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International Journal of Refrigeration xxx (xxxx) xxx

Contents lists available at ScienceDirect

International Journal of Refrigeration

journal homepage: www.elsevier.com/locate/ijrefrig

TEWI analysis of a stand-alone refrigeration system using low-GWP fluids with leakage ratio consideration

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ARTICLE INFO

Article history:
Received 23 March 2020
Revised 13 May 2020
Accepted 31 May 2020
Available online xxx

Keywords:
TEWI
Environmental analysis
R-454C
R-459B
R-457A
R-455A

ABSTRACT

In few years, stand-alone systems will rely on low-GWP refrigerants in order to reduce their direct impact, which agrees with the recent regulations and standards. However, the energy performance of the system is dependent on the refrigerant charge and thus on their annual leakage ratio. The leakage effect is not considered in the suggested methods to evaluate the environmental impact and requires an in deep analysis. We aim to extend the TEWI analysis of stand-alone refrigeration systems by considering a realistic evolution of their charge during its lifetime and to quantify the discrepancies of the classical methodology. For that, the performance of a stand-alone cabinet (four low-GWP refrigerants) has been considered as reference. It has been concluded that leakage consideration makes classical TEWI to underestimate emissions for any country, refrigerant or annual leakage ratio, up to 20% in this study. Deviation increases with higher leakage ratio, but especially for those values that do not imply a refilling during the lifetime of the system. Deviations are higher as mass and energy spans of the systems are.

1. Background

Refrigeration sector is responsible for 7.8% of the world greenhouse gas emissions, from which 37% are caused by direct escapes of refrigerants and 63% are related to indirect emissions due to consumed electricity (International Institute of Refrigeration 2017). A big effort was done with the Montreal Protocol to phase-out the chlorinated fluids in 1987 (Montreal Protocol on Substances That Deplete the Ozone Layer 1987), which has resulted in a reduction of the ozone hole (Newchurch et al., 2003). Predictions evidence that the ozone layer would reach the seventies conditions between 2040 and 2070 (Eyring et al., 2010). Thus, it seems correct to affirm that the refrigeration sector reacted responsibly.

However, from the signing of the Kyoto Protocol (United Nations 1997) in 1997, the efforts have been focused on controlling the emissions of greenhouse gases, the most used refrigerants now (HFC) being among them. The objectives of the Kyoto Protocol were reinforced through the approval of the F-Gas Regulation in the European Union in 2014 (6), which established limitations to the use of HFC refrigerants. Then, its purpose has been extended worldwide by the Kigali amendment whose phase-down schedule will reduce the use of HFC refrigerants by 80% by 2047 and aims to avoid up to 0.5K increase in global temperature by the end of the century (UNEP 2016). Although the impact of Kyoto and Kigali amendments cannot be observed yet, it is worth mentioning that the Montreal Protocol which covered chlorinated products, also covered very high-GWP refrigerants. Its effects indicate that

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https://doi.org/10.1016/j.ijrefrig.2020.05.028
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Please cite this article as: R. Llopis, D. Calleja-Anta and A. Maiorino et al., TEWI analysis of a stand-alone refrigeration system using low-GWP fluids with leakage ratio consideration, International Journal of Refrigeration, https://doi.org/10.1016/j.ijrefrig.2020.05.028

Nomenclature

AEC	annual energy consumption, MW·h
AIRAH	Australian Institute of Refrigeration, Air conditioning and Heating
ALR	annual leakage ratio, %
AR	Intergovernmental Panel on Climate Change Assessment Report
CFC	chlorofluorocarbon
COP	coefficient of performance
DEC	daily energy consumption, kW·h·day^{-1}
ED	equivalent direct CO_2 emissions, $kg_{CO2,eq}$
EI	indirect CO_2 emissions, $kg_{CO2,eq}$
EM	equivalent CO_2 emissions, $kg_{CO2,eq}$
EOL	end of life leakage ratio, %
GWP	global warming potential, 100 years horizon, $kg_{CO2,eq}$
HFC	hydrofluorocarbon
HFO	hydrofluoroolefin
IIR	International Institute of Refrigeration
L	expected lifetime of the system, yr
LCCP	life cycle climate performance, $kg_{CO2,eq}$
LK	refrigerant leakage, kg
LT	life time of the refrigeration system, year
m	refrigerant mass flow rate, kg·s^{-1}
M	total refrigerant charge of the system, g
p	pressure, bar
P	electrical power, W
RH	relative humidity, %
SEER	seasonal energy efficiency ratio
t	time, month; temperature, °C
TEWI	total equivalent warming impact, $kg_{CO2,eq}$

Subscripts

a	air
direct	refers to direct emissions
dis	compressor discharge
exp	inlet of expansion valve
ihx	internal heat exchanger
in	inlet
indirect	refers to indirect emissions
k	condenser
l	saturated liquid
min	minimum
o	outlet, evaporation
opt	optimum
p	product
r	refrigerant
refill	refers to refilling process
ret	return air to evaporator
s	compressor suction
y	year

Greek symbols

Δ	increment
ΔE	energy span: energy consumption difference between the system with optimum refrigerant charge and with the minimum charge at which it could operate.
ΔM	mass span: refrigerant charge difference between the optimum value and the minimum at which the system could maintain the desired product temperature level.

the phase-out of CFCs have mitigated about 25% of global warming and reduced by 1K the global average temperature increment (Goyal et al., 2019).

Focusing on hermetic refrigeration systems for commercial use, most of the existing equipment is still working with R-404A (UNEP 2014), with a GWP of 3945 (5th AR). However, its use has been limited by the F-Gas Regulation from 01/01/2020 and they will rely on refrigerants with a GWP below 150 from 01/01/2022 (6). This situation will be extended worldwide through the Kigali agreement with a delayed schedule. Now and until 01/01/2022, manufacturers offer solutions with moderate GWP ($500 < GWP < 1500$) and A1 classification, such as R-407H (Llopis et al., 2017), R-449A (Makhnatch et al., 2017) or R-448A (Mota-Babiloni et al., 2015), although its horizon is very short. The future for these solutions, as Llopis et al. (Llopis et al., 2019) discuses, is quite difficult, because this segment lacks of high security alternatives (McLinden et al., 2017, Calleja-Anta et al., 2020), thus it needs to rely on A2, A2L or A3 refrigerants, and the refrigerant charge for these lasts is limited (I.E. Commission 2019). Furthermore, this equipment will be subjected to strong energy efficiency standards (European Commission 2015, European Commission 2015). Nonetheless, market is evolving to obtain systems fulfilling all requirements. In relation to alternative refrigerants to R-404A or R-507A, which are nearly equivalent fluids (Llopis et al., 2010), with a GWP below 150, R-454C (Llopis et al., 2019, Mota-Babiloni et al., 2018, Bella et al., 2018), R-455A (Llopis et al., 2019, Mota-Babiloni et al., 2018, Bella et al., 2018), R-457A (Llopis et al., 2019) and R-459B (Llopis et al., 2019) have been evaluated experimentally. They are mixtures with the base fluid HFO-1234yf with different proportions of HFC-32, CO_2, HFO1234ze(E) and HFC-152a, all with an A2L security classification. General results of the experimentation with these fluids show that all present a reduction in the capacity and small variations in COP in experimental plants, but they depend on the system. For the moment, in relation to R-404A new low-GWP alternatives, only the newly presented refrigerant R-468A (Ohkubo et al., 2019) is known by the authors, nonetheless no experimental verification has been found.

