1 and 2 emissions, while LCCP also includes scope 3 emissions. While these alternatives aim to offer a more comprehensive assessment, they still fall short of providing an accurate evaluation.

TEWI is a methodology for measuring the global warming impact of equipment by accounting for both direct and indirect greenhouse gas emissions. It includes emissions from the release of refrigerants and emissions produced through energy consumption during the equipment's operation. Unlike GWP, TEWI provides a more extensive metric by encompassing both Scope 1 and Scope 2 emissions, reflecting a system's energy use and its direct environmental impact.

TEWI = direct emissions + indirect emissions =  $(GWP \times L \times N) + (Ea \times \beta \times n)$ , where

L – annual leakage rate in the system, kg (3% of refrigerant charge annually),  
 N – life of the system, years (15 years),  
 n – system running time, years (based on weather data, 4910 hours),  
 Ea – energy consumption, kWh per year (modelled for each refrigerant),  
 $\beta$  – carbon dioxide emission factor, CO<sub>2</sub>-eq. emissions per kWh (165 g CO<sub>2</sub>/kWh).

**LCCP** goes beyond TEWI by factoring in direct refrigerant emissions, indirect fossil fuel emissions, and embodied emissions. Embodied emissions cover those generated during component manufacturing, transportation, installation, maintenance, and disposal, offering a more complete picture of a refrigeration system's environmental impact. LCCP also emphasizes the importance of energy consumption during both production and operation, highlighting how indirect emissions contribute to overall climate performance.

LCCP = Direct Emissions + Indirect Emissions

Direct Emissions =  $C \times (L \times ALR + EOL) \times (GWP + Adp. GWP)$

Indirect Emissions =  $L \times AEC \times EM + \sum(m \times MM) + \sum(mr \times RM) + C \times (1 + L \times ALR) \times RFM + C \times (1 - EOL) \times RFD$  where:

C = Refrigerant Charge (kg), L = Average Lifetime of Equipment (yr),  
 ALR = Annual Leakage Rate (% of Refrigerant Charge),  
 EOL = End of Life Refrigerant Leakage (% of Refrigerant Charge),  
 GWP = Global Warming Potential (kg CO<sub>2</sub>e/kg),  
 Adp. GWP = GWP of Atmospheric Degradation Product of the Refrigerant (kg CO<sub>2</sub>e/kg),  
 AEC = Annual Energy Consumption (kWh),  
 EM = CO<sub>2</sub> Produced/kWh (kg CO<sub>2</sub>e/kWh),  
 m = Mass of Unit (kg),  
 MM = CO<sub>2</sub>e Produced/Material (kg CO<sub>2</sub>e/kg),  
 mr = Mass of Recycled Material (kg),  
 RM = CO<sub>2</sub>e Produced/Recycled Material (kg CO<sub>2</sub>e/kg),  
 RFM = Refrigerant Manufacturing Emissions (kg CO<sub>2</sub>e/kg),  
 RFD = Refrigerant Disposal Emissions (kg CO<sub>2</sub>e/kg).

Despite the greater inclusivity of alternative measurements, they come with significant limitations. A key issue is their reliance on GWP, an incomplete metric that carries its deficiencies into any derived calculations, compromising accuracy and reliability. Data limitations—particularly in material manufacturing and the carbon intensity of electric power—poses further challenges. TEWI calculations rely on several assumptions, such as the equipment's performance, usage patterns,

refrigerant characteristics, and electricity generation efficiency. These variables can vary widely based on operating conditions, geographical factors, and technological differences, potentially risking uncertainty in the values calculated. As a result, TEWI assessments are approximations, dependent on these assumptions, which may not fully capture real-world scenarios. Although the LCCP metric is more comprehensive, its complexity has limited its practical application, often fragmenting analyses by specific refrigerants or applications. Consequently, GWP remains the most used metric, despite being the least comprehensive.

The collateral effects of processes are essential in understanding the actual environmental footprint. For instance, overlooking factors such as the consumption of natural resources during the lifecycle of equipment omits an important contribution to environmental impacts. Assessing the effects of all processes is a step forward in eliminating biases from current evaluations and turns the spotlight to the impact of refrigeration system design over the vague values given to refrigerants.

