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Expanded Total Equivalent Warming Impact analysis on experimental standalone fresh-food refrigerator

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ABSTRACT

The stand-alone refrigerators for fresh food storage represent a large part of supermarket refrigeration equipment. In these devices, the usage of refrigerants with low Global Warming Potential allows the mitigation of the direct emissions due to refrigerant leakages. In contrast, the indirect emissions in these components are highly dependent on the refrigerant charge, leakage, and equivalent emission factors related to the electricity production mix. The most used index to evaluate the environmental impact of refrigerators is the Total Equivalent Warming Impact. Despite that this index presents limits on the fixed evaluation of many parameters such as refrigerant charge, electricity consumption and, electricity emission factor. Otherwise in this study, an accurate evaluation of refrigerators emissions has been realised by using the innovative Expanded Total Equivalent Warming Impact method to an experimental stand-alone refrigerator by using a dynamic approach to evaluate direct and indirect contributions. The environmental analysis considers four different refrigerants and four different countries of location. The results show that the indirect emissions due to electricity consumption cover the highest share of emissions. In addition, the operating years affected by low refrigerant charges are responsible for emissions by greater than 25% compared to other ones. The hourly equivalent emissions due to electricity consumption in countries characterized by an electricity generation mix mainly based on renewable and/or nuclear plants show an indirect environmental impact up to 5 times lower than countries with a natural gas-based electricity production mix. The study also defines new strategies to reduce the environmental impact of the stand-alone refrigerator such as the use of photovoltaic systems combined with this technology or earlier maintenance processes that could determine an equivalent emission saving of up to 38%.

Introduction

“Energy cold chain” represents the energy consumption and the environmental effects due to food storage from the production to the end-consumption. Fresh foods such as fruit, meat, fish, or vegetable, start to deteriorate after the pre-treatment. The deterioration process is slowed by reducing the food storage temperature [1]. For example, passing from a storage temperature equal to 7 °C to 4 °C, the storage life of fresh food can be extended by 50%.

The energy conversion devices of the food supply chain are one of the most energy-intensive technologies representing sustainability challenges. The refrigeration sector accounts for 7.8% of the world’s greenhouse gas emissions (GHGs), 37% of them are imputable to direct leakages of refrigerant, and 63% to indirect emissions due to electricity consumption [2]. The refrigeration sector (including air conditioning) consumes about 20% of the overall electricity used worldwide. The electricity consumption caused by refrigeration accounts for about 35% of the electricity consumption in the food industry [3]. Commercial systems such as condensing units, stand-alone equipment, and centralized systems cover worldwide about 120 million units and in addition, about 5 million refrigerated vehicles and 1.2 million refrigerated containers are used. The registered supermarkets were worldwide 477,000 in 2015 with a surface area variable from 500 to 20,000 m^2. In these retail buildings, the refrigerant processes cover a variable range equal to 30 ÷ 60% of the electricity consumption [2]. The refrigeration also involves restaurants, cafés, and fast food where the food is stored until end-consumption. The most diffused systems for food refrigeration are

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Nomenclature

AdpGWP	GWP of Atmospheric Degradation Product of the Refrigerant [$kgCO_2/kg$]
ALR	Annual Leakage Rate [y^{-1}]
C	Refrigerant charge [kg-g]
CO_2	Equivalent carbon dioxide emission[$kgCO_2$]
E	Energy [kWh/y]
EOL	Stop operating Refrigerant Leakage
ETEWI	Expanded Total Equivalent Warming Impact[kgCO- tCO_2]
$f_{el,NG}$	Percentual gas natural composition of power grid mix[%]
f_{FL}	Loss factor for natural gas grids
GWP	Global Warming Potential[$kgCO_2/kg$]
L	Lifetime[y]
LHV	Lower heating value[kJ/kg]
RL	Monthly refrigerant leakage[g]
T_p	Product temperature[K], [°C]
TEWI	Total Equivalent Warming Impact[$kgCO_2$- tCO_2]
V	Volume[m^3]

Greek symbols

α	Electric transmission grid emission factor [$kgCO_2/kWh_{el}$]
ρ	Density [kg/m^3]
ϑ	Time [h]
$\eta_{el,NG}$	Thermoelectric gas-based power plant efficiency

Subscripts and superscripts

dir	Direct
el	Electric
FL	Fuel Loss
ind	Indirect
lim	limit
mix	Fuel mix composition
PP	Power Plant
RL	Refrigerant Leakage
T&D	Transmission and Distribution

Acronyms

EEV	Electronic expansion valve
GHG	Greenhouse gases
HCFC	Hydrochlorofluorocarbon
HFC	Hydrofluorocarbons
IHX	Internal heat exchanger
LCCP	Life Cycle Climate Performance
PV	Photovoltaic
T&D	Transmission and distribution pipeline
UHI	Urban Heat Island
VCC	Vapor Compressor Cycle

solid door cabinets used for fresh food, they are based on plug-in units with the refrigeration system on board. The direct emissions due to refrigerant leakages for stand-alone systems are lower than larger remotely operated cabinets with a central refrigeration plant because the first ones show a lower yearly percentage of leakages than the second ones. Otherwise, the leakages in remote refrigeration plant can vary from an average of 3% per year at best to 20–30% per year at worst. In fact, the refrigerant leakages in the supermarkets vary considerably. To reduce the direct emissions the best practices, suggest some actions such as the refrigerant charge reduction, the use of low Global Warming Potential (GWP) fluids, the use of secondary fluids with centralized system, and the collection and evaluation of maintenance data [4]. Hydrochlorofluorocarbon (HCFC) and hydrofluorocarbon (HFC) were the most dominant refrigerants used in pre-existing supermarkets, while R744 and hydrocarbons are increasing today. In addition, to reduce the direct impact, the F-Gas Regulation for European Union imposed HFCs limits [5] following the Kyoto Protocol [6]. Despite that, in 2016, 35% of HFC uses were dedicated to refrigeration distinguished in 73%, 20%, 5%, and 2% for commercial, industrial, transport, and domestic sectors, respectively [7]. Furthermore, the indirect emissions associated with electricity consumption of refrigerators must be reduced. According to that, some directives have been defined by acting on energy sources and energy conversion devices efficiency such as Eco-Design Directive [8] and on the energy efficiency of systems in partial load operating conditions [9].

The evaluation of the environmental impact of air-to-air or air-to-water vapor compressor cycles (VCCs) in domestic, industrial, and commercial refrigeration has been usually realized by using the Total Equivalent Warming Impact (TEWI) index or the Life Cycle Climate Performance (LCCP) according to literature review formulation [10], a suggestion of the international technical committee [11,12] and European standard [13]. TEWI is the most used index for carbon dioxide equivalent (CO_2) emissions calculation in air conditioning and refrigeration sectors by including both the direct and indirect contributions since it evaluates the emissions caused by the operating lifetime of systems. Otherwise, the LCCP includes also the GHG emissions produced after and before the lifetime of the systems. Despite that, some studies have demonstrated that the complexity of calculation in LCCP analysis does not determine a substantial difference in the results compared to those one achieved through the traditional TEWI investigation [14] by showing differences lower than 10% for refrigeration sector by comparing the two methods [15]. In particular, the environmental impact of supermarket refrigerators is often investigated by using the TEWI methodology too [13]. The comparison between a system equipped with R1234ze as the primary refrigerant in indirect systems coupled with R404A multiplex and R134a/CO_2 cascade systems shows that the first plant determines a higher energy consumption but also a lower TEWI with respect to the second one [16]. A commercial refrigeration unit of 2.5 kW is investigated by considering different fluids and emission factors related to different countries. The authors have performed an analysis by using the TEWI method demonstrating that the solution with the highest performance does not correspond to the solution with the lowest environmental impact due to indirect emissions and the results highly depend on the power grid carbon dioxide emission factor [17]. TEWI analysis is also applied to demonstrate that the high efficiency multi-ejector system leads to a reduction of the environmental impact by 90.9% compared to the traditional one in supermarket located in warm zones [18]. A study on supermarket refrigeration systems is conducted by using TEWI-based environmental analysis to compare eight types of CO_2 booster refrigeration systems to an R404A-based one. The results show that the indirect avoided emission is equal to 18% [19]. An additional study considers the possibility to reduce energy consumption and indirect emissions of refrigeration systems by using artificial neural networks with the fixed-speed compressor-based systems showing a reduction of energy consumption from 2.2% to 6.8% [20]. In addition, some researchers have proposed the use of two refrigeration technologies such as vapour compression and magnetocaloric refrigeration to increase the coefficient of performance in transcritical CO_2 cycles to reduce the emissions due to electricity consumption [21]. TEWI method is also used in the air conditioning sector such as in various high-temperature heat pump applications [22]. In district heating networks, it is used to define the carbon emission savings due to the equipment with low GWP alternative fluids to HFC-245fa. Panella et al. [23] have defined a TEWI analysis for an air-source heat pump for residential air-conditioning. The analysis has been conducted by assuming different locations and by including not planned and ordinary maintenance. The impact of faults on seasonal performances and TEWI has also been analysed. The results have highlighted that the refrigerant leakages can have an impact on system performance higher than 25%, whereas heat exchangers fouling can downgrade the efficiency by approximately 15%. TEWI metric is also used to test the environmental optimum performance of a solar-assisted heat pump [24] and the environmental performance of heat pump water heaters by including the replacement of the conventional R410A with innovative refrigerants such as R32, R446A, and L41b. This replacement determines TEWI values lower than those achieved with R410A by a percentage varying in the range of 5.9 ÷ 9.9% demonstrating the high effect of GWP on environmental performance [25]. A Spanish study on an experimental comparison of low GWP refrigerants used in vapour compression cooling and heating systems defines also the TEWI evaluation of components assuming a fixed emission factor for electricity mix without considering seasonal or daily variation of electricity production [26].