A critical look to the objectives of the regulations indicates that efforts have been focused only on limiting the direct effect. However, considering that 63% of the total impact of this sector is caused by indirect emissions (International Institute of Refrigeration 2017), it is important to have a closer look to the direct and the total emissions of a refrigeration system. A good approach to understand the whole impact of a system is using an LCCP approach, such as done by Lee et al. (Lee et al., 2016) and Beshr et al. (Beshr et al., 2017) applied to air conditioning applications in buildings, or by Hafner and Nekså (Hafner and Nekså, 2005) for mobile air conditioning systems. LCCP approach considers direct and indirect emissions of the system during its lifetime and also the associated emissions due to construction of the system, refrigerant manufacturing and disposal. However, the most generalized metric to evaluate the environmental impact of a system is still the TEWI, which considers only emissions of a system during its period of use. For hermetic commercial refrigeration systems, differences between LCCP and TEWI are low, and TEWI based comparison is more intuitive (Makhnatch and Khodabandeh, 2014). Thus, this work considers TEWI to understand the environmental impact of a stand-alone commercial refrigeration system using low-GWP refrigerants.

AIRAH (AIRAH 2012) and IIR (Life cycle climate performance working group - Int 2016) published guides with considerations to evaluate TEWI, where they suggest concrete figures for the different terms that compose this metric. They indicate that TEWI is subjected to a certain amount of uncertainty, because parameters such as ALR, AEC, indirect generation emissions, etc…, are obtained from statistical studies and could vary between one or an-

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other system. However, the methods are based on an assumption that has not been much questioned: they consider constant the refrigerant charge and the system's annual energy consumption for all the lifespan of the system. This consideration assumes that the system is recharged to its optimal refrigerant charge annually, thus the effects of leakage on the energy consumed by the system are minimal. This consideration could have sense in medium to large and systems subjected to a definite maintenance schedule, however, when dealing with small stand-alone refrigeration systems this schedule does not exist since they are running until a failure is detected by the end user, when effectively, the system is recharged to the optimum conditions. Consideration of leakage in a stand-alone system during its life has strong implications on its energy consumption, since the key parameter to optimize its performance is the refrigerant charge (Antunes and Bandarra Filho, 2016). Accordingly, it is interesting to consider the energy degradation due to leakage in systems when evaluating their environmental performance.

This issue was analysed by Kim & Braun (Kim and Braun, 2012) for air conditioners and heat pumps in relation to the SEER, although they did not extend the analysis to an environmental point of view. From the best knowledge of the authors, only Beshr et al. (Beshr et al., 2014) considered the leakage and energy. They modelled systems degradation for a heat pump and a water to water chiller using thermostatic expansion valves, and for an air conditioning using a capillary tube, and they concluded that the environmental impacts where higher for systems without liquid receiver and working with capillaries. Thus, these characteristics are common in stand-alone refrigeration systems and thus require a closer analysis.

Given that the future refrigerants for stand-alone commercial refrigeration systems will have low-GWP, direct emissions will have little impact on the environment, however, energy degradation associated with leakage will increase the indirect impact. Accordingly, the objective is to analyse the influence of the leakage ratio of a stand-alone commercial refrigeration system during its lifetime from an environmental point of view. To achieve this, an evaluated open-fronted vertical cabinet for fresh product (Llopis et al., 2019) has been considered. The analysis includes the operation using four low-GWP refrigerants and it has been extended to the most representative countries of Europe, where the generalization of low-GWP solutions is imminent.

2. Reference system and refrigerant options

2.1. Reference system

The system used to contrast the TEWI approaches corresponds to a commercial open-fronted vertical cabinet with a frontal air curtain (Fig. 1) used for fresh food preservation. The system, designed for R-404A, was reconverted and optimized to be used with the low-GWP refrigerants R-454C, R-455A, R-457A and R-459B (Llopis et al., 2019). It was demonstrated that every refrigerant was able to reduce the energy consumption after charge optimization in relation to R-404A. According to the F-Gas Regulation (6), from 01/01/2022 on, this type of system will only be allowed to operate with refrigerants with GWP below 150, thus, only performance data with the low-GWP refrigerants is considered in this work.

The schematic system's diagram is detailed in Fig. 2. It is driven by a 22.37 cm^3 compressor, uses a minichannel air condenser, an electronic expansion valve and a finned-tube evaporator placed inside the cabinet. Cabinet was instrumented with 10 T-type thermocouples, a thermo-hygrometer, 6 pressure gauges, a Coriolis mass flow meter and a digital wattmeter. The standard ISO 23953-2:2015 (ISO 23953-2 2015) was followed to perform the energy optimization of the system at 25.5 °C and 50% of relative humidity. System was placed inside a climatic chamber controlling humidity and temperature. Environmental conditions were measured using another thermo-hygrometer and inside the cabinet 6 M-test packages (1000 g) measured product temperature.

Fig. 1. View of the vertical open-fronted cabinet.

24h energy consumption tests were done to evaluate cabinet's performance with different refrigerant charges for all refrigerants. More details about the energy optimization with the different combinations are detailed in Llopis et al. (Llopis et al., 2019).

2.2. Experimental performance of the system

Fig. 3 presents its DEC at an environment at 25.5 °C and 50% RH, according to the 24 h energy consumption tests, where the average product temperature of the 6 M-test packages was maintained at 5.0 ± 0.1 °C. It accounts for the electricity consumption of the compressor, fans of evaporator and condenser, lighting, control system and defrosting. System was operated with ON/OFF compressor operation according to a set point temperature measured at the air inlet to the evaporator. It was regulated with 10K superheating set point. One defrosting each six hours was performed using electrical resistors (540 W).

Charge optimization was done using 100 g steps for each refrigerant. The DEC from the minimal refrigerant charge (M_{min}) at which the system was able to maintain product temperature, that is equal to 800 g for all refrigerants, up to the optimum refrigerant charge (M_{opt}) (Llopis et al., 2019), which is assumed to be the condition at which the system leaves the factory, is considered in this work.