## IMPACT OF SYSTEM DESIGN

### Design assessment is more meaningful than GWP evaluation:

The environmental impact of refrigeration chemicals is undeniable. However, oversights and biased labeling risk inaccurate analysis of refrigeration systems. While assessment strategies have broadened their scope, evaluations must extend beyond the shortsighted fixation on chemical compositions and fragmented comparisons and include the system's dynamics.

The emphasis on chemical analysis has resulted in the neglect of system design and its broader implications which can be major contributors of scope 3 emissions. The full spectrum of effects generated by equipment is more appropriately found by evaluating the intricacies of a system's design and considering how a refrigerant's thermodynamic properties interact within that framework. Each element within a system plays a crucial role in determining its overall impact. This includes the cumulative impacts of engineering processes and the immediate effects of their operation and disposal.

## ENGINEERING IMPACT (*Inputs = footprint*)

A thorough design assessment includes evaluating the origins of components and considering emissions across all production stages. How a system is engineered carries ecological ramifications with as much weight as assessing GWP. The production of components involves various materials and processes, each with its own environmental footprint. Material sourcing can be a significant source of greenhouse gas (GHG) emissions due to the energy-intensive extraction of raw materials and associated ecological disruption. Manufacturing processes, including refining

and transportation, can require high energy and resource use and generate considerable emissions, including carbon dioxide and other pollutants.

## Infrastructure Requirements & Complexities

The environmental impact of infrastructure development demands the strategic choice of components, as complex systems require more inputs, leading to a higher carbon footprint. Streamlining systems by eliminating unnecessary components, developing conscientious designs, and optimizing device layouts can reduce resource usage, emissions, and waste. This involves considering how each part of the system affects overall performance and evaluating its inclusion and benefits.

## Refrigerant Impact on Architecture

Refrigerants have unique characteristics that play a key role in determining components and their quantities, thus shaping system architecture. For example, refrigerants with flammable or toxic properties require specialized components and safety features such as leak detection devices and ventilation systems to prevent health hazards and environmental contamination. Different operating pressures also dictate system requirements; high-pressure refrigerants demand reinforced piping and additional safety features like pressure relief valves, expansion tanks, and emergency shut-off systems, whereas low-pressure systems have fewer requirements. These variations in component design significantly impact system architecture, with some systems necessitating more extensive and complex configurations, which in turn affects their footprint.

## Refrigerant Charge Size

In considering refrigerant sourcing and manufacturing emissions, it's clear that systems requiring larger refrigerant charges contribute correspondingly to environmental impact. The production of refrigerants generates GHG emissions, and the more refrigerant a system needs, the higher these emissions will be. Additionally, systems that require large refrigerant charges often incorporate auxiliary components like large receivers and expansive piping networks to accommodate the increased volume. These larger, more complex systems consume more materials and energy during manufacturing and pose greater risks of refrigerant leaks at joints and junctions. Each connection point in the system is a potential source of leaks, which can lead to direct emissions. Consequently, systems with more extensive piping and numerous connection points have a larger overall environmental footprint.

An example of a common design approach is to adjust the refrigerant charge based on ambient temperatures, as seen in flooded condensers. These systems maintain performance by modulating the refrigerant level to maintain performance across varying conditions. However, this approach often uses more refrigerant than is necessary for heat exchange. The excess refrigerant merely occupies space within the system without contributing to its cooling efficiency, thus increasing the system's environmental impact without tangible benefits. In contrast, floating head pressure

control strategies adjust the condensing pressure setpoint according to the outdoor ambient temperature. By doing so, they maintain optimal performance without requiring additional refrigerant. This method minimizes the refrigerant charge needed for effective operation, reducing the risk of leaks and the environmental impact of refrigerant production and usage. Floating head pressure control systems demonstrate how careful design and control strategies can achieve efficient cooling while reducing environmental harm.

## Sizing Equipment

Careful consideration in sizing equipment to the cooling demand is crucial in engineering refrigeration architecture. Larger refrigeration systems require more materials and energy to manufacture, transport, and install, leading to higher energy and carbon emissions. Complex component arrangements and piping layouts in large systems often necessitate enhanced structural supports and auxiliary equipment. Additionally, longer piping runs can result in inefficiencies, greater heat loss, increased chemical use, and heightened energy consumption. By optimizing the size of the equipment, manufacturers can minimize the number of raw materials and energy consumed, thereby reducing the overall environmental footprint of the system.