All previous studies have been conducted by using the TEWI metric and by considering a static evaluation of electricity consumption, refrigerant charge and/or emission factor for electricity. In fact, some criticalities about TEWI have been defined by investigating literature review such as the use of fixed refrigerant charge and leakages; the annual electricity evaluation; the use of fixed and obsolete electricity emission factors, the absence of local emission evaluation for Urban Heat Island as a function of climate location and the absence of an evaluation of the impact of refrigerant charge on indirect emissions. In reason of that, additional studies that define TEWI upgrade to improve the analysis have been considered; they take into account the refrigerant charge variation during the operating time [27], the components corrosion [28], the dynamic evaluation of indirect term such as the use of time-varying carbon dioxide emission factor for electricity [29] or the dynamic electricity consumption evaluation [28], and the additional emissions due to atmosphere degradation products of refrigerant [15]. In [27] an environmental analysis on a commercial refrigerator system is conducted by using firstly traditional TEWI method and by considering the refrigerant charge evolution during its lifetime. The results show a variation in TEWI value in the range of 5.3 ÷ 19.9% depending on refrigerants and considered country passing from traditional TEWI evaluation to innovative one. In detail, the highest variability is showed for the country with a low emission factor for electricity production such as France which presents the highest direct effect contribution. Despite that in this study the hourly value of the emission factor for electricity production has not been considered. In [28] the TEWI methodology has been defined by including corrosion evaluation on residential air conditioning systems. The results show that the total lifecycle emissions of systems can be reduced by 6 ÷ 10% through the mitigation of the corrosion. Maiorino et al. [15] have added an additional contribution due to the degradation of refrigerant in the atmosphere to the traditional direct term by placing the TEWI method near LCCP. Otherwise in [30] a detailed analysis of energy consumption on an hourly basis for a refrigerator has been used to evaluate a solar PV-powered vaccine refrigerator in remote locations. By including all literature suggestions about the necessity to extend the TEWI index, Ceglia et al. [31] have proposed an innovative environmental index, the Expanded Total Equivalent Warming Impact (ETEWI), that is an accurate upgrade of traditional TEWI evaluation. The first novelty of this index includes the extension of formulation to natural gas-fuelled systems with respect to the TEWI index that is useful only for electric-based devices. In addition, the traditional direct (due to refrigerant leakages) and indirect (due to electricity consumption) terms have been accurately defined by using a dynamic analysis for energy consumption, the emission factor for electricity production, and refrigerant leakages. The "dynamic approach" of the ETEWI method follows the variables' trends leaving out the TEWI approach that considers the use of fixed yearly value for energy consumption, obsolete and fixed emission factor for electricity during all lifetime, and constant value of refrigerant charge into the system. ETEWI includes the dynamic behaviour of previously cited parameters by using a fixed step equal to one month for direct emissions and to one hour for indirect ones. Moreover, the greenhouse contribution depending on fuel losses in distribution and transmission pipelines and Urban Heat Island (UHI) phenomenon are included too.

In this work, the innovative ETEWI analysis has been applied to a case study for the first time in the scientific literature. In particular, an experimental stand-alone refrigerator system used for fresh food storage in a supermarket has been investigated. The study involves four low-GWP fluids (R455A, R457A, R459B, and R454C) and four countries of location (Italy, Spain, France, and Denmark) that differ in electricity generation mix. In section 2 the experimental system is defined by including the experimental results about energy consumption of the system in different refrigerant charge operating conditions. In section 3 the ETEWI methodology is recalled according to the case study and in subsection 3.2 the materials and used data are reported. Section 4 show the results for each term of ETEWI. The novelty of this study is referred to the application of the new environmental index to a real case study and to the definition of suggestions and possible upgrades for the stand-alone systems to reduce the environmental impact of these devices on supermarket emissions. The objective of this work is double. First, it is aimed to analyse the influence of the dynamic evaluation and refill process of refrigerant charge of an open-fronted vertical cabinet for fresh food system during its lifetime from an environmental point of view. Furthermore, this evaluation is aimed to investigate the direct emission effect on indirect one by evaluating the energy consumption variation (and the associated indirect emissions) as a function of refrigerant charge. The second aim regards the possibility to evaluate the hourly indirect emission thanks to the availability of experimental electricity consumption measurement and the hourly emission factor associated with electricity mix of each considered country. This type of combined analysis has never been presented in the literature referred to TEWI analyses. This dynamic evaluation influences the direct emission due to refrigerant leakages and indirect emissions caused by energy consumption and device efficiency which are influenced by refrigerant charge. In addition, the indirect emissions due to natural gas transmission leakages have been investigated to understand the differences of the environmental influence of this device in each country including a new TEWI contribution never used before. This study has been realised by using MATLAB code [32].

Reference system and experimental performance

In this section, the description of the experimental apparatus (subsection 2.1) is defined and the results of ETEWI analysis conducted by the experimental tests on the system (subsection 2.2) are showed.

Reference system

The reference system is a stand-alone refrigerator considered by Llopis et al. [27], and it is here briefly described. It is given by a commercial open-fronted vertical cabinet equipped with a frontal air curtain, intended for fresh food preservation. The system, originally designed for R-404A, is also able to operate with low-GWP refrigerants without the retrofit requirements for the compressor. In particular, four fluid R-455A, R457A, R-459B, and R-454C have been tested by considering their GWP values based on experimental results as shown in Table 1. They have been considered according to ISO 23953-2. In addition, they present a GWP below 150 $kgCO_2/kg$ and they have an A2L ASHRAE security classification.

Each refrigerant allowed an energy consumption reduction after a

Table 1
Global Warming Potential of tested fluids.

	R455A	R457A	R459B	R454C
GWP [$kgCO_2/kg$]	146	139	143	146

charge optimization, briefly described in subsection 2.2. The system consists of a finned-tube evaporator placed inside the cabinet, an electronic expansion valve (EEV), a microchannel air condenser, and an internal heat exchanger (IHX) and it is driven by a compressor with a nominal capacity equal to 22.37 cm^3, as shown in Fig. 1. Tests were carried out by instrumenting the cabinet with an energy wattmeter (accuracy of $\pm$ .5%) to measure the electrical power consumption, a Coriolis mass flow meter, 6 pressure gauges, 10 T-type thermocouples, and a thermo-hygrometer. The system was placed inside a climatic chamber so that the environmental temperature and relative humidity, respectively 25.5 °C and 50%, were controlled during tests according to the standard ISO 23953-2:2015 and measured with another thermo-hygrometer. The product temperature (T_p) was measured using 6 M-test packages (1000 g). They are T-type thermocouples according to ISO 25953-2. The schematic layout of the reference system and its real representation are shown in Fig. 1.

Experimental performance of system

Llopis et al. [27] have conducted the energy consumption tests based on 24 h to evaluate the cabinet's performance by considering different operating conditions by varying the refrigerant charges for all fluids. The system operates under ON/OFF mode, considering an average product temperature of 5.0 $\pm$ 0.1 °C. The electricity consumption is given by the contribution of both the compressor and the auxiliaries (fans, lights, control, and defrosting systems). One defrosting phase is performed every six hours. Charge optimization is done starting from a minimal refrigerant charge equal to 800 g, which allows maintaining the products temperature up to the optimal value for each refrigerant using 100 g steps. Table 2 summarizes the experimental results in terms of daily energy consumption, for each refrigerant at different charge values.

Expanded total equivalent environmental impact methodology

The ETEWI formulation has been developed by Ceglia et al. [31] as defined in the following description. The new formulation of the index is an upgrade to traditional TEWI which was in origin developed by Fischer [10]. Firstly, ETEWI can be used for environmental analysis of both electric-based and gas-driven energy conversion systems while traditional TEWI is referred only to electric ones. The two "traditional" TEWI terms, of which one depends on direct emissions due to refrigerant leakages and one is related to the indirect emissions due to electricity consumption, are analysed more in detail by considering the time variability of parameters used in the calculation. In addition, ETEWI includes additional terms due to the indirect emissions caused by fuel losses in pipelines dedicated to both distribution and transmission and the UHI phenomenon. With reference to the stand-alone refrigerator analysed in this study, the ETEWI index does not include the direct

Table 2
Experimental results of daily electricity consumption as function of measured refrigerant charge.

Refrigerant Charge [g]	Daily electricity consumption [kWh]			
	R455A	R457A	R459B	R454C
800	21.52	16.61	15.84	15.84
900	19.26	15.42	15.81	14.91
1,000	17.66	14.34	14.63	14.20
1,100	16.26	13.73	14.38	14.08
1,200	15.34	13.31	14.01	*

*Maximum possible charge 1100 g.

combustion since it is an electric-driven device, thus the ETEWI formulation is reported in Eq. (1) under this hypothesis:

$$ETEWI = TEWI_{dir}^{RL} + TEWI_{dir}^{UHI} + TEWI_{ind}^{PP} + TEWI_{ind}^{T\&D} + TEWI_{ind}^{UHI} \quad (1)$$

$TEWI_{dir}^{RL}$ is the direct emission term caused by refrigerant leakages, $TEWI_{dir}^{UHI}$ is the direct contribution related to UHI effects, $TEWI_{ind}^{PP}$ is the indirect term depending on electric energy uses for VCCs, $TEWI_{ind}^{T\&D}$ takes into account the indirect emissions due to natural-gas losses and finally $TEWI_{ind}^{UHI}$ is the indirect contribution related to UHI effects [31].

In this section the methodologies and equations that express each term are defined (subsection 3.1) and the subsection related to materials is presented (3.2).

Methodologies

The ETEWI formulation is reported in Eq. (1) for a VCC system, and each contribution will be detailed in the following description.

