Assessment of the utilization of equivalent warming impact metrics in refrigeration, air conditioning and heat pump systems

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Abstract

The refrigeration, air conditioning and heat pump (RACHP) industry is a significant contributor to the climate change through its associated direct and indirect greenhouse gas (GHG) emissions. Several policies and regulations are being approved to control the working fluids used in existing and future installations, but the equivalent environmental benefit is not clear. In works that analyze the operation of environmentally friendly refrigerants in different configurations, various metrics based on different assumptions have been used to calculate the CO_2 equivalent reduction. This work reviews and analyses the environmental metrics used in RACHP systems and the assumptions proposed for their calculation, depending on the application, to promote their inclusion in future works. The peculiarities of each work are discussed together with an interpretation of their main considerations and simplifications. From the literature review and analysis, it is seen that despite the existence of guidelines for the environmental metrics calculation, considerations with notable differences for the same applications are still assumed, even in the case of the Life Cycle Climate Performance (LCCP) metric. Recommendations for the Total Equivalent Warming Impact (TEWI) metric application are provided.

Highlights

- 100-yearGWP is onsidered for the direct contribution of leaked refrigerants.
- TEWI metric has been more widely adopted than LCCP in most of RACHP applications.
- Under many assumptions, conclusions from LCCP and TEWI metrics are comparable.
- Carbon emission factor and annual leakage rate could provide more complete results.
- Uncertainty of TEWI and LCCP metrics is not going to be reduced in the short term.

Keywords

Global Warming Potential (GWP); Total Equivalent Warming Impact (TEWI); Life Cycle Climate Performance (LCCP); greenhouse gas (GHG); sustainability; CO_2 equivalent emissions

Nomenclature

$Adp.GWP$	GWP corresponding to the atmospheric degradation product of a refrigerant ($kgCO_2$-eq)
E_{annual}	annual electricity consumption of the RACHP system (kWh)
L_{annual}	Annual refrigerant leakage (% or kg kW^{-1})
$L_{service}$	Annual refrigerant leakage (% or kg kW^{-1})
$L_{accident}$	Annual refrigerant leakage (% or kg kW^{-1})
m	mass of the refrigerant (kg)
m_{unit}	mass of the RACHP unit (kg)
m_r	mass of the RACHP recycled materials (kg)
MM	emissions per kg of material in the RACHP unit ($kgCO_2$-eq kg^{-1})
n	lifetime operation (years)
RFD	emissions associated to the refrigerant manufacturing ($kgCO_2$-eq kg^{-1})
RFM	emissions associated to the refrigerant disposal ($kgCO_2$-eq kg^{-1})
RM	emissions per kg of recycled material in the RACHP unit ($kgCO_2$-eq kg^{-1})

Greek

α_{rec}	refrigerant recovered at the EOL (%)
β	carbon emission factor ($kgCO_2$-eq kWh^{-1})

Subscripts

20, 100, 500	20-, 100- and 500-years' time horizon

Abbreviations

AIRAH	The Australian Institute of Refrigeration Air conditioning and Heating
CFA	Carbon Footprint Assessment
CFC	chlorofluorocarbon
COP	coefficient of performance
CO_2-eq	carbon dioxide equivalent
DE	direct CO_2-eq emissions
DX	direct expansion
EOL	end of life
EU	The European Union
GHG	greenhouse gas
GTP	Global Temperature change Potential
GWP	Global Warming Potential
HCFC	hydrochlorofluorocarbons
HFC	hydrofluorocarbons
HFO	Hydrofluoroolefin
HPS	Simultaneous heating and cooling
HS	high stage

HT	high temperature
IE	indirect CO_2-eq emissions
IHX	internal heat exchanger
IIR	The International Institute of Refrigeration
IPCC	Intergovernmental Panel on Climate Change
IX	indirect expansion
LCA	Life Cycle Assessment
LCCP	Life Cycle Climate Performance
LNG	liquified natural gas
LPG	liquified petroleum gas
LT	low temperature
LS	low stage
MAC	mobile air conditioning/conditioner
MP	Multiplex system
MSC	mechanical subcooling circuit
MT	medium temperature
n.c.	not considered
RACHP	refrigeration, air conditioning and heat pump
SEER	Seasonal Energy Efficiency Ratio
TE	total CO_2-eq emissions
TEWI	Total Equivalent Warming Impact (kgCO_2-eq)
WLSC	Water-Loop Self-Contained systems

1. Introduction

The past five years collectively have been reported to be the warmest ones in the modern record [1]. The observed climate change is a result of the manmade emissions of greenhouse gases (GHGs) that contribute to the mean global surface temperature change [2]. For instance, the United States Environmental Protection Agency estimates that the global GHG emissions in the refrigeration, air conditioning and heat pump (RACHP) sector are going to pass from 349 MtCO_2-eq (carbon dioxide equivalent) in 2010 to 1596 MtCO_2-eq in 2030 [3]. The International Institute of Refrigeration (IIR) agreed with the influence of the RACHP sector on climate change and indicated that 7.8% of the 2014 CO_2-eq emissions corresponded to this sector, whose related emissions caused 12% of the global radiative forcing [4].

A global agreement was reached in 2015 to hold the increase in the global average temperature to well below 2 °C above pre-industrial levels with an ambition to limit the increase to 1.5 °C by 2100 [5]. This measure requires the RACHP sector to contribute by transitioning to cooling and heating systems with a minimum contribution to climate change and therefore, more sustainable. The total CO_2-eq emissions (TE) of RACHP systems are divided into direct emissions (DE), and indirect emissions (IE). They are mainly caused by refrigerants accidental leakage and fossil fuel consumption to produce the electricity required, respectively.

Taking into account the worldwide growing global demand for cooling and the expected increase in the number of units in operation [6], the TE associated to the cooling technology is projected to grow, even considering the technical improvements across major cooling sectors [7]. At the conditions of growing global demand for RACHP applications, TE reduction can be achieved by significantly reducing both the DE and IE GHG emissions of RACHP systems [6].

RACHP DE are partly addressed by the recent Kigali Amendment to the Montreal Protocol [8], which controls the production and consumption of fluorinated substances, including many currently used refrigerants with high Global Warming Potential (GWP). Therefore, new refrigerant alternatives have been developed to substitute currently used hydrofluorocarbons (HFC) as well as still existing hydrochlorofluorocarbons (HCFC) and chlorofluorocarbons (CFC). New alternatives reduce the amount of DE, but they can also vary the IE through their influence on system efficiency. Since more than 80% of the global climate impact of RACHP systems is associated with IE [9], more advanced configurations and components are being proposed for the traditional vapor compression systems.

As a consequence of this transition, terms like "ecological" [10], "sustainable" [11], "low(er) GWP alternatives" [12], "natural refrigerants" [13] or "energy-efficient" [14]" are becoming increasingly popular in a multitude of the scientific papers published in this sector. The quantification of the equivalent environmental benefit produced by the new concept or system modification is not an easy task, and several metrics have been proposed in the last decades. The application of these environmental metrics requires assumptions and decisions, usually not normalized in the RACHP sector. This fact produces a higher uncertainty associated with the calculation of the resulting CO_2-eq emitted in the lifetime of the application, and most authors decline to consider it in their studies. This work reviews the scientific papers that have considered environmental metrics and have quantified the equivalent warming impact of the new proposed concepts. This work aims to promote the utilization of these metrics in future studies considering their particularities and to make the results comparable between them.

2. Environmental metrics in the RACHP sector

2.1. Global Warming Potential (GWP)

The Global Warming Potential (GWP) integrates the radiative forcing of a substance over a chosen time horizon, relative to that of CO_2 [15]. The GWP is commonly used in RACHP policies to calculate limits and quotas of fluorinated gases [8,16] or tax rates on certain GHGs [17]. The Global Temperature change Potential (GTP) is another metric defined as the ratio of change in global mean surface temperature from a substance relative to that from CO_2 at a chosen point in time [15].

The most commonly proposed time horizons are 20 (for short evaluations and decisions), 100 (for potential analyses) and 500 years (long-term scenario) [18]. While the GWP and GTP values for CO_2 are constant (unity), because it is taken as reference, the values of other GHG substances vary with different time horizons. Additionally, these values are regularly updated to incorporate changes in scientific understanding of the involved processes as well as to incorporate changes in the atmospheric concentration of CO_2.

GWP does not differentiate the radiative forcing for each year up to the time horizon, whereas GTP only considers the selected year. A gas with an atmospheric lifetime less than a few decades usually has a GTP_{100} much lower than GWP_{100}, and the contrary happens when the lifetime of the gas is more than 250 years [19]. The difference between both parameters is such that the share in historical GHG emissions from countries would be modified if GTP_{100} was used instead of GWP_{100}. In that case, countries with the highest methane emissions (such as China, Brazil and Australia) would reduce their calculated contribution to climate change, being increased for other countries such as the USA, Japan and the European Union (EU) [20].

The most recent GWP and GTP values are reported by the World Meteorological Organization, but the values listed in the Fifth Assessment Report of the Intergovernmental Panel on Climate Change (IPCC) are often used as well by policymakers and non-profit organizations. However, the 2007 IPCC values [21] are adopted in important legislation like the F-gas Regulation [22] and the Montreal Protocol (with the Kigali Amendment [8]), responsible for implementing the GWP metric for comparing emissions of different GHGs at a common "CO_2 equivalent" scale.