Here, we consider the DEC from the minimal refrigerant charge (M_{min}) at which the system was able to maintain product temperature, that is equal to 800 g for all refrigerants, up to the optimum refrigerant charge (M_{opt}) (Llopis et al., 2019), which is assumed to be the condition at which the system leaves the factory.

Considering data of Fig. 3, system's performance can be summarized according to the key parameters detailed in Table 1. ΔM [Eq. (1)], called mass span, that corresponds to the difference between the optimum refrigerant charge and the minimum charge that allows to maintain the product temperature. With charges

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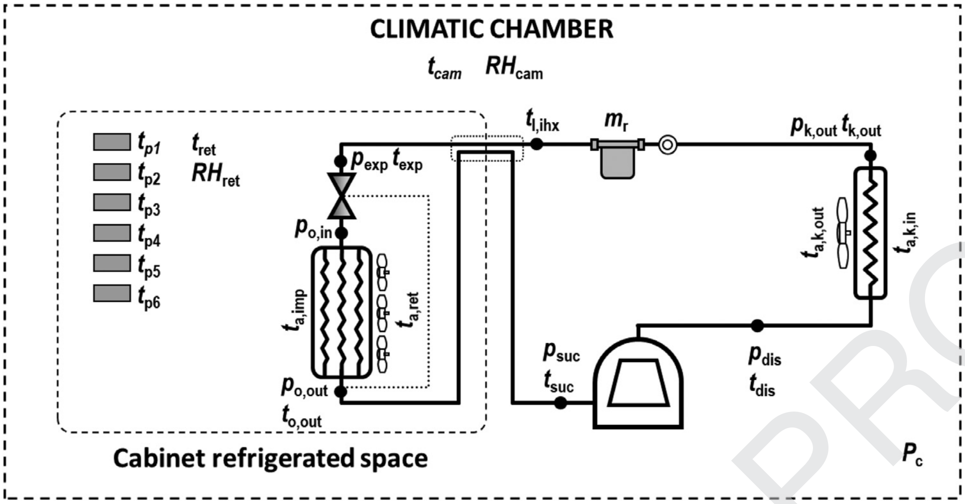

Fig. 2. Schematic refrigeration layout of the cabinet.

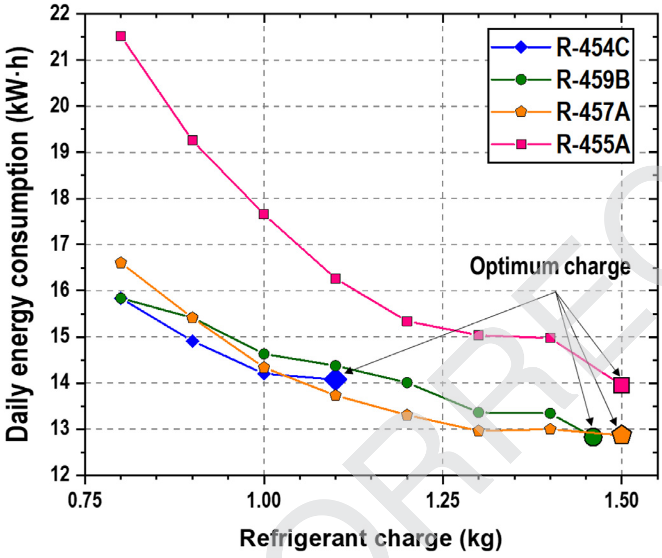

Fig. 3. System's daily energy consumption as function of refrigerant charge.

below 800g the system is not able to maintain 5 °C of product temperature. ΔE [Eq. (2)], denoted as energy span, is the daily energy consumption difference between the operation at the minimum refrigerant charge and at the optimum conditions. If the system reduces its charge, due to leakage of refrigerant, the DEC increases (Fig. 3), the increment being dependent on the considered refrigerant. This is of relevance importance, since it is well known that any refrigerant system is subjected to leakage, but usually the increment in DEC is not considered for the environmental evaluation of the system.

$$\Delta M = M_{opt} - M_{min} \tag{1}$$

$$\Delta E = DEC_{max} - DEC_{opt} \tag{2}$$

3. Classical TEWI evaluation

TEWI, Eq. (3), is the most generalized metric to compute the total impact (equivalent emissions of CO_2) of a refrigeration appliance during its use until its disposal (UNIDO 2009). It is composed of two terms: one accounting for the direct emissions due to refrigerant leakage [EM_{direct}, Eq. (4)], and another corresponding to the indirect emissions of GHG due to energy consumption [$EM_{indirect}$, Eq. (5)].

$$TEWI = EM_{direct} + EM_{indirect} \tag{3}$$

$$EM_{direct} = M \cdot (L \cdot ALR + EOL) \cdot GWP_{100} \tag{4}$$

$$EM_{indirect} = L \cdot AEC \cdot EM \tag{5}$$

In relation to the indirect emissions, Eq. (5), L represents the expected lifetime of the system in years, AEC accounts for its annual energy consumption and EM corresponds to the indirect emissions due to the electricity production, which will be discussed later.

Direct emissions, evaluated during the life of the system and during its disposal, depend on the system refrigerant charge M, the annual leakage rate of the system ALR and the end of life leakage during the phase out of the system EOL, and are fully dependent on the considered refrigerant by its GWP value.

Both, AIRAH (AIRAH 2012) and IIR (Life cycle climate performance working group - Int 2016) state that TEWI evaluation is subjected to a certain amount of uncertainty due to the large number of assumptions to be considered, however, it corresponds to a good metric to contrast the operation of systems or refrigerants for a given application. The following standard values to conduct TEWI computation for stand-alone commercial refrigeration systems are suggested:

- Lifetime of the system (L): 15 years (Life cycle climate performance working group - Int 2016).
- Annual energy consumption (AEC): for stand-alone refrigeration systems with low variation of heat rejection temperature

Table 1
Performance characteristics of the refrigeration system with the evaluated refrigerants.

	GWP_{100yr}	M_{min} (g)	M_{opt} (g)	DEC_{max} (kW·h·day^{-1})	DEC_{opt} (kW·h·day^{-1})	ΔM (g)	ΔE (kW·h·day^{-1})
R-454C	146	800	1100	15.84	14.08	300	1.76
R-459B	143	800	1460	15.84	12.83	660	3.01
R-457A	139	800	1500	16.61	12.87	700	3.74
R-455A	146	800	1500	21.52	13.95	700	7.57

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during the year, IIR (Life cycle climate performance working group - Int 2016) recommends using the AEC for optimal working conditions, since it considers that systems are refilled once a year, and thus the effects on energy consumption are minimal. AIRAH (AIRAH 2012) however, suggests performing annual energy evaluations according to heat load and environment variations to win in precision. Nonetheless, for appliances working in conditioned spaces, such as supermarkets, they recommend only to use the evaluation at a given temperature. In this case, the reference environment has been considered constant at 25.5 °C and 50% of RH according to the data given in Fig. 3.