Regarding the direct term due to refrigerant leakages, $TEWI_{dir}^{RL}$, it represents the CO_2 emissions due to refrigerant leakages of system and it is reported in Eq. (2).

$$TEWI_{dir}^{RL} = C \bullet (L \bullet ALR + EOL) \bullet (GWP + AdpGWP) \quad (2)$$

In order of appearance, C is the refrigerant charge of VCCs [kg], L is the lifetime assumed for stand-alone refrigerator [y], ALR is the leakage ratio of refrigerant charge per year [y^{-1}], EOL is the refrigerant leakage during VCCs' disposal [-], GWP [$kgCO_2$/kg] is the contribution of refrigerant to global warming expressed as a relative measure of CO_2 emissions and AdpGWP [$kgCO_2$/kg] is the emissions' contribution due to the atmospheric degradation products of the refrigerant [11]. According to Llopis et al. [27] the refrigerant charge can be calculated by using a dynamic approach. This approach implies the evaluation of refrigerant charge, leakages, and leakage factors on monthly basis. In this way the refrigerant leakages are obtained on monthly basis (RL(i)) by using Eq. (3). The latter term is evaluated by multiplying the refrigerant charge at month i-1 (C(i-1)) per ALR factor in each month by considering that ALR is constant, and the refrigerator works 12 months,

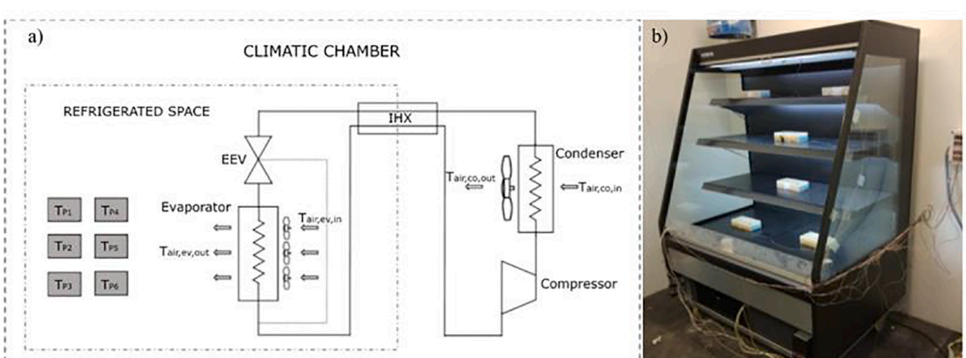

Fig. 1. Schematic layout of the reference system (a) and real representation (b).

thus the refrigerant mass inside the system is evaluated as a time function.

$$RL(i) = C(i-1) \bullet \frac{ALR}{12} \quad (3)$$

The refrigerant charge is evaluated on monthly basis by considering that for each i-th month the C(i) in the system is equal to the charge present in the previous month C(i-1) reduced by the refrigerant monthly leakage. The refrigerant change decreases from the nominal value fixed at first month C(1) up to the minimum charge that allows the operation of the system and then a refilling is realised [27]. This evaluation includes the dependence on useful lifetime, maintenance operations and operating conditions. In Eq. (4) the expanded version of $TEWI_{dir}^{RL}$ is expressed as a function of operating months.

$$TEWI_{dir}^{RL} = (GWP + AdpGWP) \bullet \left[\sum_{i=1}^{n} RL(i) + C(n) \bullet EOL + \sum_{j=1}^{m} C(j) \bullet EOL \right] \quad (4)$$

In Eq. (4) n is the number of total months for the lifetime, C(n) is the refrigerant charge in the last month of operation, C(j) is the refrigerant charge in the system in each j-th maintenance period and m is the total number of refilling maintenances. In the Eq. (4) RL is evaluated by considering the real charge presents in the system differently from traditional TEWI in which the fixed initial charge during all operating periods of devices is used, overestimating this effect. Otherwise, the evaluation of the maintenance effect by using C(j) allows considering additional leakages neglected in the traditional TEWI approach.

In this study, the leakage process is considered to have a constant composition of the refrigerant while in real conditions, the composition of the refrigerant changes through the lifetime.

Regarding the indirect term related to electricity consumption, the dependence on different aspects such as the electricity consumption due to the operating time, VCC's efficiency, and the CO_2 emission factor of the electricity production mix [33] have been considered. The $TEWI_{ind}^{PP}$ formulation is reported in Eq. (5):

$$TEWI_{ind}^{PP} = \sum_{\theta=1}^{\theta_{end}} \alpha(\theta) \bullet E_{el}(\theta) \quad (5)$$

where α(θ) represents the hourly CO_2 emission factor for the electricity production mix of a specific country or zone [29] [$kgCO_2/kWh_{el}$] and $E_{el}(\theta)$ is the hourly electricity consumption of VCC [kWh_{el}/y]. This dynamic evaluation considers all hours of the lifetime period by delating the use of annual value for energy consumption and fixed and obsolete emission factors as reported in the traditional TEWI method. In this study, α(θ) is obtained with an hourly timestep with reference to one year. It takes into account the renewable pervasion in the electricity production mix of each country and the seasonal and daily climate conditions. $E_{el}(\theta)$ is calculated by using experimental data as a function of refrigerant charge variation. The evolution of charge evaluated as reported in Eq. (3) allows determining the associated energy consumption by using experimental data listed in Table 2. Differently from the traditional TEWI approach it is possible to understand if the influence of hourly emission factor can mitigate the environmental impact evaluation of VCC.

Regarding the evaluation of the indirect contribution of natural gas leakages on transmission and distribution pipelines supplying thermoelectric power plants, $TEWI_{ind}^{T\&D}$ term is proposed, and it is expressed in Eq. (6) by considering a yearly approach. With this equation, it is possible to estimate the CO_2 emissions associated with stand-alone refrigerator operation and related to the leakages of natural gas used in the electricity production mix of each country.

$$TEWI_{ind}^{T\&D} = L \bullet V_{FL} \bullet \overline{GWP}_{mix} \bullet \overline{\rho}_{mix} \quad (6)$$

where V_{FL} [m^3] is the total lost volume of natural gas during the lifetime of VCC, $\overline{GWP}_{mix}$ is the GWP of natural gas [$kgCO_2/kg$] and $\overline{\rho}_{mix}$ [kg/m^3] is the density of the natural gas mixture. The leaked natural gas volume, V_{FL}, is calculated by considering the share of electricity ($f_{el,NG}$ [-]) produced by natural gas-fuelled thermoelectric plants and the loss factor on transmission pipelines f_{FL} as reported in Eq.(7).

$$V_{FL} = f_{FL} \bullet \frac{E_{el} \bullet f_{el,NG}}{LHV \bullet \eta_{el,NG}} \quad (7)$$

where LHV and $\eta_{el,NG}$ are the lower heating value of natural gas and the natural-gas thermoelectric power grid efficiency, respectively.

Regarding the UHI effects for generic VCCs (electric air-to-air and air-to-water devices), the evaluation of the UHI phenomenon is complex and it depends on VCC operating conditions and location. As the matter of fact, if on one hand UHI affects VCCs' electricity requests and performance, on the other hand the use of VCCs to meet space heating and cooling demands, exacerbates UHI phenomenon. For this reason, in the theoretical ETEWI definition [30], the UHI effect is distinguished in two terms. The first term is the direct contribution of UHI $TEWI_{dir}^{UHI}$ that depends on local temperature increase caused by the heat discharged from the condenser of the device in cooling operation. This ETEWI's term represents the conversion of the local temperature increase into CO_2 emissions. Otherwise, the second term, $TEWI_{ind}^{UHI}$, is the indirect effect that depends on higher electricity demand of VCC due to temperature increase. Indeed, this increase determines a lower coefficient of performance and a higher cooling demand with respect to the absence of the UHI phenomenon. In this study, both terms associated with UHI have not been evaluated. In detail the $TEWI_{dir}^{UHI}$ is not calculated due to the condenser heat is rejected in a temperature-controlled environment thanks to that the condenser of the stand-alone refrigerator is an indoor air conditioning space (such as a supermarket),and it does not influence the external air temperature. Moreover, the $TEWI_{ind}^{UHI}$ is included in the local evaluation of TEWI term due to energy consumption. As reported in the literature about ETEWI [30] the dynamic evaluation of electricity consumption allows the inclusion of coefficient of performance evolution and cooling demand variation with the environment temperature increase due to UHI phenomenon.

Materials

In this section the materials used to calculate ETEWI terms reported in subsection 3.1 will be detailed. The direct emissions due to refrigerant leakages, $TEWI_{dir}^{RL}$, have been calculated by using GWP data (as reported in Table 2), ARL and EOL values were fixed to 0.05 y^{-1} and 0.15, respectively, as suggested by International Institute of Refrigeration [11]. The AdpGWP of considered fluids is not available in the literature, in addition, this term has a little contribution on TEWI for low-GWP refrigerants and its neglection does not affect the results. The number of operating years, L, is equal to 15 (180 months). The refrigerant leakages are dynamically evaluated month by month since its hourly and daily variability during experimental test results is negligible with respect to the monthly-based one. As regards to the $TEWI_{ind}^{PP}$ term, the hourly electricity has been calculated for each hour of the day by considering a constant device operating and it is influenced by the refrigerant charge value. The α(θ) values are obtained by electricityMap software that takes into account the harmonized lifecycle greenhouse gas emission of each energy source [34]. These data are calculated thanks to the specific emission factors of each energy source. Most of them are reported in Table 3. The electricityMap uses the real-time data of electricity "production" by considering a distinction among different generation technologies and providing a real-time CO_2 emission for all actors involved making this data available online for 24 h before the visualizing time. The carbon intensity includes the emissions due to the lifecycle of the plant, infrastructure, and operations. For example, the

Table 3
Emission factor of each .

Source	α [gCO_2/kWh]
Natural gas	490
Coal	820
Fossil Oil	650
Biomass	230
Photovoltaics	45
Nuclear	12
Hydroelectric	24
Wind	11
Geothermic	38

Source [34]

operational emissions include all emissions occurring over the fuel chain and direct emissions on site for fuel-based plants. While the operational emissions are therefore higher than only direct combustion emissions for fossil fuels, finally, the emissions are strictly dependent on maintenance operations for solar, geothermal and wind [35].