The uncertainty range of listed GWP and GTP values depends on the lifetime of the gas. Thus, the GWP_{100} uncertainty is of the order of ±30% for gases with lifetimes of a century or more, ±35% in the case of a few decades, and even higher for shorter-lived gases (the GWP_{20} uncertainty is between ±5 and ±10% lower). Moreover, uncertainties associated with GTP are greater than GWP because GTP includes more physical processes for which little information is available [19]. The GTP_{100} uncertainty is approximately ±75% for a short-lived gas such as methane. However, some studies are being carried out to improve the accuracy of the GTP as metric to assess the long-term global effects of HFC emissions [23,24] or to adapt it to environmental policies [25]. For the moment, the IPCC provides GWP and GTP values without the inclusion of climate-carbon feedbacks, which would increase their final values [15].

Refrigerant families traditionally used in RACHP systems (i.e. CFC, HCFC and HFC) present relatively high GWP values. In terms of their climate impact, this only becomes relevant when these refrigerants end up being accidentally leaked, but unfortunately, this situation is still common today. The utilization of a lower GWP refrigerant is proposed as a solution, but the system energy consumption can be increased (along with the IE), and it would have a negative impact on the TE [26,27]. Total Equivalent Warming Impact (TEWI) metric can be used to consider the combined effect of the variation in both types of emissions at the same time.

2.2. Total Equivalent Warming Impact (TEWI)

The TEWI considers simultaneously the GHG emissions caused by the accidental refrigerant leakages (DE) and those caused by electricity consumption during the system operation (IE). The TEWI concept was originally developed by the US Department of Energy and Oak Ridge National Laboratories and was presented to the international community in the 1992 Copenhagen Follow-Up Conference to the Montreal Protocol [28].

The TEWI is recommended as a comparative index of global warming impacts for different options of a specific application [29]. The Australian Institute of Refrigeration Air conditioning and Heating (AIRAH) published in 2012 a complete standardized method for the TEWI in different types of RACHP systems [30]. The TEWI of a RACHP system is included in the EN 378–1:2016 standard and calculated as [31]:

$$TEWI = \left(GWP * m * L_{annual} * n + GWP * m * (1 - \alpha_{rec})\right) + (E_{annual} * \beta * n) \qquad (1)$$

where m is the mass of refrigerant (in kg), L_{annual} is the percentual annual leakage of refrigerant, n is the lifetime of the installation (in years), α_{rec} is the percentage of refrigerant recovered at the end of life (EOL), E_{annual} is the annual electricity consumption (in kWh), and β is the carbon intensity factor (in $kgCO_2$-eq kWh^{-1}).

Makhnatch and Khodabandeh [32] compared the influence of GWP and GTP metrics in the TEWI analysis of a heat pump. When using GWP_{100}, the R-134a TEWI is 16.3% higher than that of R-152a, but considering GTP_{100}, the TEWI increase is reduced by 5.2%. Therefore, R-134a TEWI could be lower than that of theoretically environmentally friendly refrigerants such as R-32 or R-1234yf, as shown in Figure 1. According to Fischer [33], TEWI shows a better approximation to the TE caused by the RACHP systems when the time horizon is significantly long in comparison to the system lifetime (GWP_{100} or GWP_{500} for a lifetime of 15 years).

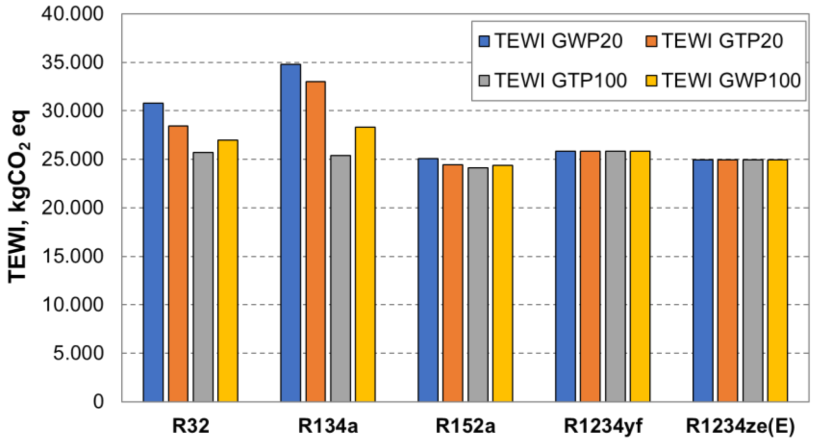


Figure 1. Influence of time horizon in GWP and GTP used in TEWI calculation [32].

Purvis et al. [34] highlighted that the debate over the meaning and utility of TEWI is not concluded and despite being a metric with a simple application, it does not the end the controversy over the real warming impact. Other environmental metrics that consider GHG emissions from RACHP similar to TEWI have been proposed by Söğüt [35], but still has not been used by other researchers.

As the TEWI does not account for the entire GHGs associated with RACHP system lifetime, Life Cycle Climate Performance (LCCP) analysis is introduced in the following.

2.3. Life Cycle Climate Performance (LCCP)

The LCCP analysis considers other CO_2-eq emissions not included in the TEWI analysis [36], as shown in Figure 2. LCCP includes the "cradle-to-grave" GHG emissions, and hence it accounts for energy embodied in the product materials, emissions from chemical manufacturing, EOL disposal of the unit and other minor emission sources. The LCCP metric builds up on the concept of life-cycle warming impact, earlier introduced by Papasavva and Moomaw [37], as they highlighted the relevance of electricity fuel choice and the breakdown products of HCFCs in a domestic refrigeration application.

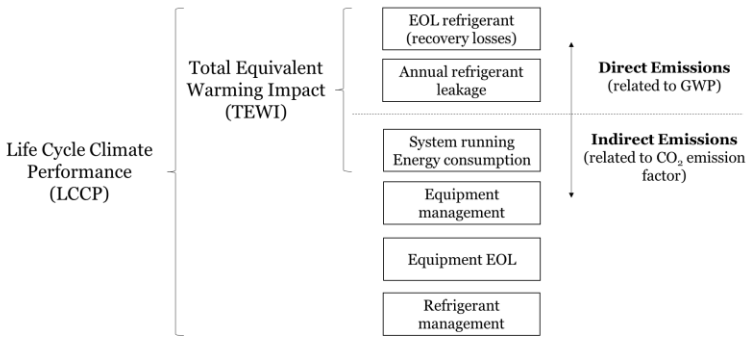


Figure 2. Schematic representation of TEWI and LCCP metrics.

The IIR has shown interest in normalizing LCCP analysis to extend its use in the different RACHP systems. A specific IIR working group was created in 2012, and they published an LCCP Guideline in 2016 [38]. According to the guideline, the LCCP is the sum of the DE and IE contributions of the RACHP systems to the greenhouse gas effect, as shown in Equations (2) and (3). A review of this work and a summary of the main results are available on the IIR website [39]. Moreover, they shared an LCCP calculation tool in 2018 [40].

$$LCCP_{DE} = m * \left(n * L_{annual} + (1 - \alpha_{rec})\right) * (GWP + Adp.GWP) \quad (2)$$

$$LCCP_{IE} = n * E_{annual} * \beta + \sum m_{unit} MM + \sum (m_r * RM) + m * (1 + n * L_{annual}) * RFM + m * (1 - \alpha_{rec}) * RFD \quad (3)$$

In comparison to the calculation of TEWI (Eq. (1)), the additional parameters introduced by LCCP are $Adp.GWP$ (adaptative GWP), that represents the GWP of the atmospheric degradation product of a refrigerant (in $kgCO_2$-eq), m_{unit} and m_r, which are the mass of the unit and the mass of recycled materials (in kg), respectively, MM and RM, that are the emissions associated with the unit and recycled material manufacturing and disposal (in $kgCO_2$-eq kg^{-1}), respectively, and, finally, RFM and RFD, which are the emissions associated with the refrigerant manufacturing and disposal (in $kgCO_2$-eq kg^{-1}), respectively.

In a 30 kW air-to-water heat pump, Makhnatch and Khodabandeh [41] observed that additional parameters accounted in the LCCP such as emissions related to manufacturing and transportation of the system and refrigerant are less relevant than those considered by the TEWI, particularly for lower GWP refrigerants. Then, Makhnatch and Khodabandeh [42] have observed that the parameters L_{annual}, n and β have a significant contribution to the LCCP value and uncertainty of a heat pump. Despite the low β in Sweden, the IE were more relevant than DE, and material manufacturing was the only slightly relevant emissions added by the LCCP analysis, in comparison with the TEWI. This work has been complemented by Boström and Ljungberg [43], who proved that the additional LCCP parameters had a negligible influence on the outcome sensitivity analysis.

LCCP considers CO_2-eq emissions as the only factor contributing to climate change. In turn, Life Cycle Assessment (LCA) can provide a complete picture of all the different environmental impacts of any technology. Additionally, it is being standardized by the ISO 14000 family of standards, and hence its calculation methodology is well developed. LCA software, in combination with different databases facilitates the calculation. It is predicted to become more relevant for RACHP systems in the coming years if not-in-kind technologies are developed to a level in which they can compete with vapor compression systems [44].