Efficient design and appropriately sized equipment ensure that the system operates at its optimal performance levels. Oversized systems tend to cycle on and off more frequently, which can lead to inefficient operation, increased wear and tear, and higher energy consumption. Adequately sized systems run more smoothly and efficiently, using less energy and reducing greenhouse gas emissions.

## Additional Resource Consumption

Consuming additional resources to accommodate system performance requirements is crucial in assessing the environmental impact throughout a system's lifecycle. Every resource utilized in routine operation, maintenance, and disposal contributes to the system's carbon footprint and should be factored into environmental assessments.

Over-specifying components and accommodating refrigerant properties can lead to excessive resource usage, impacting natural resource consumption, especially in systems that rely on water or oil. For instance, CO<sub>2</sub> refrigeration systems often require water or a secondary refrigerant to cool condenser coils effectively, as air alone may not suffice. This additional cooling medium is necessary for effective operation. Still, it increases resource usage, energy consumption, and auxiliary components like water towers. The energy needed to circulate water and maintain temperature further increases the system's total energy use.

Designs that minimize resource consumption will reduce environmental impact throughout the system's entire lifecycle.



## Material Durability & Compatibility

Distinct chemical properties and operating conditions can require different types of material durability. Refrigerant selection demands meticulous consideration of materials to sustain proper function and avoid failures contributing to emissions. Materials must withstand a range of pressures and temperatures without degrading and maintain their integrity and performance under thermal stresses for efficient and long-lasting operation.

Incompatible materials can lead to degradation due to interactions between refrigerants and components such as elastomers, seals, and metals -compromising system integrity. For instance, corrosive refrigerants can hasten component deterioration, causing potential leaks and frequent maintenance or replacement. Repeated part replacements escalate the demand for raw materials and energy, increasing the system's environmental footprint.

## Repairability

The ease with which a component can be fixed or replaced directly influences the environmental impact of system failures. The repairability of equipment extends the system's lifespan by enabling faulty components to be replaced or repaired instead of requiring replacement. It helps to conserve valuable resources by reducing the need for sourcing new parts, consuming raw materials, and the resulting manufacturing impacts. Extending the lifespan of products through repairability contributes to a more circular economy model, where resources are utilized more efficiently, and waste is minimized.

# OPERATIONAL IMPACT

## Energy Consumption

Energy consumption emerges as the most determinative factor for a system's operational impact on the environment. The predominant reliance on non-renewable resources such as coal, oil, and gas for energy production has profound ecological implications. The processes involved in electricity generation take a toll on the environment with extensive consumption and resource depletion. Burning these fossil fuels constitutes the primary cause of climate change, exacerbating global warming and its associated impacts. The energy consumed during operation accounts for a significant portion of a refrigeration system's overall footprint. According to the International Energy Agency, indirect greenhouse gas (GHG) emissions from electricity generation comprise over 70% of total emissions (ASHRAE, 2018). Prioritizing energy-efficient design and implementation strategies is essential in minimizing environmental harm.

## Refrigerant Properties' Impact on Energy Consumption

Refrigerant thermodynamic properties play a key role in determining the performance and efficiency of the system as well as potential environmental stressors. The efficiency of a refrigeration system is often measured using the **Coefficient of Performance (COP)**, which compares the amount of heat removed from the area being cooled to the energy needed to accomplish this.

Different refrigerants have different properties that affect their efficiency. For instance, some refrigerants need more energy to change from a liquid to a gas, while others need less. A refrigerant with a high **latent heat of vaporization** can absorb more heat during evaporation, meaning it can cool more effectively with less refrigerant. This improves efficiency and reduces the risk of leaks and their environmental impact. Similarly, a refrigerant with a higher **specific heat capacity** can absorb more heat for a given temperature change, making it more effective for cooling.

Refrigerants react differently to changes in **ambient temperatures** based on their physical and thermodynamic properties, as well as the design of the refrigeration system. Different refrigerants have varying abilities to conduct heat and respond to temperature changes, affecting their performance in different environments. The relationship between temperature and pressure for different refrigerants is crucial. The boiling and condensing points of refrigerants vary with pressure changes. A refrigerant with a high boiling point may not cool effectively in high temperatures, while one with a low boiling point might not perform well in cold conditions. Refrigerants with good heat transfer properties can maintain efficiency across a range of temperatures. These refrigerants facilitate better heat exchange with the surrounding environment, reducing the workload on the compressor and other system components, which helps lower overall energy consumption.