In Fig. 2 the hourly α(θ) value of each considered country is reported for 2019. The emission factor of France has a low seasonal variability due to the high use of the nuclear source in the electricity production mix during all months of the year. Otherwise, the countries that have a high variability of the electricity mix, show greater seasonal variability than France. For example, in Italy, the mean monthly value of emission factor is equal to 426.9 gCO_2/kWh_{el} in January while it decreases to 380.8 gCO_2/kWh_{el} during August due to the highest penetration of solar source in the electricity production mix in this month. In Spain, the mean monthly value of α(θ) factor is equal to 241.8 gCO_2/kWh_{el} in January while it shows the lowest mean monthly value during September accounting for 218.4 gCO_2/kWh_{el}. In the same way, in Denmark, the mean monthly value of the emission factor is equal to 293.3 gCO_2/kWh_{el} in January while it reaches 113.8 gCO_2/kWh_{el} during July. This observation clarifies that the evaluation of indirect emission by using a fixed annual-based value of CO_2 emission factor for electricity production (as reported in traditional TEWI) can jeopardize the correspondence of the results to real operating conditions.

Regarding the indirect term due to the natural gas leakages $TEWI_{ind}^{T\&D}$, the yearly mean percentage of natural gas $f_{el,NG}$ used in the electricity production mix in each country (Table 4) has been considered [36] to evaluate the corresponding volume of natural gas lost in transmission pipelines by considering a fixed loss factor, f_{FL} , equal to 0.05% [37].

The numerical algorithm of the ETEWI procedure is implemented in MATLAB. The algorithm consists of a main code and three different

Table 4
Percentage of natural gas used in the electricity production mix in 2019.

Country	$f_{el,NG}$ [%]
Spain	26
Italy	49
Denmark	4
France	7

MATLAB functions to solve separately the direct refrigerant leakage TEWI evaluation, the indirect TEWI calculation for the power plants, and the indirect TEWI due to natural gas leakages. The $TEWI_{dir}^{RL}$ function allows the evaluation of charge and leakage of refrigerant on monthly basis by using 180 iterative steps. The parameters at step *I* can be evaluated by Eq. (3) by considering the leakages of *i-1* step. Step by step (month by month) $TEWI_{dir}^{RL}$ is calculated by including the refrigerant leakage due to operation and the refilling and phase-out ones too. For the definition of the refilling process, a counter variable has been introduced. Otherwise, the functions associated with both indirect contributions ($TEWI_{ind}^{PP}$, $TEWI_{ind}^{T\&D}$) are determined through an hourly-based calculation procedure. Finally, in the main code, all contributions are combined to evaluate the yearly ETEWI.

Results

In this section, the results of ETEWI environmental analysis is presented following the methods described in the previous sections.

In subsection 4.1 the main results about $TEWI_{dir}^{RL}$ are reported, in subsections 4.2 and 4.3 the main outcomes about $TEWI_{ind}^{PP}$ and $TEWI_{ind}^{T\&D}$ are described, respectively, and finally, in subsections 4.4 and 4.5 the discussion on ETEWI global results and possible solutions are defined.

Results about direct refrigerant leakage emissions

The results referred to direct emissions are strictly linked to the refrigerant loss and refrigerant charge into the system during the maintenance operations and plant phase-out. The time step of direct emissions evaluation is fixed equal to a month. The initial charge inside the system at first month C(1), which corresponds to the maximum charge value (equal to 1200 g for R455A, R457A, R459B, and 1100 g for R454C as reported in Table 2), decreases to the limit charge (C_{lim}) equal to 800 g for all considered fluids. During the month when C(i) is lower or equal to C_{lim}, the refilling work is carried out. The first three fluids

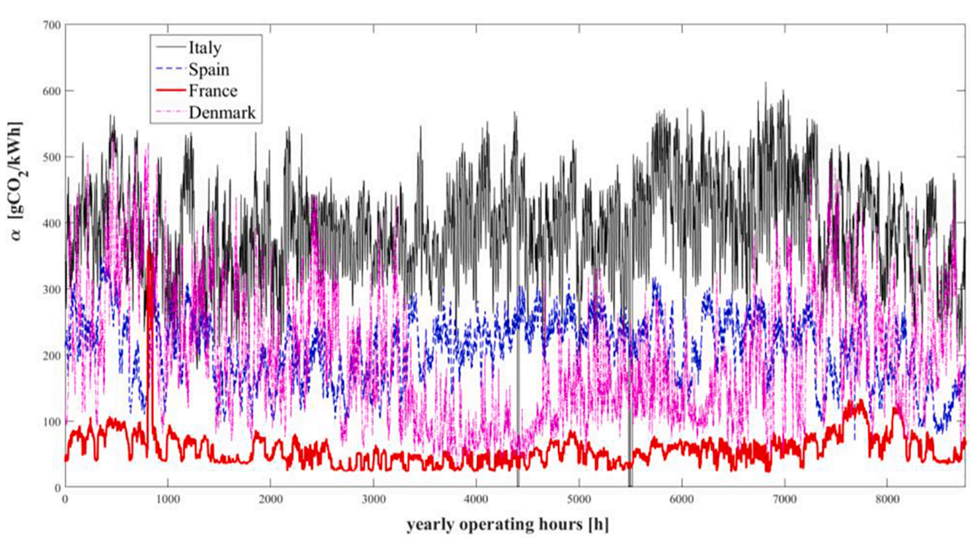

Fig. 2. Hourly emission factor in 2019.

(R455A, R457A, and R459B) require one maintenance work to refill the refrigerant charge during the whole lifetime, occurring at the 98th month (ninth year). Differently, the last fluid (R454C) requires two refilling processes one during the 7th year (77th month) and another one at the 13th year (154th month) due to its lower maximum refrigerant charge (1.1 kg) than the other three fluids (1.2 kg), as reported in Table 2. In Fig. 3, the trends of refrigerant charge are reported for each fluid during the operating time, and the refill processes are shown too, by evaluating the monthly leakage of refrigerant (RL(i)) as reported in Eq. (3). The refrigerant charge varies in range of 3.3 ÷ 5.0 g for the first three fluids and 3.3 ÷ 4.6 g for R454C. The highest monthly refrigerant leakage is verified during the operating months that show the greatest refrigerant charges, such as the first months and the months following the refill process. The lowest refrigerant leakages are verified during the months before the refilling. During the last operating month (phase-out of the system) and the month of refilling, the system undergoes ALR and EOL effects by showing the highest refrigerant leakages. In addition, in the last month, the residual refrigerant charges in the system are equal to 991 g for R454C and 859 g for the other ones. This condition determines higher direct emissions for R454C than other fluids.

Because of both events: double refill processes and the highest refrigerant charge during phase-out, the R454C determines the greatest $TEWI_{dir}^{RL}$ as showed in Fig. 4. The yearly bar shows that for the most years the $TEWI_{dir}^{RL}$ value for all fluids is lower than 10 $kgCO_2/y$ except for the year of refill and phase-out of the system. For R454C the highest values among years of $TEWI_{dir}^{RL}$ are verified in the 7th, 13th, and 15th year with 24.6, 23.8 and 29.1 $kgCO_2/y$, respectively. Otherwise for the other three fluids the greatest values of $TEWI_{dir}^{RL}$ are recorded in the 9th and 15th year with 25.6, 24.4 and 25.1 $kgCO_2/y$ during the 9th year and 25.1, 23.9 and 24.6 $kgCO_2/y$ during the last year for R455A, R457A and R459B, respectively. The $TEWI_{dir}^{RL}$ eferredd to lifetime system is equal to 145.9, 138.9, 142.9, 161.6 $kgCO_2$ for R455A, R457A, R459B, and R454C, respectively. R454C is disadvantageous regarding the direct emissions if the lifetime of system is 15 years while the other three fluids give similar values.

This procedure allows a correct evaluation of direct emission contribution due to refrigerant leakages. In this case study, it can be affirmed that by assuming the same ARL the not-dynamic evaluation of $TEWI_{dir}^{RL}$ overestimates the total CO_2 emissions for all the fluids, by considering a fixed value of refrigerant charge into the system. The dynamic approach could be used easily by implementing a simple algorithm. In other applications, such as big supermarket plants, the higher number of maintenance and refilling processes could be underestimated without a punctual C(i) evaluation.

Results about indirect emissions for electricity consumption

By using the experimental measurement as reported in Table 2, the electricity consumption is hourly calculated as a function of the refrigerant charge. This information is reported on a yearly basis in Fig. 5. Among all fluids, R455A is responsible for the highest electricity consumption. The system equipped with R455A consumes 97.6 MWh in 15 years, followed by R459B with 81.6 MWh, R454C with 80.1 MWh, and R457A with 80.0 MWh. The first operating year and the years following refilling ones (the tenth for R455A, R457A, R459B, and the eighth and fourteenth for R454C) show the lowest electricity consumption with respect to the other years. Otherwise, the years before the refilling (the eighth for R455A, R457A, R459B and the sixth and twelfth for R454C) present the greatest yearly electricity consumption. In detail, the electricity consumption is equal to 5138, 5681, 4889, and 5136 kWh/y for R454C, R455A, R457A and R459B, respectively, at the first operating year. Otherwise, the required electricity is equal to 5638 kWh/y for R454C (during the sixth year) and 7628, 5941, and 5781 kWh/y for the eighth year of R455A, R457A, and R459B, respectively, which are the highest energy-consuming years. The yearly electricity consumption increases from the first to sixth years for R454C by 9.1%, and from the first to the eighth year for R455A, R457A, and R459B by 25.5%, 17.7% 11.2%, respectively. For R454C, R457A and R459B, the primary daily energy consumption is often lower than 15 kWh per day, while for R455A, this value is ever higher than 15.5 kWh per day. The statistic box plot graph in Fig. 6 shows the distribution of daily energy consumption for each fluid. The central red segment represents the median value on each box, and the bottom and top edges of the box represent the 25th and 75th percentiles, respectively.

The whiskers, or lines extending below and above the box, have endpoints that correspond to the lowest and highest daily electricity consumption equal to 15.3 and 21.5 kWh per day, respectively, for R455A. In addition, in this analysis, no outliers are present. The shade in each box represents the dependence of energy consumption on refrigerant charge distribution, as indicated in the colour bar. The highest median value is verified for R455A (greater than17 kWh per day). Otherwise, R459B and R454C present a lower variability than others and the R454C (red outline box plot in Fig. 6) shows a lower median but negative asymmetry.