2.4. Overview of environmental metrics utilization

In recent years, there is a growing interest in sustainable RACHP systems, as can be seen in Figure 3. Still, despite the apparent simplicity of the TEWI metric, it is not commonly included in the RACHP works that consider the GWP of refrigerants used. Therefore, the higher uncertainty of input data for the LCCP metric makes it even less used than TEWI. LCA concept is more commonly found than TEWI and LCCP, but the works that mention LCA are neither pioneers nor do they provide extensive information about the new environmental technologies.

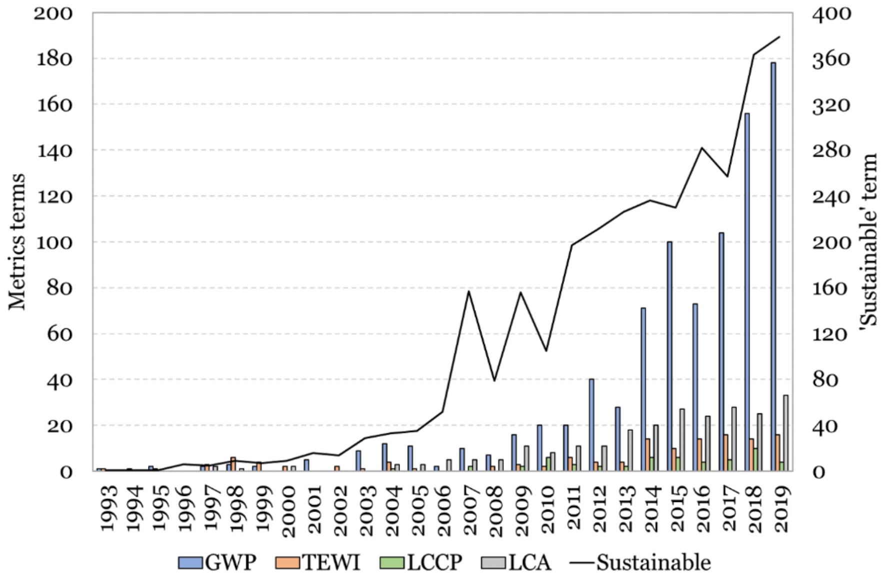


Figure 3. 1997 and ongoing documents found in Scopus (a peer-reviewed literature database) searching the terms mentioned in the vertical axis AND refrigeration OR "heat pump" OR "air conditioning" in the abstract, keywords or title.

In the following, the scientific papers that included TEWI and LCCP analysis are compared. The input parameters and the assumptions made are analyzed. The main findings resulting from this assessment are presented to help the readers to apply these metrics more accurately into future RACHP sustainable works.

3. Studies including TEWI

In the past, works that compared alternative refrigerants have been mostly motivated by replacement of chlorine substances such as CFCs and HCFCs using HFCs [45]. Nowadays, a lower global warming contribution is justified to study the benefits of the fourth generation of refrigerants [46]. This section focuses on works that have considered the TEWI metric to verify the benefits of the new RACHP proposals. It is divided into subsections according to the application and the studies are presented in chronological order.

3.1. Domestic refrigeration

Rasti et al. [47] raised the energy efficiency index of a domestic refrigerator replacing R-134a with R-436A without additional modifications (drop-in replacement). Then, Rasti et al. [48] continued with a modified compressor and included the use of R-600a in a 238 L top-mount freezer refrigerator. R-436A and R-600a resulted in a 16% and 21% lower TEWI than R-134a due to lower energy consumption (especially with the modified compressor), GWP, and m (down to 52.3%). Ghadiri Modarres et al. [49] considered the previous refrigerator (named as case 1 in this paper), and another with greater volume (case 2) for a study of adaptive defrost. The latter decreased the overall system energy consumption and it was able to reduce the TEWI by 12.5% and 5.2% (case 1 and 2, respectively), compared to the baseline method. Consequently, DE became more relevant, especially in the larger model. Raveendran and Sekhar [50] replaced the air-cooled evaporator by a water-cooled model connected to a hot water tank in a R-134a domestic refrigerator. The TEWI was decreased between 5% and 43% because the coefficient of performance (COP) was from 57 to 75% higher, and m lowered down to 16% (more compact condenser). Belman-Flores et al. [51] optimized the m parameter of R-1234yf in a R-134a 300 L top mounted freezer refrigerator with automatic defrost. Tests were performed under the Mexican Norm NOM-015-ENER-2012 and β was based on GEI Program Mexico. Although R-1234yf DE were almost negligible, the TE were 1.1% higher than R-134a.

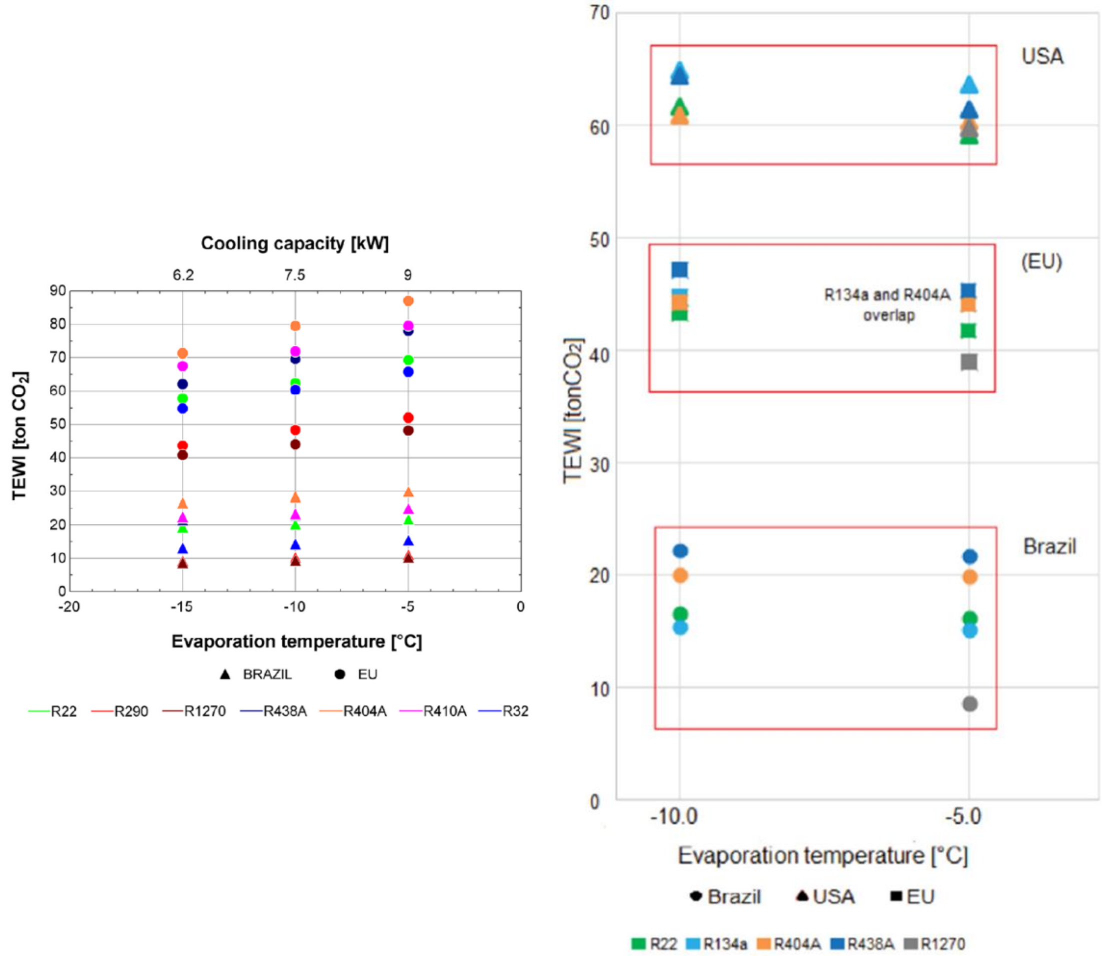
Table 1 summarizes the values selected by the aforementioned works as the input parameters of the TEWI calculation. Some points in common are the optimization of m, 15 years lifetime, not consideration of the refrigerant EOL, and an standardized E_{annual} measurement.

Table 1. Parameters selected for the TEWI evaluation of domestic refrigeration experimental studies.