As the ambient temperature changes, so does the pressure of the refrigerant, impacting the system's efficiency. For example, higher ambient temperatures can increase refrigerant pressure, potentially putting extra strain on system components and increasing energy use. Some systems may experience extreme heat performance drops, while others struggle in cold environments. Platform designs with pressure-driven controls experience precision limitations in extreme conditions. Integrating components like electronic expansion valves and VFD-controlled compressors can accommodate the fluctuation in ambient conditions, significantly improve energy efficiency, and reduce impact.

Understanding the differences between refrigerant properties helps engineers choose the right chemical and manage its behavior to optimize the system's performance and efficiency for various applications and climates.

## Pressures

The operating pressures of refrigerants are crucial in determining a system's components, construction, installation, and overall performance. Higher operating pressures necessitate more robust materials for components, as they increase mechanical stress, leading to potential refrigerant loss, higher maintenance, and a reduced equipment lifespan. These platforms also require additional devices, like relief valves, regulators, and expansion tanks, to accommodate

increased pressures. In contrast, lower operating pressures ease the strain on system components like pipes, valves, and compressors, minimizing direct emissions and extending the equipment's lifespan. This reduction in mechanical stress and required devices also lowers maintenance needs and decreases the environmental impact related to manufacturing and transporting replacement parts.

Additionally, operating pressures significantly influence system efficiency and performance. Refrigerants with higher pressures require more energy for compression, resulting in higher consumption rates and greenhouse gas emissions. Such systems may also need larger, more powerful compressors, further increasing their environmental footprint. Conversely, refrigerants operating at lower pressures use less energy for compression, allowing the compressor to achieve the desired cooling effect more efficiently.

## Compression Ratios

Refrigerant pressures are determined by their specific pressure-temperature characteristics and influence the compression ratio of a system. The compression ratio is the discharge pressure to suction pressure ratio and reflects the workload required to reject heat. As refrigerant pressure increases, suction and discharge pressure rise, resulting in a higher compression ratio. Higher operating pressures generally lead to higher compression ratios, which often results in increased energy consumption, as compressing refrigerant to higher pressures demands more work. Conversely, systems designed for lower-pressure refrigerants tend to have lower compression ratios, reducing the energy required for compression. This reduction in compression ratio is a key strategy for minimizing energy waste and lowering the system's overall environmental footprint. By decreasing the work required by the compressor, these systems operate more efficiently, leading to cost savings and a reduced environmental impact.

Compressors designed for lower compression ratios or those with variable speed capabilities can further optimize performance. Variable speed compressors adjust their operation to match the cooling load, thus operating more efficiently based on actual demand. In contrast, fixed-speed compressors run at maximum output regardless of the system's needs, leading to greater energy consumption. Systems with the ability to vary compressor speed based on demand and conditions can significantly reduce the work required by the compressor, leading to lower energy use and minimized waste.

## Mechanical vs Electronic Controls

The choice of controls in a system's architecture has a major impact on efficiency and environmental impact. Mechanical and analog controls rely on pressures and manual adjustments and are less efficient. They operate on simple on/off protocols based on maximum parameters and lack precision, resulting in higher energy consumption, increased wear and tear, and greater emissions. These systems cannot adapt to changing conditions or monitor the interactions between components, leading to inefficiencies. In contrast, electronic controls and digital integration offer precision and responsiveness. Digital systems use sensors and real-time data to

dynamically adjust parameters, optimizing performance based on current conditions. Electronic controls make fine-tuned adjustments that enhance efficiency and reduce energy consumption by continuously monitoring variables such as temperature, pressure, and load.

Digitally linking components to share real-time data allows each device to adjust based on the performance of others. This interconnected approach ensures consistent and efficient operation. For instance, if one component underperforms, connected devices can compensate. Mechanical systems lack this capability and fail to generate critical performance data, potentially allowing inefficiencies to go unnoticed until a failure occurs. Digital integration improves monitoring and maintenance by facilitating easy data sharing and issue notifications, enabling immediate intervention to prevent poor performance. This optimization reduces energy consumption, minimizes failures, and extends equipment lifespan by lowering the need for replacement parts.