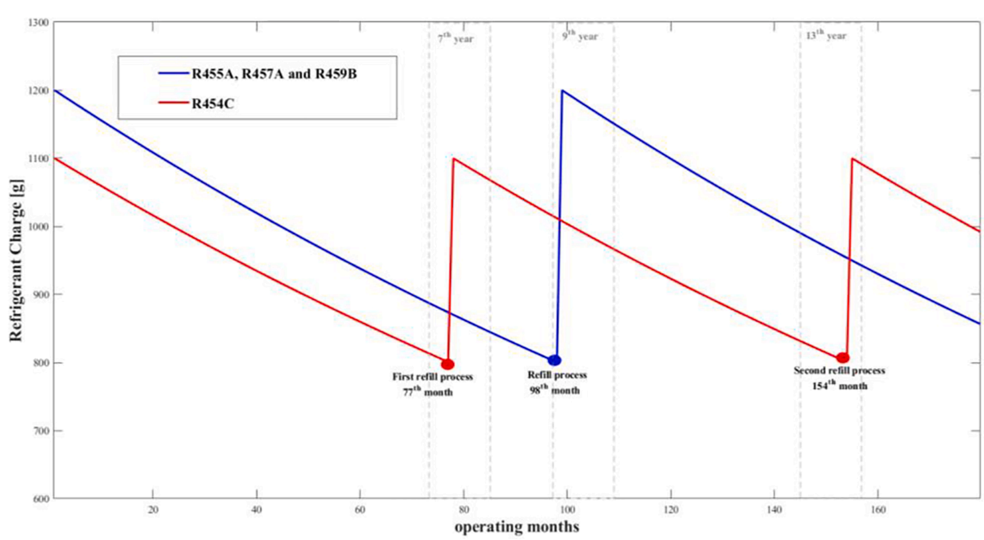

Fig. 3. Monthly trend of refrigerant charge during lifetime of system.

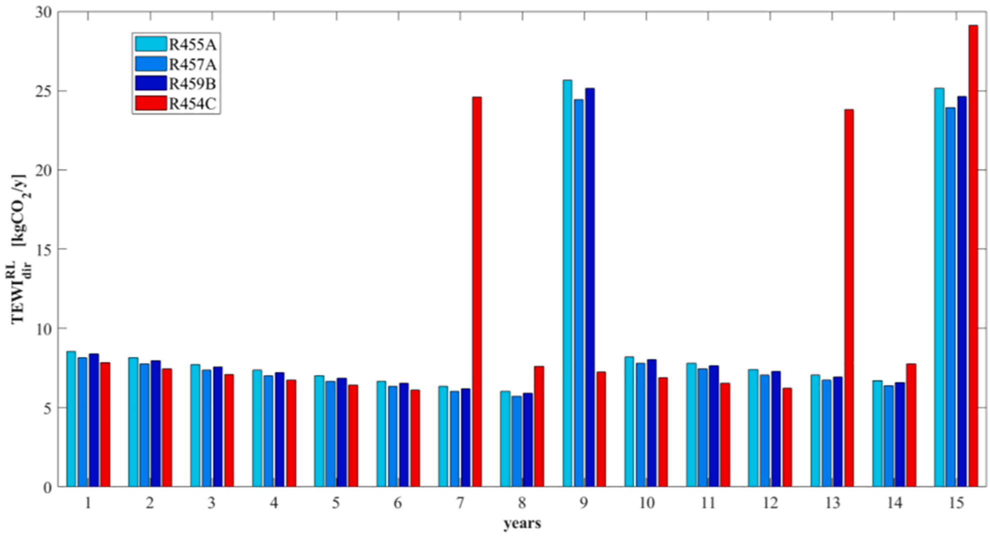

Fig. 4. Yearly $TEWI_{dir}^{RL}$ results.

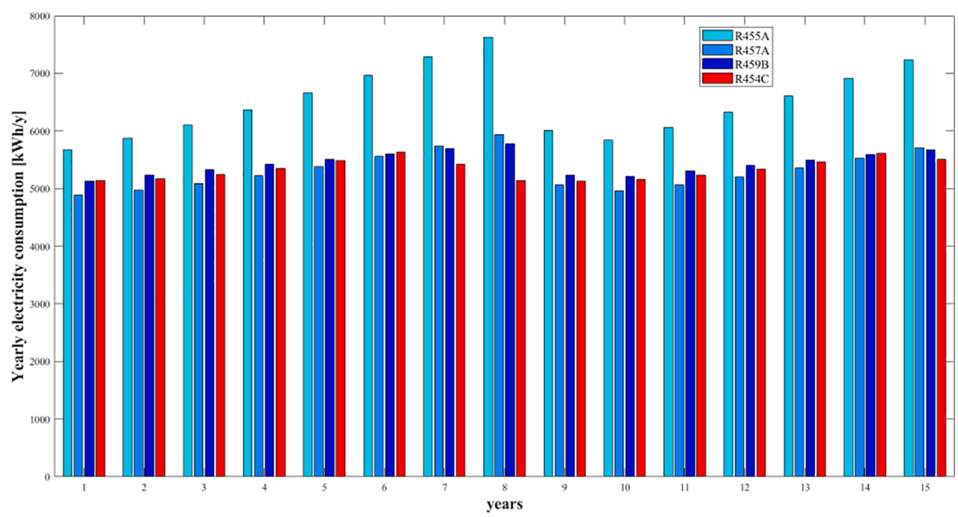

Fig. 5. Electricity consumptions for each operating year.

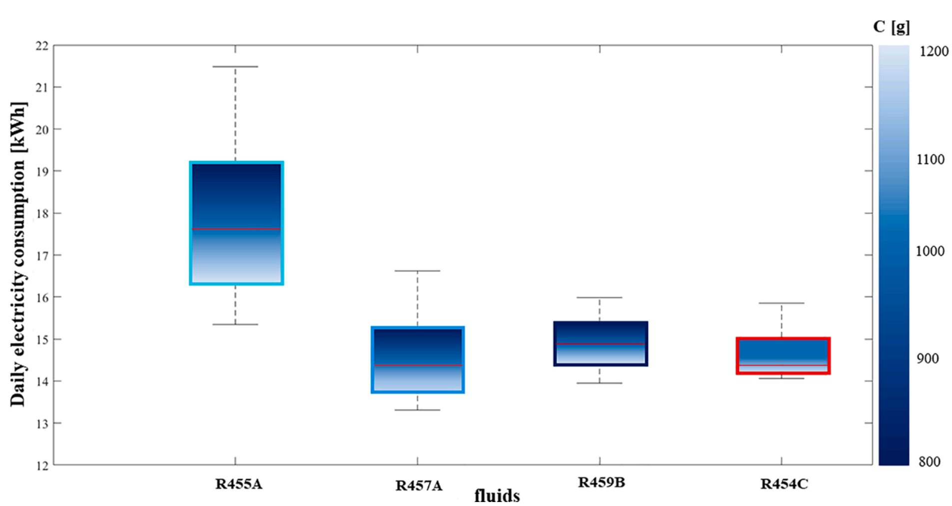

Fig. 6. Daily energy consumption variation as a function of refrigerant charge.

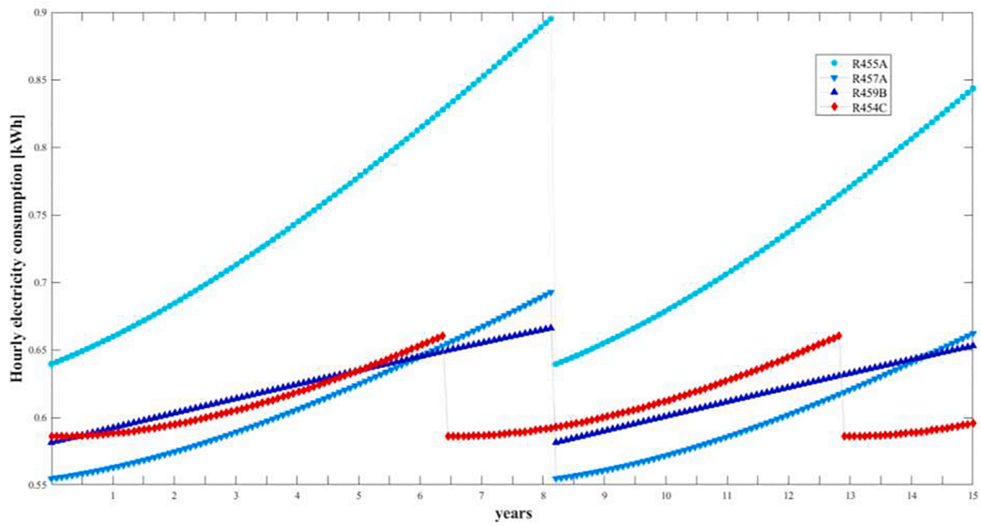

Fig. 7. Hourly electricity consumption of stand-alone.

The hourly electricity consumption of each refrigerant is shown in Fig. 7 by using the mean hourly value a monthly basis and the refill processes are reported in broken lines too. The mean hourly electricity need assumes different values as a function of refrigerant charge. The electricity requested on an hourly basis varies in the range of 0.64 ÷ 0.90 kWh from the first year (1st month) to the 8th year (96th month) for R455A, 0.55 ÷ 0.69 kWh for R457A, and 0.58 ÷ 0.67 kWh for R459B. Differently, the variability for the R454C is lower than other ones, and it corresponds to 0.58 ÷ 0.66 kWh. The refilling process reduces the energy consumption from the last hour before the refill to the first-hour post refilling, by 29.2%, 19.9%, 12.8%, and 11.3%, for R455A and R457A, R459B, and R454C, respectively. This evaluation cannot be realised with a static calculation of the electricity consumption and the refrigerant charge. For this reason, this method could be applied to correctly compare different technologies, refrigeration fluids and operation procedures of energy conversion devices for HVAC&R.