- End of life leakage (*EOL*): for this type of systems, IIR recommends considering that 15% of the refrigerant inside the system is lost during the recovery process (Life cycle climate performance working group - Int 2016) and AIRAH suggests increasing this value up to 30% for small systems (AIRAH 2012). Here, IIR recommendation has been followed. Nonetheless, since the system is working with low-GWP refrigerants its contribution in the overall impact is minimum, as mentioned below.
- Global Warming Potential: (*GWP*): it represents the impact of a substance in relation to the emission of 1 kg of CO_2 to the atmosphere, this metric being updated in the IPCC assessment reports. The UNFCCC and European Regulations considered the 4th assessment report values, however, the most recent values (5th AR (IPCC 2014)) have been used.
- Annual Leakage Ratio (*ALR*): it accounts for the total annual refrigerant leakage during a year, including catastrophic and maintenance escapes, and is expressed as percentage of the initial charge. AIRAH suggest to use 2% for self-contained refrigeration systems (AIRAH 2012), whereas IIR increments this percentage up to 5% (Life cycle climate performance working group - Int 2016). For the first analyses a 5% value has been considered in this work, and then it has been extended from 0 to 30% to evaluate the impact of this term on the environmental behaviour of the system.
- Electricity generation emissions or indirect emission factor (*EM*): it accounts for the carbon intensity of an electric generation system, measured in $kg_{CO2,equ} \cdot kWh^{-1}$. It is dependent on the selected country and is usually considered as a constant value. However, the report of Koffi et al. (2017) indicates that they are dependent on the year and show a reduction trend over the years, therefore, it is not convenient to use a constant value for systems with expected lifetime of 15 years. To increase in precision the methodology proposed by Maiorino et al. (2020) has been followed, which is detailed in Section 3.1.

3.1. Prediction of indirect emission factor

Results of any environmental evaluation are strongly correlated to the carbon intensity of a country; it being quantified by the indirect emission factor (*EM*). Generally, *EM* factor is used as a constant value, such as the carbon intensity values reported by Brander et al. (Brander et al., 2011), through all the evaluated time span. However, carbon intensity is variable and dependents on the considered year and it is not convenient to use a constant value. Maiorino et al. (2020) suggested to use a prediction of the *EM* based on historical data (Koffi et al., 2017) to evaluate the trend of carbon intensity for each country with the exponential function detailed in Eq. (6), where *a*, *b* are the adjustement parameters for each energy mix and *s* is a scalle factor equal to 1989.

$$EM(y) = a{*}e^{-b{*}(y-s)} \tag{6}$$

Fig. 4 illustrates the evolution of the *EM* factor for five european countries along the historical data provided by Koffi et al. (Koffi et al., 2017) and the predictions using Maiorino's fitting relation up to 2034. Furthermore, Table 2 details the average *EM* factor from 2019 to 2034 according to Eq. (6). The forecast prediction and the average *EM* factors will be used as reference for the evaluation of the environmental metrics here.

Table 2
Average *EM* factor from 2019 to 2034 using forecast predictions according to Eq. (6).

COUNTRY	Germany	UK	Italy	Spain	France
$\overline{EM}_{19-34}$ ($kg_{CO2} \cdot kWh^{-1}$)	0.4501	0.4129	0.3213	0.2759	0.0673

3.2. Results of TEWI under classical evaluation

Fig. 5 illustrates the TEWI values calculated with Eqs. (3)–(5) according to the methodology proposed by IIR (Life cycle climate performance working group - Int 2016) and AIRAH (AIRAH 2012) for stand-alone commercial refrigeration systems, where the following figures are assumed:

- *L*: 15 years
- *ALR*: 5%
- *EOL*: 15%
- GWP_{100}: 5th Assessment Report value (IPCC 2014) with 100 years integration time, Table 1.
- *AEC*: that corresponding to the operation of the system at optimum charge conditions (Table 1). In agreement with IIR recommendations (Life cycle climate performance working group - Int 2016), it assumes that the system is refilled once a year at the optimum refrigerant charge.
- *EM*: to be coherent with the calculations of Section 4, *EM* factor considered here is the integrated value from 2019 to 2034 according to the prediction forecast presented in Section 3.1. Used values for the considered countries are detailed in Table 2.

From results of TEWI calculation under the classical methodology (Fig. 5), the following observations can be made:

- The direct emissions associated to the use of the refrigeration system with the low-GWP refrigerants are constant for all the countries. They maximum contribution to TEWI depends on the *EM* factor and are between 0.59% for economies with high carbon intensity values such as Germany and 3.8% for economies with low carbon index, such as France. Nonetheless, is important to highlight that the use of refrigerants with a GWP<150 minimizes the direct effect.
- The indirect emissions, associated with electricity consumption, represent from 96.2% to 99.4% of the total contribution to TEWI. It indicates that for the evaluation of the TEWI index using low-GWP refrigerants it is crucial to represent with the highest accuracy the energy behavior of this fluids.
- Among the refrigerants, maximum variation of TEWI index is 3.0% (Germany) and minimum of 0.4% (France), what indicates that under the classical TEWI methodology no appreciable differences are found among the use of one or another refrigerant.
- Among the countries, differences between TEWI values are high, being them nearly directly correlated with the emission factor (Table 2). However, the quotient TEWI between EM gives values with maximum deviation of 2.5% between the countries, therefore, the quotient could be used to extend TEWI calculation to any country.

As summary of the observations derived from the classical TEWI methodology, it can be said that when low-GWP refrigerants are used in a system, nearly all the emissions of greenhouse gases are related with the electricity consumption, thus the most reliable representation of the energy behaviour is important to obtain more conclusions. This is made in Section 4.