Reference	Situation	DE Parameters			n, years	IE Parameters		TEWI (%DE), $kgCO_2$
		m, kg	L_{annual}	α_{rec}		E_{annual}, kWh	β, $kgCO_2$ kWh^{-1}	
Rasti et al. [48]	R-134a (original)	0.105	6.6%	n.c.	15	711 (measured)	0.47	5161.0 (2.9%)
	R-436A Modified compressor	0.050				614 (measured)		4329.2 (0.0%)
	R-600a Modified compressor	0.050				577 (measured)		4068.3 (0.0%)
Ghadiri Modarres et al. [49], case 1	Original defrost	0.105	6.6%	n.c.	15	590.67	0.47	4312.7 (3.4%)
	Adaptive defrost					513.86		3771.2 (3.9%)
Raveendran and Sekhar [50], R-134a	Air-cooled (original)	0.135	6.6%	n.c.	15	700.8 (measured)	0.47	5131.76 (3.7%)
	Water-cooled	0.108				511.0 (measured)		3755.45 (4.1%)
Belman-Flores et al. [51]	R-134a	0.1000	2.0%	70%	15	361.35 (measured)	0.49	2733.9 (2.9%)
	R-1234yf	0.0922 (optimized)				375.95		2763.3 (0.0%)

3.2. Stationary refrigeration equipment

Aprea et al. [52] compared a R-744 transcritical cycle and R-134a in a commercial refrigerator cold store, among other systems. They calculated the optimum m that minimizes the TEWI and obtained that the internal heat exchanger (IHX) decreases approximately 3% the TEWI because it improves energy efficiency. A sensitivity analysis of the L_{annual} determined that the R-744 TEWI in this application is higher than that of R-134a in all operating conditions. Antunes and Bandarra Filho [53] tested alternatives to R-22 in a system equipped with a semi-hermetic reciprocating compressor, tube-in-tube heat exchangers and electronic expansion valve. They considered the AIRAH guideline [30] for centralized systems (L_{annual} of 12.5% and α_{rec} of 70%) and optimized the m for each refrigerant. Then, Panato et al. [54] published a second work using an installation with a variable-speed scroll compressor and calculated the E_{annual} through a fixed thermal energy requirement (194.2 kWh per day) and the measured COP. In both works, they proved the great influence of the selected β parameter (significant differences for the case of the USA, the EU and Brazil), and that R-1270 ends up with a lower TEWI than the other refrigerants, especially when β is lower and the energy efficiency becomes less relevant (Figure 4).



a) b)

Figure 4. TEWI results for different countries and refrigerants based on the systems of a) Antunes and Bandarra Filho [53] and Panato et al. [54].

Mendoza-Miranda et al. [55] studied the effect of β from different electricity generation sources [56] on the TEWI of a variable speed liquid chiller, taking most of the assumptions from

Makhnatch and Khodabandeh [41]. The R-1234yf TEWI was 3.5% lower than that of R-134a, but IE were approximately 2% higher than R-134a. Therefore, R-1234yf is benefited from clean energy sources such as nuclear or renewables. Considering the average β for North America, Japan, and Europe (0.47 $kgCO_2$ kWh^{-1}) was a common practice for Söğüt [57]. In the case of 1 kW display cases refrigeration units under constant load, he varied L_{annual} between 3% and 22% and α_{rec} between 0.50% and 0.95% to create different TEWI scenarios.

In stationary refrigeration systems, studying the influence of different β and L_{annual} is a common practice, and TEWI is applied to different types of studies: theoretical, experimental, and simulation based on experimental data.

3.3. Large supermarket refrigeration systems

Kruse [58] concluded that R-717 and hydrocarbons represent a good alternative in terms of TEWI in commercial refrigeration systems. Long refrigerant pipelines of conventional HFC direct expansion (DX) systems require higher m and result in greater L_{annual}. Sharma et al. [59] compared a classical HFC refrigeration system with seven R-744 configurations. They considered different USA regions to study the effect of the ambient temperature in the energy efficiency. This work was a pioneer in the utilization of TEWI in supermarket refrigeration systems with R-744 in different configurations taking an HFC plant as the baseline.

Llopis et al. [60] modeled five 125 kW two-stage refrigeration systems using low-GWP refrigerants. They adopted the TEWI values corresponding to centralized commercial refrigeration from the AIRAH guideline [30] and differentiated United Kingdom) and Athens. Again, the magnitude of DE is almost negligible, and the variation of E_{anual} was entirely reflected in the TEWI. The system with the lowest TE was the R-744 booster with a bypass compressor.

Mylona et al. [61] studied four supermarket configurations for medium temperature (MT) and LT stages simultaneous refrigeration in London. They simulated the E_{annual} using the EnergyPlus model and found that ambient temperatures below 27 °C benefit the transcritical R-744 booster system, Therefore, TEWI emissions dropped by 44% compared to the baseline (caused by a 17.4% E_{annual} reduction). Islam et al. [62] varied the L_{annual} (between 10 and 15%) depending on the operating pressures of the refrigerants. The β of Japan was considered, 0.571 CO_2 kWh^{-1}. They concluded that the R-744 system requires a minimum COP of 1.1 (for LT) and 2.5 (for MT) to have a TEWI comparable to that of a R-134a system.

Makhnatch et al. [63] measured the operation of an indirect MT refrigeration system originally designed for R-404A to study the light R-449A retrofit. The m was adjusted for both refrigerants, and the main TEWI assumptions were extracted from the IIR LCCP guideline [38]. Two values of L_{annual} were considered, 12%, according to the guideline, and 0.4%, as the smallest L_{annual} reported for this type of systems. R-404A TEWI nearly doubled that of R-449A for the higher L_{annual} (DE of R-404A represented 70% of its TE). For the lower L_{annual}, R-449A only presented a 16% reduction of TEWI compared to the baseline. Sawalha et al. [64] studied the HFC substitution in three Swedish supermarkets using data from field measurements, but they did not propose a TEWI analysis until their next work [65]. There, various supermarket refrigeration systems (200 kW for MT, 250 and 35 kW for the high (HS) and low stages (LS) of the cascade system) were proposed considering two locations, Stockholm (Sweden) and Barcelona (Spain). Higher IE were obtained in Spain because of the higher ambient temperature and the value of β (retrieved from the International Energy Agency), which is approximately eight times higher. The TEWI of the HFC refrigeration systems were between two and seven times higher than those for the R-744 solutions, as can be seen in Figure 5.

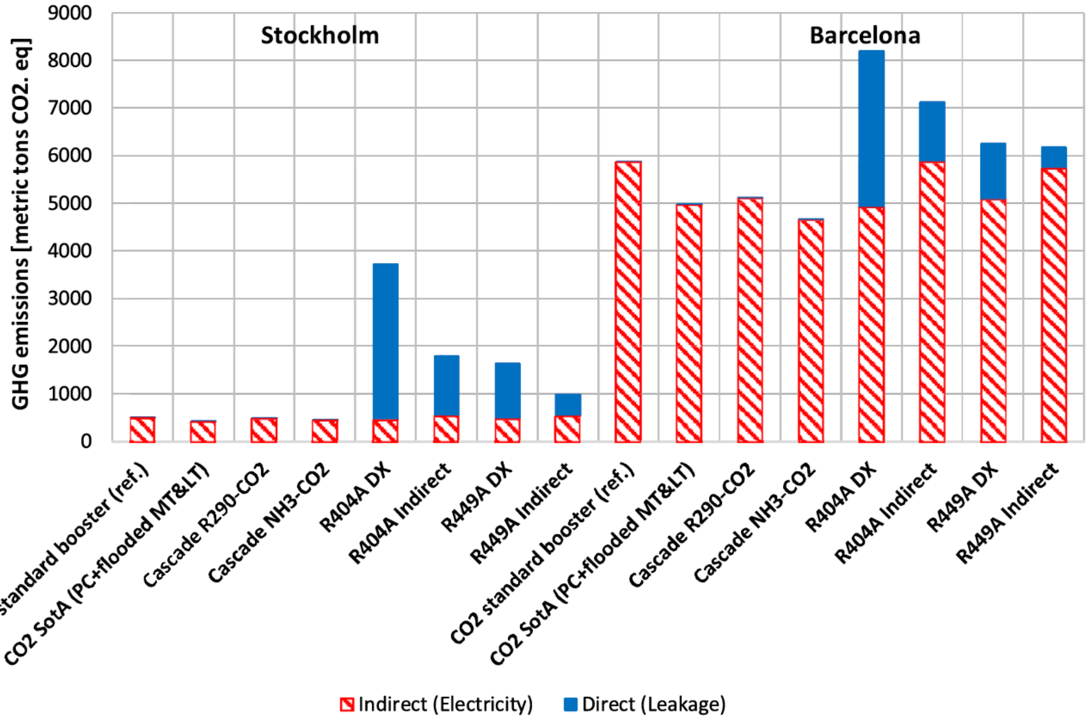


Figure 5. TEWI comparison of different refrigeration systems in Stockholm and Barcelona [65].

Bagarella et al. [66] proposed a water-loop self-contained refrigeration system with variable speed compressors to reduce the TE of a 900 m^2 Italian supermarket with 28 MT and 10 LT cabinets. They conducted a survey and recorded the main parameters of the plant over a year and developed a model. Results were compared with a multiplex compressor rack with fixed and floating suction pressure systems, without replacing the R-404A refrigerant. The new system required a much lower m and the E_{anual} was reduced. Consequently, TEWI lowered from approximately 6 to 2.56 MtCO_2-eq, and the DE decreased from between 52 and 54% of the TEWI, to only 4%.

Supermarket refrigeration systems usually apply the TEWI concept to compare very different configuration-refrigerant pairs. Most of the new architectures, especially those using R-744 as a refrigerant, are not considered in TEWI or LCCP guidelines and hence additional assumptions become necessary. As a major part of the research is based on theoretical calculations and simulations, the m value cannot be optimized for the new situation, but this is almost irrelevant if the refrigerant has a very low GWP. Still, contrary to other applications, the L_{annual} is given depending on the refrigeration capacity (in kg per kW) and the evaporation temperature (MT or LT) instead of a fixed percentage. The country is specified for the β, but also the city is relevant for the temperature hourly bin. Because of the great values of m and E_{annual} in supermarket refrigeration, the appropriate selection of the TEWI parameters becomes more relevant for the uncertainty of the final calculations, so this type of systems is more sensitive. A summary of the parameters selected for the TEWI analysis in this application can be found in Table 2. As in some cases it not easy to find all the necessary inputs for the TEWI, the table format is different compared to Table 1.