By using the electricity consumption results, the $TEWI_{ind}^{PP}$ is calculated according to Eq. (5) for all fluids and countries combinations. This term is highly influenced by the country electricity production mix. The hourly indirect emissions term due to electricity consumption, $TEWI_{ind}^{PP}(\theta)$, is reported in Fig. 8 for each country and fluid combination with the reference to the first year of operation. Each subplot is related to a specific fluid showing the corresponding $TEWI_{ind}^{PP}(\theta)$ behaviour in different electricity mix scenarios. The countries that present a high fossil fuels contribution in the electricity generation mix, such as Italy and Spain, show the greater $TEWI_{ind}^{PP}(\theta)$. In addition, France shows the lowest hourly value for each fluid with respect to other countries due to the high share of nuclear-based electricity production. The greatest hourly $TEWI_{ind}^{PP}$ value is verified in Italy by using R455A as a working refrigerant during October (400.9 $kgCO_2/h$). In the same period with the same fluid this value accounts for 33.9 $kgCO_2/h$ in France due to the different α(θ) which is equal to 51.9 $kgCO_2/kWh$ in France and 578.4 $kgCO_2/kWh$ in Italy.

Fig. 9 shows $TEWI_{ind}^{PP}(\theta)$ for R445A comparing the first operating year and the eighth year which represents the year before the refill process when the highest energy consumption is recorded. In addition, the figure depicts the $TEWI_{ind}^{PP}(\theta)$ dependence on emission factor in each considered country as showed by colour bars. The maximum hourly $TEWI_{ind}^{PP}(\theta)$ between the years varies from 400.9 gCO_2/h to 540.5 gCO_2/h in Italy. The maximum $TEWI_{ind}^{PP}(\theta)$ is higher than 450 gCO_2/h for Denmark during the eighth year. The mean value of $TEWI_{ind}^{PP}(\theta)$ is equal to 37.6 gCO_2/h for the first year while 50.4 gCO_2/h during eighth one for France. In 2020 about 45% of the Italian electricity production mix is based on renewables while a high share of electricity has been produced by fossil fuels. Despite that Italy and Spain are characterized by similar renewable contribution in electricity production mixes and similar

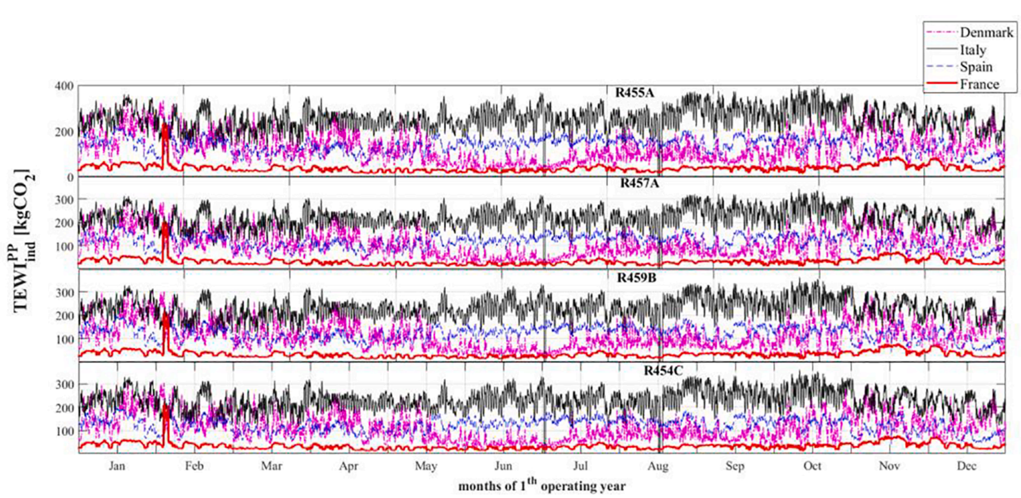

Fig. 8. Indirect term due to electricity consumption during the 1st operating year.

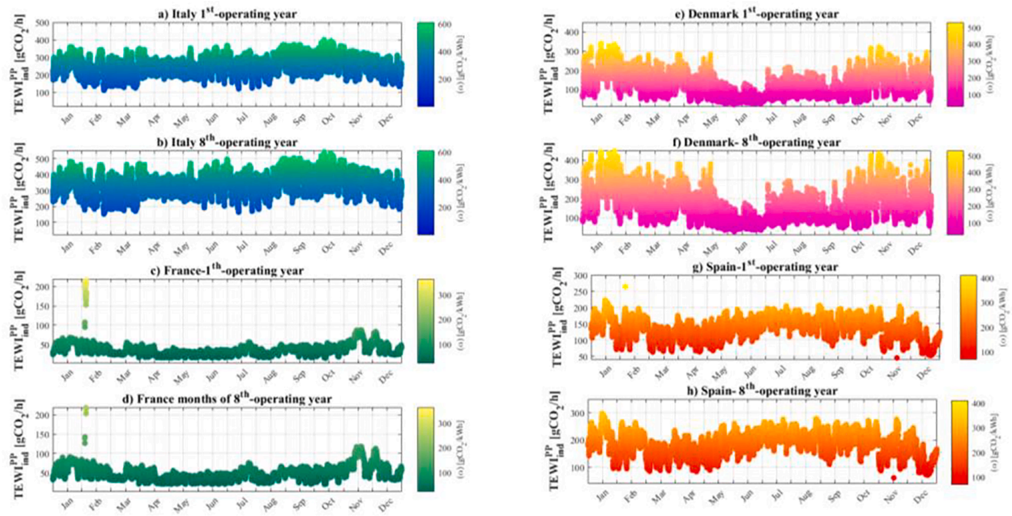

Fig. 9. Indirect emissions due to electricity during first and eighth years for R455A for Italy (a; b), France (c; d), Denmark (e; f) and Spain (g; h).

climate conditions, Spain shows lower indirect emissions than Italy due to the nuclear-based electricity generation. In fact, in Italy no nuclear plants are used while, in 2020, about 22% of electricity was produced by nuclear source in Spain. Otherwise, Denmark represents the country with the highest presence of renewable sources in the electricity generation mix (greater than 80% in 2020) but during the winter period the lower availability of renewable energy sources than in summer, is replaced by natural gas, oil, and coal [36]. For this reason, in Denmark the $TEWI_{ind}^{PP}(\theta)$ is highly influenced by seasonality. In France about 65% of electricity is produced by nuclear plants and the emission factor is very low determining $TEWI_{ind}^{PP}(\theta)$ lower than 100 gCO_2/h except for a few winter days.

The yearly values of the $TEWI_{ind}^{PP}$ are reported in Fig. 10 for each country and two significative fluids, R455A and R454C, representing the fluids with the highest energy consumption and the highest direct emissions, respectively. The $TEWI_{ind}^{PP}$ is equal to 31.0, 17.0, 15.6, and 4.7 tCO_2 in Italy, Spain, France, and Denmark, respectively, by using the fluid R457A that determines the lowest energy consumption than other ones. In Italy, the emissions can be mitigated by about 18.4%, replacing R455A with R457A and R454C and, in Spain, the potential emissions saving is equal to 20.2% by considering the same replacement. The impact of a stand-alone refrigerator with the same fluid in Italy is 6.6 times higher than in France, 2.0 than in Denmark and 1.9 than in Spain.

Without real hourly evaluation of emission factors (as in traditional TEWI [10]) yearly electricity needs are multiplied by a fixed emission factor neglecting the hourly and seasonal variability of the electricity mix. This effect is amplified if the devices show a high electricity consumption variability (or ON/OFF operating cycles) during the hours of

Table 5
Lifetime $TEWI_{ind}^{PP}$.

Fluid	Country	$TEWI_{ind}^{PP}[tCO_2]$
R455A	Italy	38.0
	Spain	20.3
	Denmark	18.7
	France	5.7
R457A	Italy	31.0
	Spain	16.6
	Denmark	15.2
	France	4.6
R459B	Italy	31.8
	Spain	17.0
	Denmark	15.6
	France	4.7
R454C	Italy	31.1
	Spain	16.7
	Denmark	15.3
	France	4.6

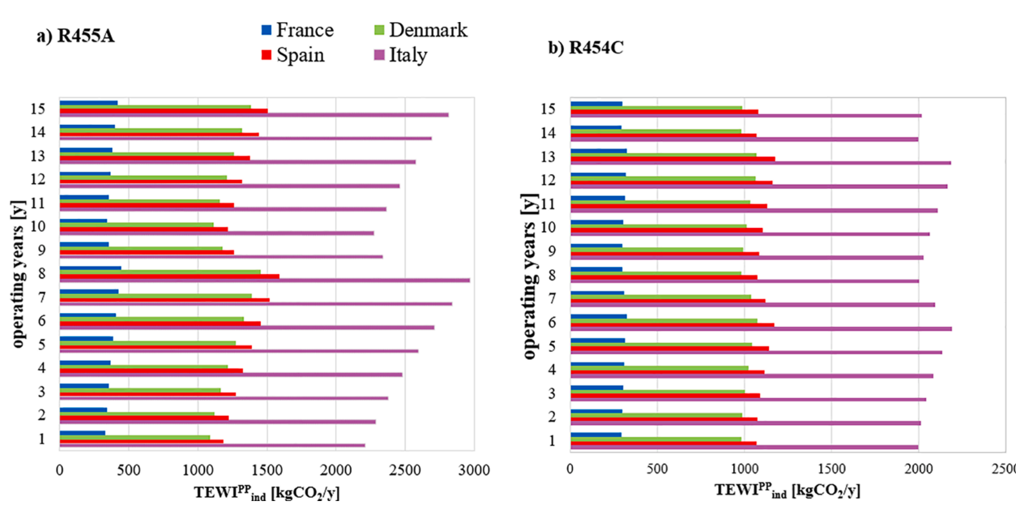

Fig. 10. Yearly $TEWI_{ind}^{PP}$ for R455A (a) and R454C (b).