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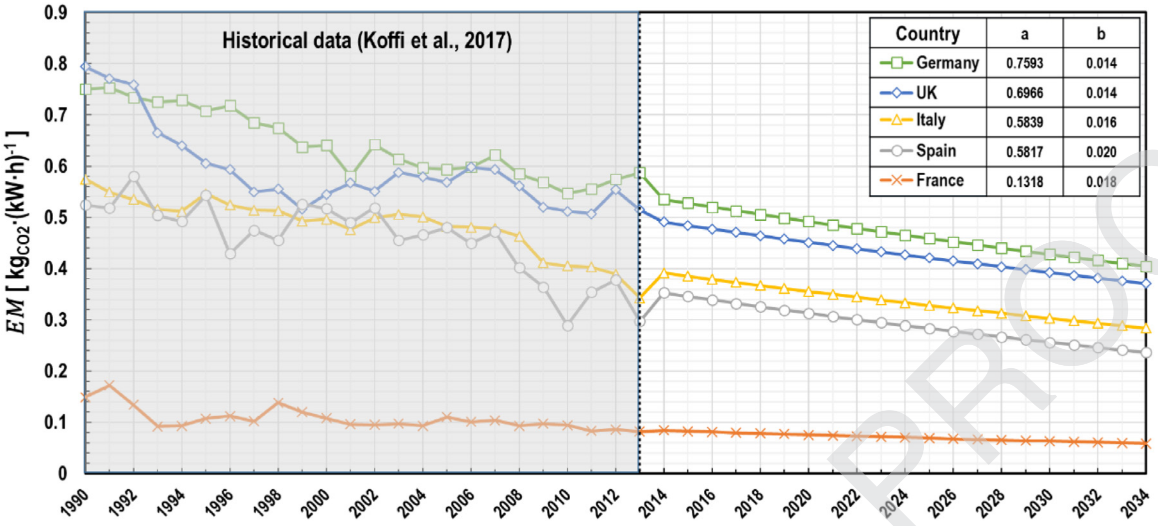

Fig. 4. Forecast prediction of indirect emission factor from 2013 to 2034.

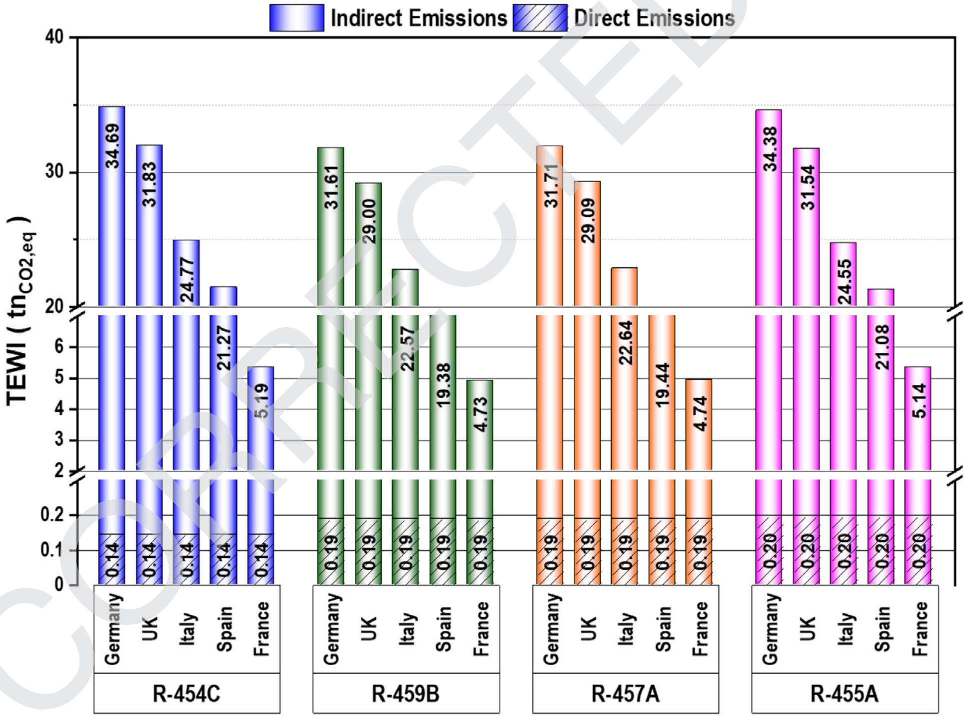

Fig. 5. TEWI of refrigeration system under classical evaluation. Emission factor predicted for 2019. ALR=5%.

4. TEWI evaluation considering leakage ratio

Daily energy consumption of a stand-alone refrigeration system is dependent on its refrigerant charge (Fig. 3). However, consideration of an ALR invalidates the classical TEWI methodology, since it considers both refrigerant charge and energy consumption constant and equal to the values obtained in the optimization process. Therefore, results obtained in Section 3 can be questioned and a closer look to the TEWI evaluation is mandatory for this type of systems.

4.1. Operation of stand-alone system considering leakage ratio

For stand-alone refrigeration systems, assuming that ALR is always constant, the refrigerant mass inside the system as function of time can be expressed by the differential relation (7), where the temporal variable is expressed in months.

$$\frac{dM(t)}{dt} = -\frac{ALR}{12} \cdot M(t) \tag{7}$$

Integration of Eq. (7) from the initial situation of a system, corresponding to the moment it is delivered from the factory with an initial charge coincident to the optimum refrigerant charge (M_{opt}), the evolution of mass over time is expressed by Eq. (8).

$$M(t) = \begin{cases} M_{opt} \cdot e^{-\frac{ALR}{12} \cdot t} \; if \, M \geq M_{min} \\ M_{opt} \; if \, M < M_{min} \end{cases} \tag{8}$$

Starting from the initial charge M_{opt}, the refrigerant mass in the system decreases according to an exponential relation until the minimum refrigerant charge at which the system could operate (M_{min}) is reached. At this moment, user of the refrigeration system detects the failure and refills the system with the optimum charge.

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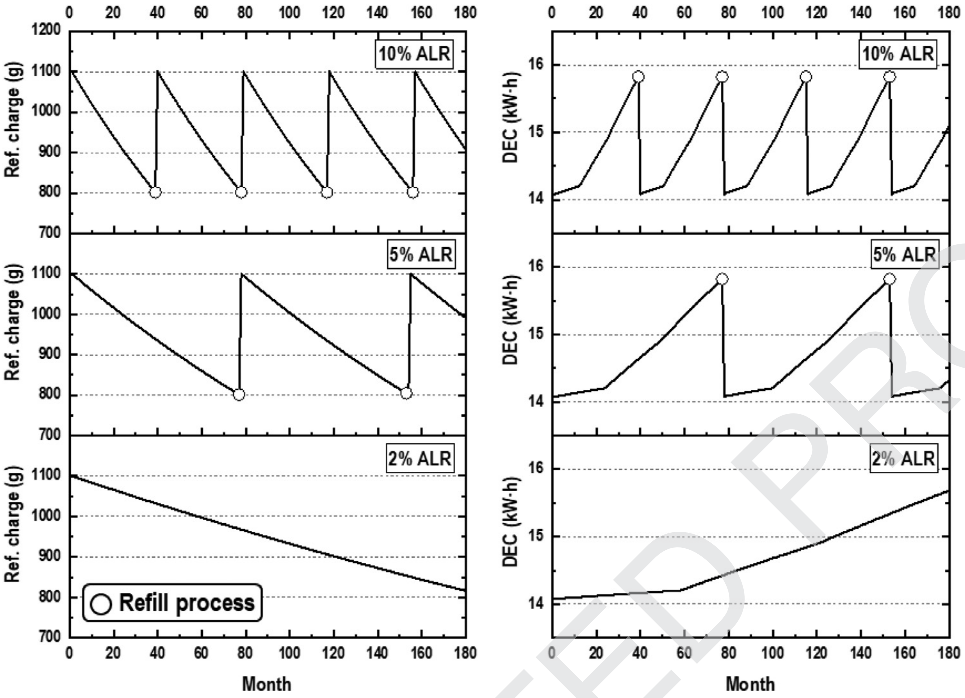

Fig. 6. Evolution of refrigerant charge and daily energy consumption during lifetime of system. R-454C case.