Table 2. Parameters selected for the TEWI evaluation of commercial refrigeration studies.

Reference	Situation	DE Parameters			n,	IE Parameters
		m	L_{annual}	α_{rec}	years	β, kgCO$_2$ kWh^{-1}
Llopis et al. [60]	R-717, R-1234ze(E), R-290, R-152a, R-134a two-stage: DX with subcooler or flash tank, IX and R-744 cascade	In kg: 500 (DX), 25 (IX), 500 (R-744 and LT)	12.5% (5% machinery room)	n.c.	25	0.241 (Spain)
Gullo et al. [67]	R-134a/R-744 cascade, R-744 booster conventional or with subcooler/parallel compression/ R-290 or R-1270 mechanical subcooling	In kg kW^{-1}: 2 (R-134a), 2 (R-744), 70 (R-290 and R-1240)	15% (R-744), 5% (MSC)	95%	10	0.241 (Spain), 0.720 (Greece)
Tsamos et al. [68]	R-744 booster or cascade with gas bypass or bypass compressor	In kg kW^{-1}: 1.2 (HS and one-stage), 1 (LS)	15%	95%	10	0.72 (Greece) 0.53 (UK)
Mylona et al. [61]	R-404A and R-134a stand-alone, R-134a centralized, R-134a/R-744 cascade, R-744 booster	In kg kW^{-1}: 2 (cabinets, centralized and HS), 1.2 (others)	5% (remote), 15% (others)	95%	10	0.53 (UK)
Islam et al. [62]	Two-stage and cascade: R-134a and R-507A	2 kg kW^{-1}	10% (R-134a), 47% (R-507A), 15% (R-744A)	n.c.	n.c.	0.571 (Japan)
Karampour and Sawalha [65]	R-744 booster, flooded, R-290 or R717/R-744, R-404A or R-449A DX or IX	In kg kW^{-1}: 3 (R-744 MT and LT, and IX LT), 0.75 (HS cascade), 4 (LS cascade and DX LT), 2 (DX MT), and 1 (IX MT)	10% (DX), 5% (IX)	95%	15	0.079 (Sweden), 0.639 (Spain)
Bagarella et al. [66]	R-404A multiplex compressor rack with fixed and floating suction pressure systems (MP) and water-loop self-contained	In kg: 322 (MP), 76 (WLSC)	20% (MP), 3% (WLSC)	n.c.	15 years	0.65 (Italy)[1]

	(WLSC) with modulating compressors					

3.4. Self-contained and low capacity refrigeration systems

Makhnatch et al. [69] adapted the LCCP guideline [38] to perform the TEWI analysis in small capacity refrigeration systems for high ambient temperatures. Although m was optimized at intermediate operating conditions, it represented a small share of the TEWI. Moreover, they normalized the TEWI to the cooling capacity of the respective refrigerant, which penalizes the refrigerants with lower values. Therefore, R-450A passed from being the best option for standard TEWI to the worst refrigerant for normalized TEWI. López-Belchí [70] used conclusions from an experimental mini-channel condenser assessment at high ambient temperatures for determining the TEWI of R-134a, R-450A and R-513A. He produced a figure to minimum possible carbon emission contribution at different cooling capacities (0.3 to 0.9 kW) and carbon emission factors (0 to 2 $kgCO_2\ kWh^{-1}$).

Despite the availability of standards to test self-contained (or small) systems, the possibility of using climate chambers, and the low uncertainty in L_{annual}, TEWI is not commonly considered for this application. This is possibly caused by the small share of refrigerant losses that can make the TE comparable with the IE.

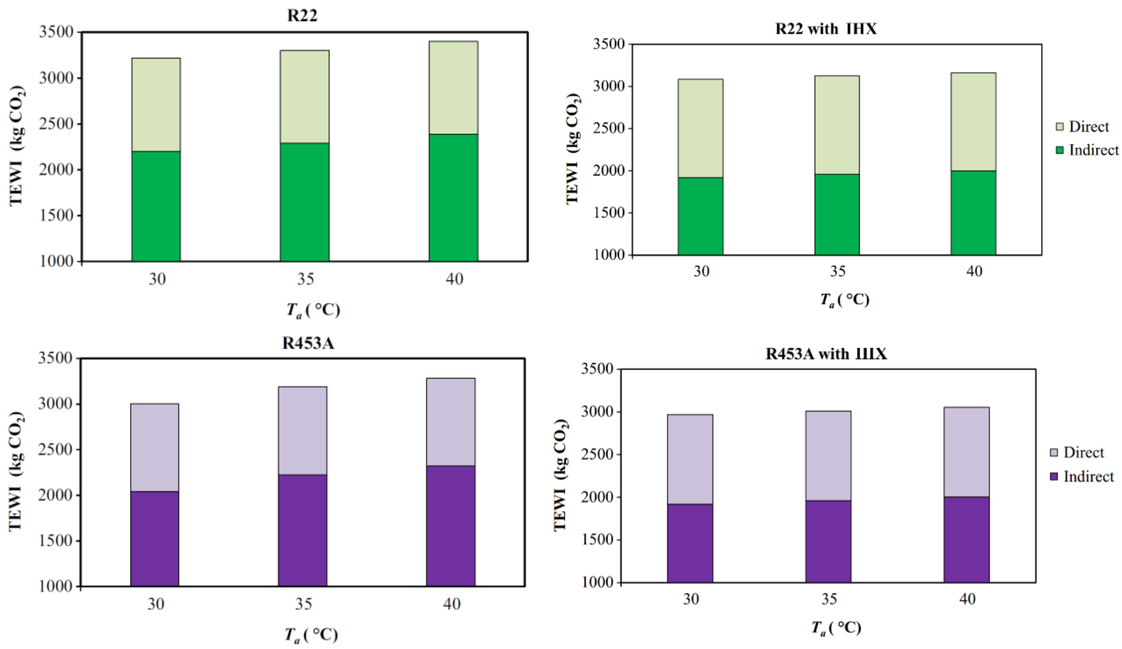
3.5. Heat pumps and air conditioning for space cooling and heating

Byrne et al. [71] simulated a heat pump for simultaneous heating and cooling (HPS) of a 45-bedroom hotel in France. DE of R-407C represents 9% of the TEWI (95 tCO_2-eq), and therefore the utilization of R-744 reduced the final value of the latter. Moreover, the authors proposed a more energy efficient system which required additional components (variable volume receiver, secondary condenser, and subcooler at high pressure) that increases m.

Izquierdo et al. [72] studied summer peak and seasonal electricity consumption for residential air conditioning in the region of Madrid (Spain). The outdoor temperature used for the calculations was taken from an onsite weather station. The value of β, 0.4 $kgCO_2\ kWh^{-1}$, was retrieved from a report issued by the Spanish Ministry of the Environment and Rural and Marine Affairs, but those for L_{annual} and α_{rec} were obtained from a report of the Japanese Ministry of Economy, Trade and Industry. The resulting TE for the region was 572 $ktCO_2$-eq (20 years period), being 57% of that corresponding to DE.

Söğüt [73] evaluated 119 different split units sold in the Turkish market through thermodynamic calculations and a modified TEWI metric. In general, the environmental impact of R-410A units was higher than that of R-22, especially in split standing types, and hence another ozone-friendly alternative was needed to replace R-22 different to R-410A. Devecioğlu and Oruç [74] compared R-453A and R-22 in a domestic air-conditioner test bench equipped with IHX. They optimized the m parameter for both refrigerants with and without IHX. E_{annual} was determined for the summer period, and the Turkish β has been adopted, which is equivalent to 0.52 $kgCO_2\ kWh^{-1}$. R-453A TEWI was smaller than R-22 (down to 10.2%). IHX increased m (and hence DE), but the IE saw a greater reduction because of the more significant energy efficiency improvement, as shown in Figure 6.

It is worth tioning that Mateu-Royo et al., [75] proposed to apply the TEWI metric in various high-temperature heat pump applications. For instance, in district heating networks, it can help to determine the carbon emission savings produced by low GWP alternatives to HFC-245fa applying comparable assumptions to other RACHP applications.



a) b)

Figure 6. R-22 and R-453A TEWI results in the work of Devecioğlu and Oruç [74]: a) without IHX and b) using IHX, for different ambient temperatures.

Only a few examples of application of the TEWI metric in domestic air conditioners and heat pumps (included in Table 4 of Section 4.3.) have been found, which may be due to the LCCP metric being more likely to be used since the composition of the components of those systems is more well known. As in the case of supermarkets, the geographical location is very important, as it influences both DE and IE. The TEWI reduction caused by the IHX has been confirmed for refrigerants that improve energy efficiency.

3.6. Other RACHP equipment

This section groups other RACHP applications such as marine refrigeration, train passenger transport, and mobile air conditioners (MAC). Pigani et al. [76] used the AIRAH guideline [30] to study R-717, R-744, R-1234yf and R-1234ze(E) in different configurations for marine refrigeration. They fixed m depending on the temperature level, used β for electricity generated by marine engines, and L_{annual} was the maximum allowed for systems classified as CLEAN-AIR by the Italian Naval Register. The R-717 cascade system with economizer was the most efficient system, with the lowest TEWI. As it happens for other applications, once low-GWP refrigerants are considered, the DE becomes negligible compared to the IE and the attention is turned to the configuration that brings higher energy efficiency.