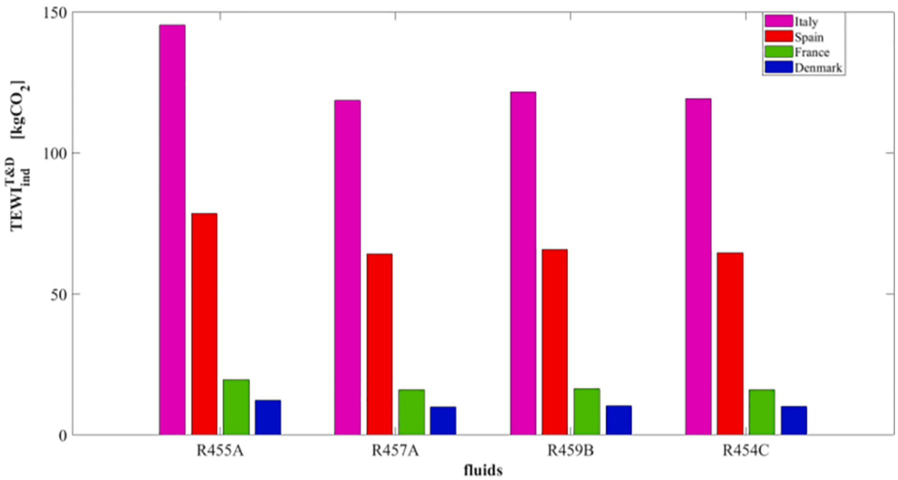

Fig. 11. Indirect term due to natural gas leakages on transmission pipelines.

the day (such as air-to-air heat pumps for air conditioning).

Finally, in Table 5 the indirect emission term is listed considering the lifetime system in each country and refrigerant.

Results about indirect emission due to natural gas transmission

Fig. 11 shows the indirect contribution due to natural gas leakages on transmission pipelines linked to electricity produced by natural gas-fuelled thermoelectric plants. According to the electricity production mix, the highest contribution due to natural gas leakages is verified in Italy, followed by Spain, France, and Denmark, assuming values equal to 145.3, 78.6, 19.6, and 12.2 kgCO_2, respectively, for R455A. Even if the CO_2 emission factor for electricity in France is lower than in Denmark, the indirect emissions due to natural gas leakages assume a higher value because in France a higher percentage of natural gas is used in the electricity generation mix. Despite that $TEWI_{ind}^{T\&D}$ determines a low effect on the ETEWI index with respect to the $TEWI_{ind}^{PP}$ (assuming a value equal to 0.4% or less of the $TEWI_{ind}^{PP}$ in Italy and 0.7% in Denmark), this term could be very useful for the evaluation of the decarbonization level of electricity production mix in each country.

Discussion

Fig. 12 reports the yearly ETEWI value for each country and fluid match. The yearly ETEWI varies in the range of 1918 ÷ 2983 kgCO_2/y in Italy, 1030 ÷ 1599 kgCO_2/y in Spain, 292 ÷ 449 kgCO_2/y in France and 942 ÷ 1462 kgCO_2/y in Denmark depending on the operating years and fluid. The ETEWI value presents the same trends of $TEWI_{ind}^{PP}$. Indeed, for a low VCC size system, the refrigerant charge highly influences the electricity consumption while the direct contribution due to refrigerant losses is low. According to the results reported in subsection 4.2, the year responsible for the maximum emissions is the 6th for R454C and the 8th for the other three fluids. During the worst years for total emissions, the direct terms are lower than other years while the indirect terms increase. Generally, from the "best" year to the "worst" one, the ETEWI value increases by 25% for R455A, 17% for R457A, 11% for R459B, and 9% for R454C.

In Fig. 13 the ETEWI for each country and fluid is reported for the lifetime stand-alone system. The combination fluid/ country with the highest environmental impact is R455A in Italy according with indirect emissions too. In Italy, the ETEWI assumes the value of 38.3 tCO_2 by using R455A but this value is reduced to 31.3, 32.0 and 31.4 tCO_2 by using R457A, R459B and R454C, respectively. Differently, in Spain, the

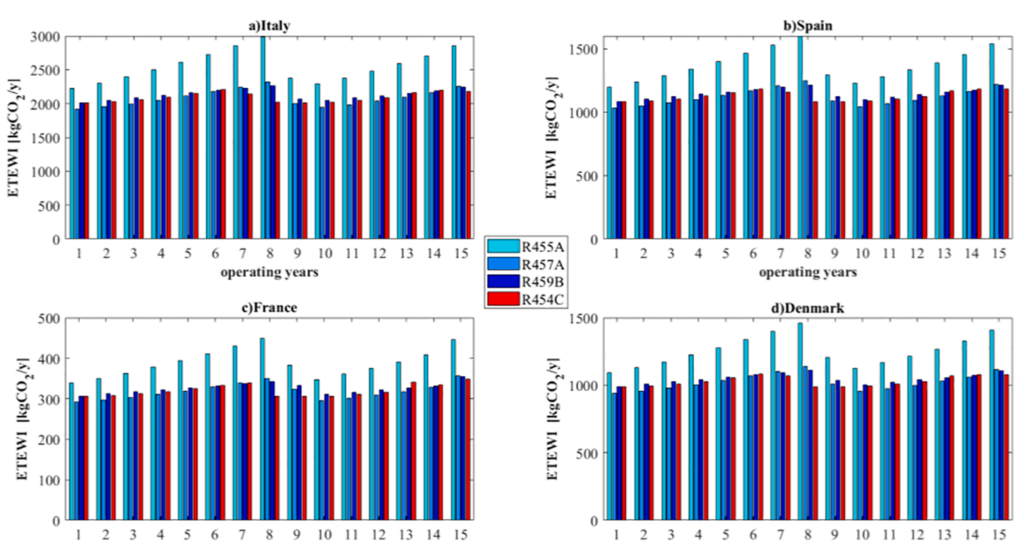

Fig. 12. ETEWI yearly results.

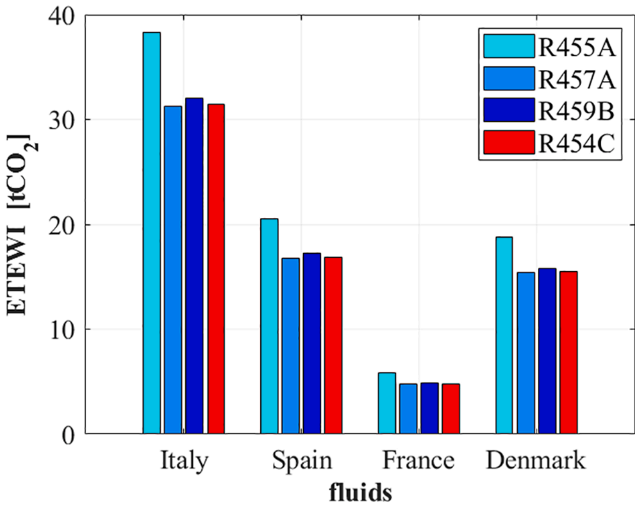

Fig. 13. ETEWI of stand-alone refrigerator for each country and fluid.

ETEWI assumes the values of 20.6, 16.8, 17.2, and 16.9 tCO_2 by using R455A, R457A, R459B, and R454C, respectively. Furthermore, in Denmark, the ETEWI reaches the values of 18.8, 15.4, 15.8, and 15.5 tCO_2 by using R455A, R457A, R459B, and R454C, respectively. The use of low energy-intensive fluid R457A instead of R455A, determines emissions saving equal to 7 tCO_2 in Italy and 1 tCO_2 in France.

Proposed solutions

In this section, two possible solutions are defined to reduce the environmental impact of the analysed stand-alone refrigerator. The first one is a light strategy to reduce the emissions caused by the electricity consumption by using an earlier refilling process. To evaluate the effect of earlier refill maintenance, additional simulations are carried out by considering a higher value of C_{lim} with respect to real cases, in detail this value is set to equal to 1000 g. This analysis gives an idea of the electricity consumption mitigation and its effect on global emissions of the device. In Fig. 14 the statistical daily electricity distribution is depicted for new considered C_{lim}. The results show that the maximum value of daily consumption (upper whisker) decreases by 18.6%, 13.5%, 6.9%, and 10.2% for R455A, R457A, R459B, and R454C, respectively, compared to the real case (Fig. 6). In addition, the amplitude of boxes in this simulation is lower than the real case, demonstrating a reduction in the operating condition with the daily electricity consumption higher than the medium value. Therefore, in this new condition, the median shows a lower value than the real case for all fluids. For example, by considering R455A, the box amplitude passes from 19.3 ÷ 16.3 kWh (Fig. 6) to 15.7 ÷ 16.9 kWh (Fig. 14).

The contribution of $TEWI_{dir}^{RL}$, $TEWI_{ind}^{PP}$ and $TEWI_{ind}^{T\&D}$ are evaluated for this new simulation in Italy and France, representing the countries with the highest and lowest ETEWI values.

The direct effect with C_{lim} = 1000 g is up to 80% higher than the real case while the indirect effects decrease by 8.4% in Italy and 8.6% in France. This result depends on the greater number of maintenance processes that leads to an increase in refrigerant leakages. In Table 6 the term related to direct refrigerant leakages, $TEWI_{dir}^{RL}$, is reported for the real case study (C_{lim} = 800 g) and for the new simulation which considers a limit charge equal to 1000 g. In addition, in the third column of Table 6, the difference percentage between the cases is listed.

Table 7 shows the indirect terms $TEWI_{ind}^{PP}$ and $TEWI_{ind}^{T\&D}$. The increase of C_{lim} from 800 to 1000 g leads to a reduction of indirect emissions due to electricity consumption and natural gas leakages. The reduction of indirect emissions is higher for the fluids responsible for the greater electricity consumption. The new condition determines a reduction of 3.2 tCO_2 by using R455A, while 1.0 tCO_2 by adopting R454C in Italy. Despite that, in France, the indirect emissions are 6.7 times lower than in Italy, an emission saving of 0.5 tCO_2 is obtained by using R455A.