According to Eq. (8), the evolution of charge and its associated energy consumption is represented in Fig. 6 for 2, 5 and 10% ALR using R-454C as reference. As it can be observed, for low ALR (2%), the system has always enough refrigerant charge to operate, but energy consumption degrades with time, with significant increments. However, for higher ALR (5 and 10%) the minimum operating charge in the system is reached at least once and the system is refilled to manufacturing conditions (represented with a circle). Thus, along its lifetime the energy consumption increases and decreases through time, more times as larger the ALR is. It needs to be mentioned that for the calculations under leakage conditions it has been assumed that the composition of the refrigerant is always the same.

Eq. (7), as a positive term, represents the leakage from the system over time, thus integrating this relation, the leakage as a function of time can be evaluated with Eq. (9), it decreasing exponentially in time; and during the maintenance process with Eq. (10), depending the leakage on the grade of recovery of refrigerant during the refilling.

$$LK(t) = M_{opt} \cdot \left(1 - e^{-\frac{ALR}{12} \cdot t}\right) \tag{9}$$

$$LK_{refil} = M \cdot \left(\frac{EOL}{100} - 1\right) \tag{10}$$

Using Eqs. (9) and (10), lifetime refrigerant leakage in relation to the ALR has been integrated for the four refrigerants along 15 years under two scenarios: first, according to a grade of recovery of refrigerant during the maintenance of 15% (Life cycle climate performance working group - Int 2016); and second, assuming that the remaining refrigerant in the system during each refilling process is sent totally to the atmosphere. Fig. 7 represents leakage during lifetime in relation to the ALR. If the gas is recovered during the maintenance, there are no appreciable differences among the refrigerants. However, if it is not recovered, refrigerants with low mass span will produce larger direct emissions. Difference between two scenarios in terms of emitted refrigerant kilograms ranges from 1.8 to 2.5 times. Nonetheless, considering of a larger or lower EOL using low-GWP refrigerants will have small effect on the environmental metrics, since their contribution is low (Fig. 5).

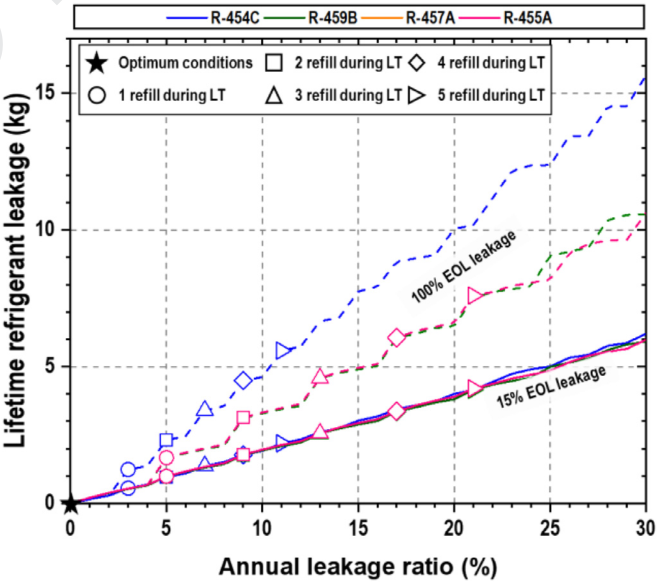

Fig. 7. Refrigerant leakage during lifetime vs. ALR.

Lifetime energy consumption bounded to the ALR has been calculated considering mass charge evolution of Eq. (8) and the experimental measurements given in Fig. 3 using a monthly integration for 15 years. To compute DEC at charges between the experimental measurements a linear interpolation between the measurements has been done. Fig. 8 depicts the results for the considered refrigerants and Fig. 9 the increment in lifetime energy consumption in relation to the energy consumption during lifetime at optimum conditions.

Results of Fig. 8 and Fig. 9 evidence there is an important increment on the energy consumption until a reduced ALR (3% for

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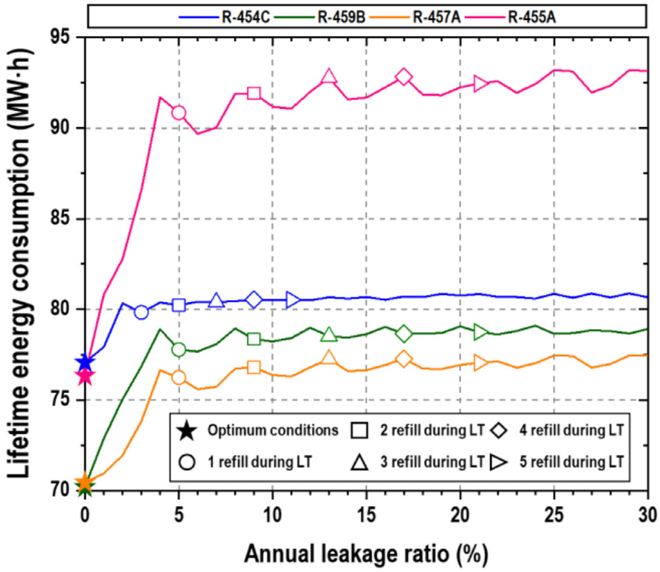

Fig. 8. Lifetime energy consumption vs. ALR.

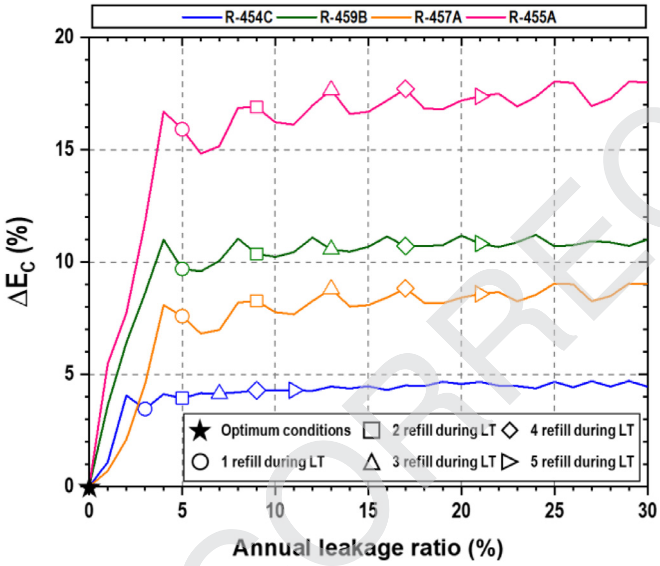

Fig. 9. Variation of energy consumption during lifetime in relation to Ec at optimum charge vs. ALR.