## Zero-Leak Strategy in Design

Direct emissions from refrigeration systems harm the environment primarily due to refrigerant leakage during maintenance, operation, and disposal. Leaks lead to frequent refrigerant top-ups and repairs, increasing resource use for manufacturing, transporting, and disposing of refrigerants and system components. Undetected leaks reduce refrigerant charge, impair system performance, force the system to work harder, and result in higher energy consumption and carbon emissions.

Complex systems with numerous joints and devices are more prone to leaks, often from safety relief valve discharges, ruptured pipes, compromised joints, seals, valves, or vibrations. Each joint or weld represents a potential weak point that can fail over time. Increased pressures and corrosive refrigerants can cause component failures or degradation, especially at connection points, while operational vibrations can exceed material limits. Gases released into the atmosphere require replacement, further exacerbating environmental impacts.

The severity of direct emissions is related to the amount of refrigerant released, emphasizing the need for maintaining system integrity and efficiency. Simpler systems with smaller charge sizes use less refrigerant and have fewer potential leak points, reducing the risk of emissions. Adopting a zero-leak strategy involves refining system architecture, reducing complexity, designing for lower pressures, and integrating monitoring systems for early leak detection and rapid response.

## Recovery, Recyclability

The recoverability and recyclability of refrigerants are crucial for reducing environmental impact. Effective recovery practices ensure refrigerants are contained and managed rather than vented into the atmosphere. Recycling allows refrigerants to be reused, cutting down on the resources and energy required for production, transportation, and disposal, thereby lowering the overall environmental footprint. Recycled refrigerants can be cleaned and processed to remove impurities, making them suitable for use in other systems.

Refrigerants with properties that facilitate easy recovery, such as moderate operating pressures and predictable phase change behaviors, can be recycled more efficiently, reducing their environmental

impact. Considering the significant environmental effects of manufacturing refrigerants, any refrigerant vented into the environment must be included in the system's overall ecological impact evaluation.

The accepted practice of venting CO<sub>2</sub> fails to consider the replacement charge and the fundamental difference between industrially manufactured CO<sub>2</sub> and naturally occurring CO<sub>2</sub>. Industrial CO<sub>2</sub> is specifically processed and purified for refrigeration systems, unlike naturally occurring CO<sub>2</sub>, which is part of the Earth's carbon cycle. Venting industrial CO<sub>2</sub> into the atmosphere disregards the energy and resources expended in its production and purification, thereby ignoring the true environmental cost.

Overall, venting refrigerants ignores the potential for recovery and recycling, which can significantly mitigate environmental impact. Effective recovery practices ensure that refrigerants are contained, managed, and reused, reducing the need for virgin production and minimizing resource use and emissions.

## A BETTER ASSESSMENT

To align systems with environmental objectives, OEMs must prioritize energy efficiency and holistic system design. Focusing on equipment design, including material selection, has a greater impact than simply considering the GWP of chemicals. Addressing Scope 3 emissions offers opportunities to implement effective management strategies and enhance transparency across the value chain, allowing for the identification of high-impact sources and informed decision-making. Every component, from materials to operational efficiencies and recyclability, shapes the environmental and economic footprint of a refrigeration system. Since the GWP metric fails to capture these impacts accurately, selecting systems based on its values is skewed.

The correct assessment of different refrigerants requires acknowledging their complete lifecycle and performance in equipment. Comprehensive metrics that capture the full spectrum of effects associated with the entire system are needed to achieve accurate and unbiased environmental impact assessments. These metrics must go beyond carbon equivalents to incorporate secondary effects and externalities inherent in complex systems. Manufacturers' transparency and accountability are essential for this process. We cannot accurately assess environmental impacts until a governing body uncovers these processes.

Refrigerants marketed as 'natural' or 'environmentally friendly' must undergo rigorous assessments to reveal their complete lifecycle impact. We can only uncover the truth behind marketing rhetoric and make informed decisions regarding refrigeration systems through an unbiased and comprehensive examination. By meticulously analyzing the engineering, manufacturing, operation, and disposal processes, we can uncover opportunities for improvement and minimize our environmental footprint. Ultimately, understanding and addressing the full impact of our systems is essential for moving towards a more sustainable future.

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