Finally, Table 8 reports the ETEWI results. In Italy, the indirect emissions decrease is predominant on the ETEWI results assuming values lower than the case with C_{lim} = 800 g by 8.2%, 5.3%, 3.1%, and 3% for R455A, R457A, R459B, and R454C, respectively. This effect is less marked in France, where the ETEWI does not undergo improvement by using R454C and the maximum reduction is equal to 6.9%.

The second solution to reduce the emissions of the stand-alone refrigerator contemplates coupling the refrigeration system with a PV plant having a nominal namely 3 kW. This PV size allows supplying the electricity needs of residential users during daytime in hot climate countries such as South of Italy and thus, it certainly can meet the stand-alone refrigerator electricity requests. This assumption is often stated by

Table 6
$TEWI_{dir}^{RL}$ in the real case and for C_{lim} equal to 1000 g.

Fluid	$TEWI_{dir}^{RL}$ [$kgCO_2$]	$TEWI_{dir,C_{lim}=1000g}^{RL}$ [$kgCO_2$]	$\Delta TEWI_{dir}^{RL}$ [%]
R455A	145.9	234.1	60.4%
R457A	138.9	222.8	60.4%
R459B	142.9	229.3	60.4%
R454C	161.6	290.8	80.0%

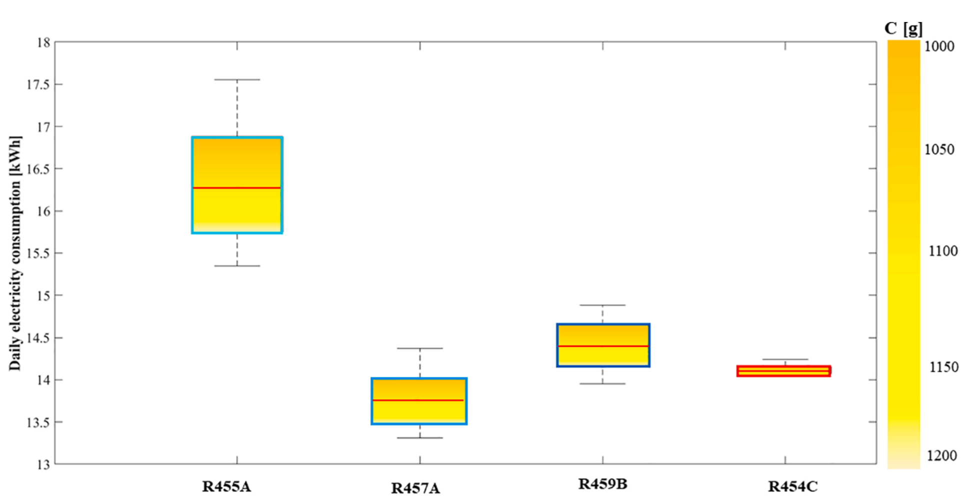

Fig. 14. Daily energy consumption distribution with C_{lim} = 1000 g.

Table 7
Indirect emission with C_{lim} = 1000 g.

Fluid	$TEWI_{ind}^{PP}[tCO_2]$	$TEWI_{ind,C_{lim}=1000g}^{PP}[tCO_2]$	$TEWI_{ind}^{T\&D}[kgCO_2]$	$TEWI_{ind,C_{lim}=1000g}^{T\&D}[kgCO_2]$	$\Delta TEWI_{dir}^{PP}, \Delta TEWI_{ind}^{T\&D}$ [%]
	Italy				
R455A	38.0	34.8	145.3	133.1	−8.4%
R457A	31.0	29.3	118.7	112.1	−5.5%
R459B	31.8	30.7	121.6	117.5	−3.4%
R454C	31.1	30.1	119.2	115.1	−3.4%
France					
R455A	5.7	5.2	19.6	18.0	−8.4%
R457A	4.6	4.4	16.0	15.2	−5.5%
R459B	4.7	4.6	16.4	15.9	−3.4%
R454C	4.6	4.5	16.1	15.6	−3.4%

Table 8
ETEWI in the real case study and for C_{lim} = 1000 g.

	Italy			France		
Fluid	$ETEWI[tCO_2]$	$ETEWI_{C_{lim=1000g}}[tCO_2]$	$\Delta ETEWI$[%]	$ETEWI[tCO_2]$	$ETEWI_{C_{lim=1000g}}[tCO_2]$	$\Delta ETEWI$[%]
R455A	38.3	35.1	−8.2%	5.8	5.4	−6.9%
R457A	31.3	29.6	−5.3%	4.8	4.6	−3.7%
R459B	32.0	31.0	−3.1%	4.9	4.8	−1.6%
R454C	31.4	30.5	−3.0%	4.8	4.8	0%

Table 9
ETEWI variation with C_{lim} = 1000 g and PV plant in Italy.

	R455A	R457A	R459B	R454C
ETEWI [tCO_2]	38.26	31.27	32.02	31.46
ETEWI with PV and C_{lim} = 1000 g [tCO_2]	23.45	19.78	20.71	20.36
ΔETEWI [%]	−38.7%	−36.7%	−35.3%	−35.3%

using the results of dynamic simulations in different areas of Southern Italy [38]. With this hypothesis, the emission factor assumes a value equal to 45 gCO_2/h (Table 3), from 8 am to 5 pm. In Table 9 the value of the ETEWI is reported for the real case and simulated case including C_{lim} = 1000 g and PV system, by showing a potential ETEWI mitigation of 38.7%.

Conclusion

In this work, an environmental analysis of a stand-alone refrigerator system is conducted by using the Expanded Total Equivalent Warming Impact index in four different countries (Italy, Spain, France, and Denmark) and four fluids (R455A, R457A, R459B, and R454C). The study has been realised using an experimental apparatus and a MATLAB code for date analysis. The results show that the higher impact on environmental emissions depends on the electricity consumption of devices and emission factor for the electricity generation mix of each considered country. The following main results have been found:

- The dynamic evaluation of refrigerant charges allows reducing the errors in the direct emissions evaluation due to refrigerant leakages.
- In this case study for 15 operating years, two events are verified: double refill process and the highest refrigerant charge during the phase-out. R454C determines the highest direct emissions up to 15% over the other fluids, otherwise, the fluid with the lowest direct emissions is R457A.
- The dynamic evaluation of refrigerant charge allows also to optimize the accuracy of indirect emissions evaluation with respect to the traditional TEWI methods. In fact, the energy consumption results are highly dependent on refrigerant charge value.
- The electricity consumption increases from the first year to the refilling year (minimum charge of refrigerant) with an increasing percentage of 9.1%, 25.5%, 17.7%, and 11.2% for R454C, R455A, R457A, and R459B, respectively.
- The indirect terms also depend on the electricity generation mix. Italy is the country with the greatest indirect emission terms due to the highest share of electricity produced from fossil fuels-based plants while France shows the lowest indirect values thanks to the greatest share of nuclear electricity production (65%).
- Despite Italy and Spain are characterised by similar renewable contributions in the electricity generation mix and similar climate conditions, Spain shows lower indirect emissions than Italy due to the high nuclear use. Otherwise, Denmark represents the country with the highest presence of renewable sources in the electricity generation mix (higher than 80 % in 2020). However, during the winter period, the low availability of renewable energy sources than in summer is replaced by natural gas, oil, and coal showing a significant influence on emission factor by seasonality.
- The dynamic evaluation of energy consumption and emission factors determines a high variability in season and day observations of the indirect emissions evidencing the limit of the traditional yearly-based TEWI analysis.
- The indirect terms due to natural gas transmission pipelines determine the low effect on the overall index concerning other ones, assuming a value equal to 0.4% or less of the indirect term for electricity in Italy and 0.7% in Denmark. However, this term could be useful to evaluate the electricity production mix decarbonization in each country.
- The highest contribution to global emissions depends on electricity production.
- A light strategy to reduce the indirect emissions is to move up the refilling process. The solution that assumes a limit charge equal to 1000 g (versus 800 g in real condition) shows direct emissions up to 80% higher than the real case while the indirect effects decrease, for example, by 8.4% in Italy and 8.6% in France.

It can be inferred that a yearly maintenance program should be promoted to decrease the impact of the refrigeration sector.

- Moreover, in Southern Italy, the avoided emissions by 38% could be obtained by coupling the stand-alone refrigerator with a PV system.

These results demonstrate that the ETEWI index will be used in the future to overcome the limits and possibility of potential errors in the environmental analysis of electric-based systems by considering the large pervasion of RES in the electricity production mix and the intermittent RES availability. Future studies will test the dynamic evaluation of emissions factors due to electricity by using predictive analysis about country emission factors and introducing the local urban heat island effect. Furthermore, additional studies will be conducted by using other low-GWP refrigerants or mixtures and by evaluating more complex energy conversion systems in the supermarkets.

CRediT authorship contribution statement

Ciro Aprea: Conceptualization, Methodology, Software, Resources, Data curation, Writing – original draft, Investigation, Writing – review & editing. **Ceglia Francesca:** Conceptualization, Methodology, Software, Resources, Methodology, Data curation, Writing – original draft, Investigation, Writing – review & editing. **Rodrigo Llopis:** Conceptualization, Methodology, Software, Resources, Data curation, Writing – original draft, Investigation, Writing – review & editing. **Angelo Maiorino:** Conceptualization, Methodology, Software, Resources, Data curation, Writing – original draft, Investigation, Writing – review & editing. **Elisa Marrasso:** Conceptualization, Methodology, Software, Methodology, Writing – original draft, Investigation, Writing – review & editing. **Fabio Petruzziello:** Conceptualization, Methodology, Software, Resources, Writing – original draft, Investigation, Writing – review & editing. **Maurizio Sasso:** Conceptualization, Methodology, Software, Resources, Data curation, Writing – original draft, Investigation, Writing – review & editing.

Declaration of Competing Interest

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

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