R-454C and 5% for R-459B, R-457A and R-455A). However, this increment stabilizes when at least a refilling is done in the system, which happens at a higher ALR. From the third refilling, the increment on lifetime energy consumption in relation to the optimum conditions achieves a stable value, approximately of 4.45% for R-454C, 10.82% for R-459B, 8.54% for R-457A and 17.34% for R-455A. This percentage is dependent on two parameters that characterize the operation of the system with a given refrigerant (Table 1): the percentage is higher as higher is the mass span, which implies that the system is working with reduced refrigerant charge more time or that the refillings are more spaced in time; and the percentage is higher when higher the energy span is, which implies a higher energy penalty in low charge conditions.

Obviously, consideration of energy consumption at optimum charge could bring about important differences on the real energy consumption and on the TEWI computation. Therefore, next section evaluates the impact of real operation of stand-alone systems on the TEWI.

4.2. Results of TEWI evolution considering leakage ratio

TEWI evaluation considering a close operation to real systems considers leakage of refrigerant during the operation, the dependence of the DEC on the charge, the needed refillings and the forecast prediction of the indirect emission factor.

To evaluate it, a monthly integration has been done along 15 years using the same assumptions as taken in Section 3.2 for the classical evaluation (L =15 yr, ALR =5%, EOL =15%) using the measured operation of the system for the different refrigerants (Fig. 3). Refrigerant mass charge at each month, denoted with the index '*i*' has been evaluated with Eq. (11). First, direct emissions, Eq. (12), are split into two terms: the first that considers the monthly leakage of refrigerant during operation and the second the direct contribution due to the refrigerant unrecovered during each refilling process. Each refilling task is denoted with the index '*j*'. Second, indirect emissions, Eq. (13), consider the DEC for the corresponding refrigerant charge, the number of days of each month and the corresponding carbon index according to Section 3.1.

$$M_i = \begin{cases} M_{opt}\cdot e^{-\frac{ALR}{12}\cdot i}\ if\ M_i \geq M_{min} \\ M_{opt}\ if\ M_i < M_{min} \end{cases} \tag{11}$$

$$EM_{direct} = \sum_{i=0}^{180} M_i\cdot\frac{ALR}{12}\cdot GWP_{100} + \sum_{j=1}^{n} M_i\cdot EOL\cdot GWP_{100} \tag{12}$$

$$EM_{indirect} = \sum_{i=0}^{180} DEC(M_i)\cdot days\cdot EM_i \tag{13}$$

TEWI index has been evaluated for the same economies and refrigerants than those considered in Section 3.2, being the results presented in Fig. 10 and the percentage differences from the classical methodology in Table 3.

It can be affirmed for all the cases and countries that the classical methodology to evaluate TEWI underestimates the total CO_2 emissions. Larger differences occur in the direct emissions, ranging from 38.6 (R-457A) to 148.9% (R-454C) and being correlated with the mass span and GWP of the refrigerant (Table 1). However, its impact in the total emissions is still low. The deviation in indirect emissions ranges from 4.7 (R-454C) to 19.2% (R-455A). In this case, increments are nearly independent on the considered country or carbon index, but they depend on the mass and energy spans (Table 1), so refrigerants with low mass and low energy spans, such as R-454C have lower deviations in the indirect emissions calculation. However, refrigerants with high mass and high energy spans, such as R-455A, have larger discrepancies. In global, deviation of TEWI between the methodologies ranges from 5.25% (R-454C, Germany) to 19.93% (R-455A, France), differences being larger as larger the energy and mass spans are and lower the carbon intensity of a country is.

5. Methodologies discussion

Methodologies contrast made in Section 4 considered a constant ALR of 5%, value recommended by IIR (Life cycle climate performance working group - Int 2016). This section contrasts both methodologies as function of the ALR, since ALR is the most influential variable on the energy consumption of the refrigeration system during its operating lifetime.

To contrast hypothesis, Fig. 11 represents the TEWI differences from both approaches considering a lifetime of 15 yr and an *EOL* of 15% for ALR from 0 to 30%. Three countries are selected, Germany, with the highest carbon index (0.4501 $kg_{CO2}\cdot KWh^{-1}$); Italy, with medium index (0.3213 $kg_{CO2}\cdot KWh^{-1}$); and France, with the lowest carbon intensity (0.0673 $kg_{CO2}\cdot KWh^{-1}$).

Classical TEWI methodology underestimates the emissions for any refrigerant, country and ALR. For ALR tending to zero, devi-

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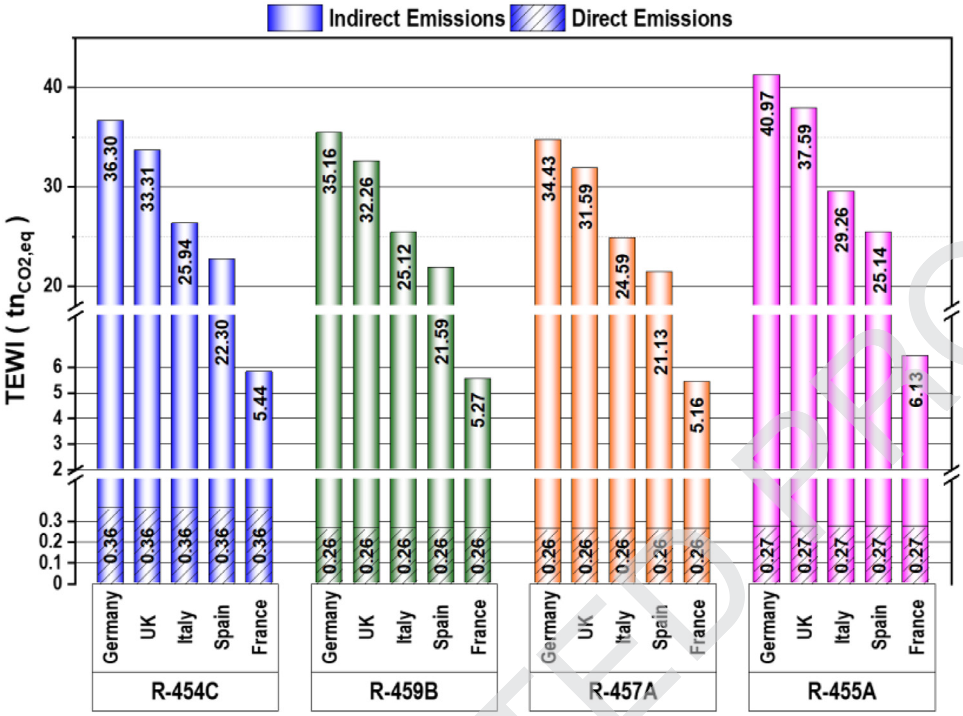

Fig. 10. TEWI of refrigeration system under proposed evaluation. Emission factor predicted from 2019 to 2034. ALR=5%.