Mastrullo et al. [77] simulated the dynamic evolution of the internal temperature in a passenger car of a high-speed train. The temperature was controlled by a reversible heat pump and was affected by the ambient temperature, solar radiation, train speed, and the number of passengers. Real trips of the Italian railway line were considered over the year. The TEWI results (calculated for a week) demonstrated that R-1234ze(E) was the best option for the summer, whereas, for winter, the R-134a, R-1234yf and R-1234ze(E) results were comparable. DE of R-134a were only 4%, and for the rest, negligible. TEWI was lower in winter than in summer, as a result of the radiation heat gain and contributions from passengers and auxiliaries.

Andrew Pon Abraham and Mohanraj [78] studied the replacement of R-134a using R-430A in a MAC test setup at high-temperature ambient conditions varying the compressor rotation speed. The TEWI values of R-430A, compared to that of R-134a, were lower by about 47%, 35% and 32% for liquified petroleum gas (LPG), petrol and diesel vehicles, respectively. The near azeotropic behavior of the mixture was valid even in the case of 90% L_{annual}.

Less commonly studied applications, such as transport or marine refrigeration, were found in a lower number of papers dealing with TEWI. In the case of MACs, they directly consider LCCP. Unlike in other previously assessed applications, β of mobile applications are based on the fuel consumption and the engine efficiency and, to follow guidelines, assumptions for other common applications should be made. A summary of the values taken for the TEWI evaluation can be found in Table 3.

Table 3. Parameters selected for the TEWI evaluation of other RACHP studies

Reference	Application	Situation	DE Parameters			n,	IE Parameters
			m, kg	L_{annual}	α_{rec}	years	β, kgCO$_2$ kWh^{-1}
Pigani et al. [76]	Marine refrigeration	R-717, R-744, R-1234yf, R-1234ze(E) basic cycle, IHX, economizer, cascade with economizer or chillers, two-stage with flash tank	200 (MT), 300 (LT), 100 (HVAC)	10%	90%	30	0.8 (marine engines)
Mastrullo et al. [77]	Train reversible heat pump	R-134a, R-1234yf and R-1234ze(E)	11	3%	n.c.	Not found	0.483 (Italy)

Andrew Pon Abraham and Mohanraj [78]	MAC	R-134a and R-430A variable frequency driven	0.350 (R-134a), 0.175 (R-430A)	20%	n.c.	15	0.141 (petrol), 0.149 (diesel), 0.104 (LPG)

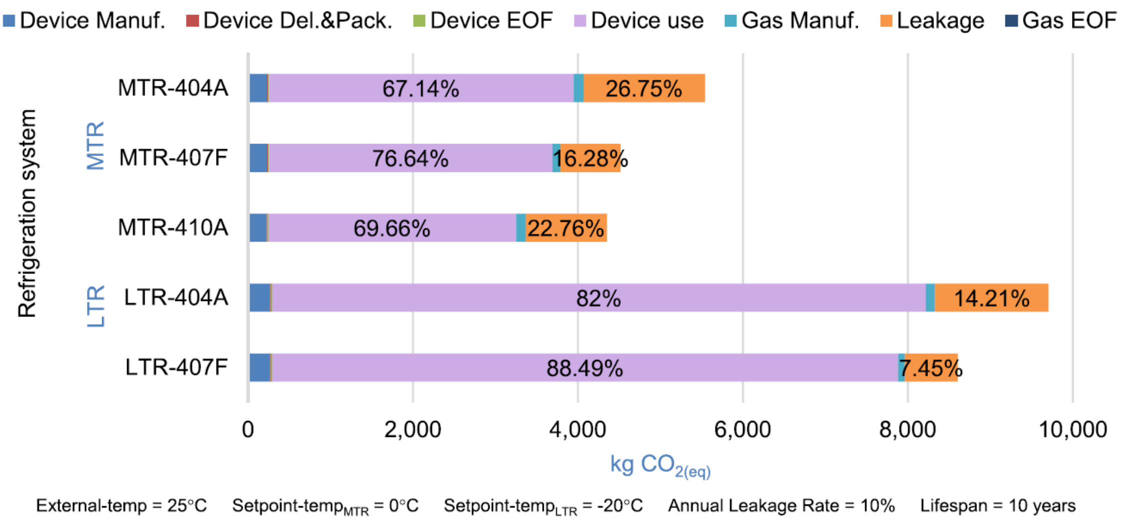
4. Studies including LCCP

4.1. Domestic refrigeration

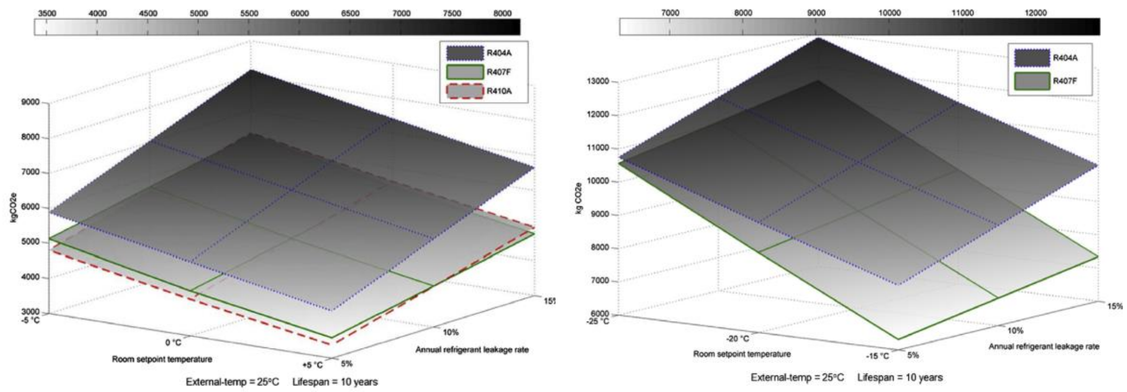
The research group headed by C. Aprea at the University of Salerno, Italy, tested different HFO alternatives to R-134a in domestic refrigeration and applied LCCP analyses using 24-hour test measurements. In Ref. [79], they demonstrated that the R-134a system LCCP DE are four times higher than that calculated with the TEWI. For R-1234ze(E), DE remained below 1% of the TE in both metrics. Then, they considered R-1234yf and R-1234ze(E) and their binary mixtures with R-134a (90/10% wt.) [80]. The lowest LCCP resulted with R-134a/R-1234yf (17% lower than that of R-134a) and if the β of Norway, 0.017 $kgCO_2\ kWh^{-1}$, is considered instead that of Italy, 0.435 $kgCO_2\ kWh^{-1}$, the LCCP emissions of HFOs and mixtures are around 23% lower than that of R-134a. They retrieved the composition of the refrigerator from the Italian waste electrical and electronical standard, and β from the Ecometrica 2011 evaluations [81]. The other parameters were extracted from the IIR LCCP Guideline [38].

4.2. Supermarket refrigeration

Beshr et al. [82] used the EnergyPlus software package to model the hourly load and energy consumption of a 4181 m^2 supermarket considering four refrigeration systems, in six different US climate zones. The annual average temperatures varied from -2.1 (Fairbanks, AK) to 24.9 °C (Miami, FL), and the average hourly β from 0.351 (Los Angeles, CA) to 1.1 $kgCO_2\ kWh^{-1}$ (Albuquerque, NM). The transcritical R-744 booster system had the lowest LCCP TE. A sensitivity analysis revealed that β has a greater influence for lower GWP refrigerants and m for regions with smaller β. Selected L_{annual} shows the benefits of using a secondary circuit R-448A/L-40 system in different climates. They also provided uncertainties for the parameters considered and the final LCCP values. Cascini et al. [83] applied a streamlined version of LCA methodology, the Carbon Footprint Assessment (CFA), to different alternatives to R-404A in MT and LT commercial walk-in refrigeration systems. The critical parameter for the CFA using HFCs is the E_{annual} (directly influenced by the system COP), followed by the L_{annual}, and finally, by MM, RM, RFD and RFM. For LT, R-407F reduced up to 14% the TE and, for MT, the result depended on the selected setpoint temperature and L_{annual}, as can be seen in Figure 7.



a)



b)

Figure 7. CFA results of Cascini et al. [83]: a) at different evaporation temperatures and refrigerants and b) multi-scenario analysis, MT (left) and LT (right)

4.3. Heat pumps and air conditioning systems for space cooling and heating

Chen et al. [84] simulated and compared R-22 and R-410A optimized split prototypes with R-410A compact and high-efficiency types. R-410A high-efficiency prototypes showed a reduction of the LCCP of the order of 11% in comparison with the R-22 system. DE were always below 5% of the LCCP, possibly because of the low values considered for m and L_{annual} , and the high β of China. The production of the refrigerant was considered in the analysis. Zhang et al. [85] simulated a residential heat pump as defined in the AHRI Standard 210/240. After validating the model, they studied the R-134a, R-1234yf and R-410A LCCP. The only significant emissions were related to E_{annual}, L_{annual} and EOL. R-1234yf was the alternative with the lowest LCCP results, and St. Louis (MO, USA), the city with the highest LCCP because of the extreme weather.

Li [86] considered several seasonal energy efficiency ratio (SEER) categories of R-22 and R-410A heat pumps. The IE associated with E_{annual} accounted for approximately 90% of the total LCCP emissions, and the SEER rating had the most significant impact. The fourteen R-410A heat pumps presented LCCP reductions between 7% and 19% in comparison with the 13 SEER R-22 because of the more efficient scroll compressor, thermostatic expansion valve setting, and uniform refrigerant flow line distribution in the coil associated with the former. Additionally, the authors highlighted the effect of cycle degradation coefficient on the LCCP. They considered different refrigerant leakages, such as L_{annual} of 5%, $\alpha_{recovery}$ of 85%, $L_{service}$ of 5%, and $L_{accident}$ of 0.3%, and n of 15 years.

Lee et al. [87] published the first article to consider the IIR LCCP guideline [38] for various configurations (expander, ejector, vapor injection, and saturation cycles), including ten different refrigerants, and five different locations in the USA. Figure 8 shows the LCCP evaluation with different configurations in Chicago and Seattle. Common assumptions were m of 6 kg, L_{annual} of 4%, α_{rec} of 85%, and n of 15 years. DE contributed to 10% of the LCCP (93.8 tCO_2-eq). As m and L_{annual} were not varied, DE were the same for the different configurations, and the improvement in energy efficiency was the only parameter that reduced LCCP. The LCCP additional parameters and α_{rec} were also kept fixed in the different proposed situations. In comparison with the baseline system, the saturation cycle with R-290 in Miami (Florida, USA) showed the largest LCCP reduction, 24.3%. Choi et al. [88] extended the work to South Korean cities, including the option of gas boiler for heating purposes. The same β has been considered for all cities, 0.499 $kgCO_2$ kWh^{-1}, and 0.637 $kgCO_2$ kWh^{-1} for the liquified natural gas (LNG) boiler. The rest of the parameters were taken from the previous work. The IE caused by E_{annual} decreased until representing 80% of the LCCP. Other relevant parameters were L_{annual} and α_{rec}, for which the associated emissions represented 12% and 3% of the LCCP, respectively. Although a 20% increase of MM is considered when the heat pump is used for both heating and cooling, its IE is still below 1% of the LCCP. The vapor injection technology reduces LCCP between 7% and 10%.

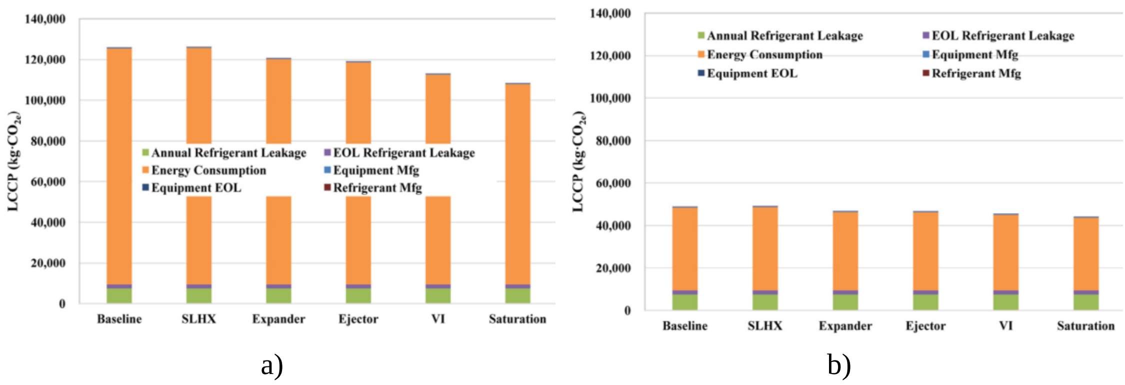


Figure 8. Lee et al. [84] LCCP evaluation with different configurations: a) in Chicago and b) in Seattle.

Beshr et al. [89] extended the work performed in Ref. [82] to different residential air conditioning systems. They considered R-32, and two prototype mixtures, D2Y60 and L-41a, as low GWP alternatives to R-410A. The contribution of DE to the LCCP is lower than in supermarket refrigeration. Therefore, the LCCP reduction when using low GWP alternatives is lower.

Although the GWP of L-41a is not the lowest among the tested refrigerants, it is the best alternative in terms of LCCP (reduction from 5.22 $GtCO_2$-eq to 3.76 $GtCO_2$-eq).

As demonstrated in the IIR LCCP guideline [38], most LCCP software has been developed for heat pump and air conditioning for space cooling and heating. Therefore, LCCP is more likely to be used than TEWI in this application. Higher and varied values of L_{annual} are considered for different operating levels and, hence, DE become significant. There is a wide variety of solutions proposed to reduce CO_2-eq emissions, beyond refrigerants replacement. A summary of the values taken from the aforementioned studies which evaluated the TEWI and LCCP of heat pumps and air conditioning systems for space cooling and heating can be found in Table 4.

Table 4. Parameters selected for the TEWI and LCCP evaluation of different heat pump and air conditioning for space cooling and heating studies

Reference	Situation	DE Parameters			n,	IE Parameters
		m, kg	L_{annual}	α_{rec}	years	β, $kgCO_2\ kWh^{-1}$
Byrne et al. [71]	Simultaneous heating and cooling, R-407C and R-744	18 (HPS), 6 (standard)	3%	75%	20	0.13 (France)
Devecioğlu and Oruç [74]	Basic cycle IHX using R-22 and R-453A	optimized	7%	n.c.	10	0.52 (Turkey)
Chen et al. [84]	R-22 and R-410A compact, optimized and high efficiency	0.804 (R-22_Optd), 0.504 (R-410A_Comt), 0.552 (R-410A_Optd), 0.688 (R-410A_High)	2%	85%	15	0.88 (China)
Beshr et al. [89]	Reversible heat pump using R-410A, R-32, D2Y60 and L41a	4.54 (R-410A)	12% (general), 5% (service, every 5 years), 35% (reused)	35%	15	5 values from 0.351 (Los Angeles, USA) to 1.1 (Albuquerque, USA)

4.4. Mobile air conditioning (MAC)

Koban [90] used the GREEN-MAC-LCCP© Model [91], which included the emissions related to the production, use and disposal of refrigerants and components. In different LCCP scenarios (no added components, and IHX with 3 and 5% improvement) and cities; R-1234yf provided LCCP reductions from 17% to 20% in comparison with the R-134a baseline scenario. When an IHX was added, the value of m used for R-1234yf is 23% higher than that of R-134a (without IHX is 5% lower), and system weight is increased by 1 kg (5.6% increase). Given the global action against the use of the R-134a in MACs, Taddonio [92] studied different life-cycle policies to reduce the

CO_2-eq emissions besides phasing out R-134a. The technologies with the highest potential (30% CO_2-eq emissions reduction) were lower superheat, variable-displacement compressor, and default to recirculated air whenever the ambient temperature is above 24 °C.

Hafner and Neksa [93] studied MAC systems using R-134a and R-744 in nine different locations and different car sizes. They adjusted the distance driven in a year and the temperature over the year for each specific location. The weight of the R-744 refrigeration system was higher than that required by R-134a, 16.0 kg instead of 14.4 kg. In most situations, the LCCP was reduced using R-744 and was equivalent only in the warmest situations, operating during a higher number of hours and above 35 °C with the largest cars.

Zhiyi et al. [94] analyzed China's future CO_2-eq emissions according to the vehicle population prediction (depending on human population and gross-domestic-product evolution), considering different refrigerant (R-134a, R-152a, R-1234yf and R-744). They assumed specific emissions values for different periods of the life cycle (assembly, operation, service, recycling and disposal) and type of vehicles (private passenger, transit buses, taxis, environmental sanitation, non-transit buses and light-duty trucks). Taking R-134a as the baseline (52.84 MtCO_2-eq by 2050), R-152a can reduce 91.3% of TE, and for the very low GWP refrigerants, the emissions are less than 1%. This work was later improved in the study of Yuan et al. [95] in which the analytical model for MAC life cycle CO_2 emissions was described and used in the same scenarios. They considered that the annual distance traveled, gasoline consumption and β will be reduced in the future.

As mentioned for the previous application, LCCP software is also easily available for MACs, which facilitates the utilization of this metric. Moreover, since MAC system is quite standardized, the assumptions and input values can be easily generalized. Unlike other applications, in mobile units, the size of the air conditioning system must be considered, as well other factors such as distance covered by the automobile. Additionally, the observed sensitivity analysis for β considers mostly different fuels but not the size of the automobile or the efficiency of the motor. For MACs, L_{annual} is generally high, as a result of vibrations (and other hazardous conditions), but the value selected for this factor is not mentioned in LCCP works.

4.5. Transport refrigeration

Wu et al. [96] presented a CFA for transport refrigeration including all systems in the cold chain. They considered R-404A, R-410A, and R-744 for various ambient temperatures (those of Beijing, Berlin, Shanghai, Madrid, Osaka, and Tokyo), refrigeration temperatures (0 and -18 °C), n (2, 5 and 10 years) and refrigerator drive modes (main or auxiliary engine, electric). As in other applications, R-744 was not the refrigerant with the lowest TE under high ambient temperature conditions. Refrigerators driven by engines other than the main vehicle or electricity resulted in higher CO_2 emissions. If LCCP analysis would be used instead of the CFA, the TE would be 40% lower because LCCP does not include the CO_2 emissions associated to the following factors: refrigerant transport, refrigerator production, transport, weight, and recycling.