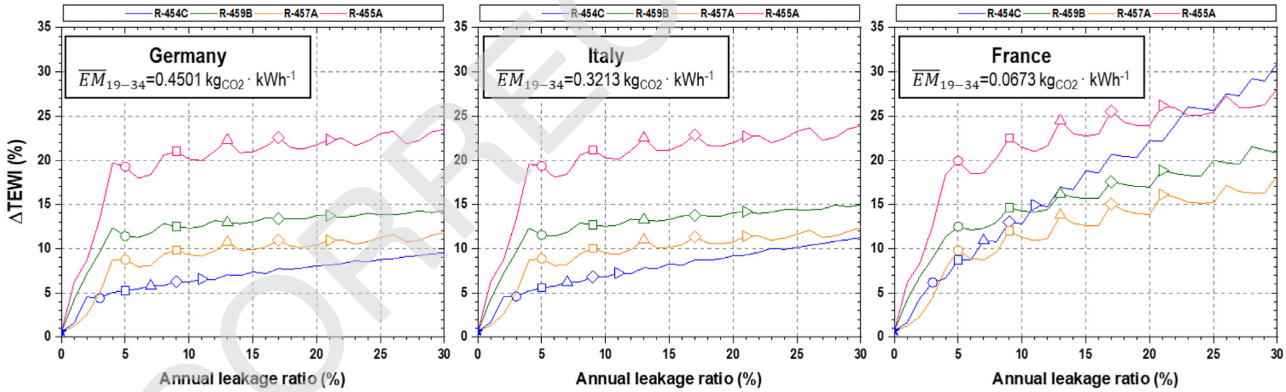

Fig. 11. Difference in TEWI metric between classical and proposed approach vs. ALR.

Table 3
Percentage differences between classical and proposed TEWI methodologies (ALR=5%, EOL=15%, L=15yr).

	R-454C			R-459B			R-457A			R-455A		
	ΔED (%)	ΔEI (%)	ΔTEWI (%)	ΔED (%)	ΔEI (%)	ΔTEWI (%)	ΔED (%)	ΔEI (%)	ΔTEWI (%)	ΔED (%)	ΔEI (%)	ΔTEWI (%)
Germany	148.9	4.7	5.3	40.6	11.2	11.4	38.5	8.6	8.8	38.5	19.2	19.3
UK	148.9	4.7	5.3	40.6	11.2	11.4	38.5	8.6	8.8	38.5	19.2	19.3
Italy	148.9	4.7	5.6	40.6	11.3	11.5	38.5	8.6	8.9	38.5	19.2	19.4
Spain	148.9	4.9	5.8	40.6	11.4	11.7	38.5	8.7	9.0	38.5	19.2	19.4
France	148.9	4.8	8.7	40.6	11.4	12.5	38.5	8.7	9.8	38.5	19.2	19.9

ations are low; however, they quickly increase as the ARL does. TEWI increment slope relaxes when the system is refilled for the first time (represented with a circle), showing stabilizations for economies with high or medium EM. However, for countries with low carbon index the deviation increases as the ALR does.

Differences between methodologies are higher for refrigerants with higher mass and energy spans, such as R-455A, and lower for refrigerants with low mass and energy spans, like R-454C. However, it is important to highlight that among the countries, with different EM values, deviations are of the same order of magnitude.

It can be affirmed that the discrepancies between TEWI methodologies depend on the ALR, energy or mass span and the EM index. Authors have tried to correlate these variations among the countries and refrigerants, but we have not been able to obtain a general rule to quantify the deviation.

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6. Conclusions

This work contrasts the classical TEWI methodology, based on constant ALR, to evaluate the environmental performance of a stand-alone refrigeration system using low-GWP, with a new approach considering the energy dependence of the system with the ALR.

Classical TEWI method shows that for systems with low-GWP refrigerants (GWP<150), the direct emissions can be neglected, but the influence of underloaded systems on its annual energy consumption is high. With these refrigerants it is crucial to represent with the highest possible accuracy the energy behaviour of the systems. Classical TEWI for the different low-GWP refrigerants do not show differences between them inside a country, and differences between countries are correlated with the carbon index.

In relation to the real operation, the energy consumption during the lifetime of a system, if it has leakage, increases in relation to that at optimum conditions. If no refilling is needed during the lifetime, the increment reaches between 4.06% (R-454C) to 16.70% (R-455A). But from the third refilling on, the increment in energy consumption during lifetime stabilises, the increments being between 4.45% (R454C) to 17.34% (R-455A). These increments depend upon the energy and mass spans of the system.

New TEWI methodology, considering the dependence of energy consumption with the charge evolution, indicates that the classical approach always underestimates the total emissions. Increments in direct emissions range from 38.6% to 148.9%. However, its contribution in the total emissions is still low and they can be neglected. Nonetheless, increments in indirect emissions range from 4.7% to 19.2%, they being independent on the carbon economy, but being related with the mass and energy spans. In general terms, TEWI discrepancies between both methodologies go from 5.25% to 19.93%.

It can be affirmed that the classical TEWI approach underestimates emissions for any country, any refrigerant and any ALR. Deviations increase with ALR, especially for those that do not imply a refilling during the lifetime of the system, and trend to stabilise for subsequent refillings only for medium and high carbon economies. The deviations are higher as higher the mass and energy spans are.

Therefore, we must advice that for employing the TEWI evaluation for stand-alone systems working with low GWP refrigerants it is crucial to consider the dependence of the energy consumption with the charge of the system, since considering for the evaluation that the refrigerant charge keeps constant in the optimum value brings about deviations of this parameter that can reach up to 20%.

Declaration of Competing interests

The authors declare that they have no known competing financial interests or personalrelationships that could have appeared to influence the work reported in this paper

Acknowledgments

Authors gratefully acknowledge Conselleria d'Educació, Investigació, Cultura i Esport de la Generalitat Valenciana (project AICO/2018/058) and the Ministry of Science, Innovation and Universities of Spain (RTI2018-093501-B-C21) for financing this research work.

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