Bagheri et al. [97] collected field data from refrigerated trailers in Vancouver (Canada) during different seasons of two consecutive years and developed a mathematical model to simulate the transient behavior of a trailer refrigeration system. They concluded that it is possible to reduce 8.32 tCO_2-eq per year per truck-trailer (considering a yearly distance travelled of 60000 km) by replacing the current diesel engine-driven vapor compression systems with Li-ion battery-powered types, because the total weight of the truck would be reduced by around 1.5%.

Li [98] investigated the total lifetime CO_2-eq emissions of a food transport refrigeration system using R-452A using different assumptions related to L_{annual}, ambient temperature, refrigerated temperature, refrigeration technology, annual insulation degrade rate, sunny/night condition, etc. The most significant TE reductions were caused by the modification of the operating temperatures. Moreover, adsorption technology seems very interesting as it can be activated from free available waste heat or renewable energy. The emissions apart from those associated with fuel consumption for electricity production, L_{annual}, and α_{rec} can be considered negligible.

Life cycle analysis (LCA) is performed instead of TEWI or LCCP metrics in scientific works covering transport refrigeration systems. This application is not targeted to end-use consumers and, therefore, the starting point and the end of this process cannot be easily defined. Therefore, each researcher decides the scope of the information to be included in the analysis without linking it to any existing methodology. In this application, some influencing factors related to weight, distance covered and motor efficiency, as those mentioned in the MAC subsection, are even more relevant.

5. General comments about the metrics and their use

Once the metrics and the input parameters used in the scientific papers have been reviewed and analyzed, the following conclusions can be drawn.

5.1. TEWI vs LCCP

TEWI metric is used in the majority of the RACHP studies, while the LCCP metric is mostly present in studies regarding space cooling and heating and MAC systems. However, in most RACHP applications, the number of LCCP studies is not significant enough to extract definitive conclusions about the input parameters selected. Moreover, in most of the analyzed papers, it seems that LCCP does not represent a substantial improvement compared to TEWI in terms of technology benefits, in agreement with Boström and Ljungberg [43]. Still, for a material intensive system with a small magnitude of the m, L_{annual}, and E_{annual} parameters, the manufacturing and EOL emissions included in the LCCP analysis are noticeable, as in the example presented by Aprea et al. [80]. This is the situation for small and self-contained commercial refrigerators and packaged air conditioners.

TEWI or LCCP analyses have not been found for industrial refrigeration, possibly because low GWP R-717 is the dominant refrigerant, and the technology is rather mature [99]. Therefore, for any modification, the environmental benefit is directly derived from energy consumption reduction. Similarly, these metrics are not applied for ultralow-temperature refrigeration (below -50 °C), which is out of the scope of some of the most important environmental regulations [16,100].

Although the differences in the RACHP applications, the lessons learned on how to apply the environmental metrics or the selection of parameters in one industry segment can be transplanted to another, so every advance results in a global benefit. For example, Wu et al. [96] suggest that their CFA developed for transport refrigeration can be used to evaluate the TE of other systems, such as MACs, because of their similar characteristics.

TEWI and LCCP metrics are applied in RACHP research studies with advanced or modified configurations and components, or alternative refrigerants. While the proposed measures contribute to reducing the TE, a significant reduction can also come from the solution of a technical problem or from better practices in design, construction, service, and EOL operations. According to Ref. [98], 90% of RACHP DE happen at the EOL, so “Refrigerant management” (controlling their leakages and recovering, recycling, and destroying them at the EOL) is listed as the most important solution, since 89.74 $GtCO_2$-eq emission can be avoided.

It is very difficult to compare absolute and relative results of LCCP and TEWI metrics between different works for the same application, resulting in delays in the advance of the technology and duplicity of the employed resources. The publication of guidelines is a step forward in this matter, but much effort is still needed. To compare absolute values of LCCP or TEWI, further standardization is necessary to establish a transparent methodology. Relative results of LCCP and TEWI are somewhat easier to compare, as some inputs are cancelled out and, thus, contributing to the certainty of the calculated results.

5.2. Selection of parameters

Some common concerns in the selection of the parameters for the environmental metrics have been identified in most of the analyzed works. Table 5 presents some possible problems related to TEWI together with recommendations for future works aiming at increasing the impact, accuracy, and reproducibility of the environmental studies.

Table 5. Recommendations about TEWI parameters

Parameter	**Possible problem**	**Recommendation for future works**
GWP_{100}	Different references are taken in the same study	Use a single reference for the GWP values
	Reference is not given	Clearly mention and cite reference the first time that the GWP value of studied refrigerants appears in the paper

m	Not modified between options	Study m variations when introducing modifications to the system or changing refrigerant
	Not optimized for new refrigerants	Check for last studies on the topic, apply correlations to calculate the appropriate value, or consider the fluid density
L_{annual}	Different acceptable values	Include sensitivity analysis considering the range proposed by the guidelines
	Leakage affects COP	Consider the reduction of performance during annual operation
	Zeotropic mixtures	For mixtures with significant glide, leakage affects the existing composition and hence the thermodynamic behavior
n	Not studied in depth	Check for more realistic and recent values of the lifespan of the specific application, include sensitivity analysis for this parameter
	Not varied between configurations or refrigerants	The modified or retrofitted system can operate at lower compressor revolutions or discharge temperature and hence increase its lifespan
α_{rec}	Not considered	If this parameter is not included, it means that 100% of the refrigerant is recovered. Must be mentioned
	Not standardized	Try to follow guidelines when including it
	Close to 100% in developed countries	Given the exhaustive regulations in these regions, most of the refrigerant is going to be carefully recovered
E_{annual}	Brings uncertainty in theoretical analysis	Include comments about the accuracy of the results and how it is going to be propagated in TEWI or LCCP
	Not explicitly mentioned in the text	Include the basis for calculation of the E_{annual} values
β	A limited set of values investigated	Extend the number of values to include more territories in which the analyzed systems might be placed at
	Sensitivity not justified or comes from the ambient temperature selection	Try to select different levels of β to cover a wide range of situations and argue the selection
	Average for a region is used	Global or regional averages are not representative for a stationary RACHP system. Local values should be used, and the discussion at regional or global levels can be made referring to the TEWI and LCCP at local levels.
	Value of energy generation is used	Use β of the energy used by a system (e.g. including transmission losses, and the effect of energy exchange with neighboring grids)
	Values not updated	Most of the papers consider values given in Ecometrica from 2011, but they have been reduced thanks to renewable energy in most of the cases
	Future values	β is likely to be reduced in the time horizon proposed with the increase of the share of renewable energies

A common belief for all parameters is that the environmental impact coming from different factors are going to be reduced as the technology and the good practices continue to improve. In this sense, parameters such as β, L_{annual}, or α_{rec} can be highlighted through higher utilization of renewable energies, and better operation, service and maintenance practices.

The concerns identified for TEWI parameters can also be applied to LCCP. When the LCCP metric is applied in a modification from an existing system, additional emissions caused by material manufacturing, transport or EOL, are not evaluated by the authors even though the system is going to be different. Therefore, if the environmental analysis is going to consider many assumptions, the LCCP metric does not present many advantages in comparison with the TEWI metric since the only variation considered is that observed in the E_{annual}.

5.3. Conclusions and future recommendations

The environmental impact of RACHP systems has been documented and quantified for many decades. Numerous players are participating in RACHP evolution, including chemical companies, policymakers, society, components suppliers. More efficient solutions and refrigerants with lower GWP are considered to reduce their climate impact. Moreover, regulations are being approved to intensify the transition and bring new solutions to the market. This paper provided a critical review of the current ways of quantifying and determining the equivalent warming impact used in the RACHP sector.

The environmental metrics used today to determine the climate impact of RACHP systems are not perfect, and their accuracy depends on many factors that are not likely to change in the medium term. GWP is generally implemented by many regulations to quantify the contribution to the GHG effect of the refrigerants because it is a simple metric which allows comparing different substance at a single CO_2-eq scale. While GWP metric is uncertain, it has a lower uncertainty than GTP. Meeting environmental targets will require a substantial reduction in GHG emissions in all sectors, including RACHP. Given that the majority of global GHG emissions from this sector are those from IE, the LCCP and TEWI are relevant metrics to be implemented in future policies, simpler than LCA to quantify the climate impact.

The literature review has revealed that the analysis of the GHG emissions is being applied to different types of RACHP systems undergoing energy efficiency improvement (as advanced components or configurations) and refrigerants substitution. Depending on the application, the degree of uncertainty and assumptions related to the TEWI and LCCP parameters can have a significant variation. For instance, domestic refrigerator climate analysis is more accurate than commercial refrigeration, particularly when considering low-GWP refrigerants in advanced configurations due to the major novelty of the proposed low carbon emission alternatives such as cascade or transcritical R-744 systems.

If a sensitivity analysis is included in the TEWI or LCCP metric, the most commonly varied parameters are the L_{annual} and β. Both parameters are the most influential in the TEWI and LCCP results, thus, their definition should be justified carefully. Another parameter that has a significant impact is the lifetime of the system, but the effect of its variation is not usually investigated. LCCP analysis is based on a greater amount of input parameters. However, if it is not going to be evaluated in detail, it might not provide better results than a simpler TEWI analysis, while being perceived as more comprehensive.

The revision of the TEWI and LCCP analysis confirms that the transition to lower environmental impact systems is already ongoing, using more efficient solutions and lower GWP refrigerants. However, the quantification of the environmental benefits is still far from being a common practice in research, despite the efforts of different organizations in publishing detailed guidelines.

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