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# An experimental evaluation of the greenhouse effect in the substitution of R134a with $CO_2$

C. Aprea [a], A. Greco [b,*], A. Maiorino [a]

[a] Dipartimento di Ingegneria Industriale, Università di Salerno, via Ponte Don Melillo, 84084 Fisciano, Salerno, Italy
[b] DETEC, Università degli Studi di Napoli Federico II, P.le Tecchio 80, 80125 Napoli, Italy

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ABSTRACT

This paper addresses the problem of R314a substitution with a natural refrigerant fluid. Attention is devoted to the evaluation of the environmental impact, in terms of greenhouse effect. R134a and R744 ($CO_2$) are compared to one another. The hydrofluorocarbon R134a has a large direct warming impact (GWP), whereas the R744 contribution is negligible. The greenhouse effect is determined by the experimental evaluation of the TEWI index (Total Equivalent Warming Impact) that takes into account both direct and indirect contributions to global warming. This paper compares a commercial R134a refrigeration plant and a prototype R744 system working in a trans-critical cycle. The experimental results clearly show that the latter has a larger TEWI than the system operating with R134a. The indirect contribution to global warming provided by R744 is always greater than that of R134a. This contribution prevails in most cases. Only few operating conditions corresponding to a refrigerating plant working as a classical split system benefits, in terms of greenhouse effect, of the substitution of R134a with R744.


## 1. Introduction

About 15% of the worldwide energy consumption originates from refrigeration [1–3]. Most modern refrigeration units are based on vapour compression plants. Since the very beginning of their commercial diffusion, their development is strictly related to the characteristics of working fluids. The traditional refrigerant fluids, i.e. CFCs and HCFCs, were banned by the Montreal Protocol [4] because of their contribution to the disruption of the stratospheric ozone layer (Ozone-Depleting substances ODs) [5].

CFCs were banned since 1996. In most European countries, HCFCs were phased-out by 2010 and will be banned in new equipment by 2020. HFCs and natural fluids are candidates to their substitution.

Human activities have increased the concentration of greenhouse gases in the atmosphere. This resulted in a substantial warming of both the earth surface and the atmosphere, that adversely affected the natural ecosystem [6,7]. The impact of a given greenhouse gas on global warming is quantified by its GWP (Global Warming Potential). GWP is defined as the mass of $CO_2$ that would yield the same net impact on global warming as the release of a single unit (kg) of the given atmospheric component [8–12].

The Kyoto Protocol [13], pursuant to the United Nations Framework Convention on Climate Change (UNFCCC), sets binding targets for greenhouse gas emissions.

National laws and regulations implementing the Kyoto Protocol differ from one another, but they typically prohibit avoidable releases of HFC and PFC refrigerants. In some countries, their use undergoes control and/or taxation. More recent measures (either already adopted or proposed) at local level (regional, national, municipal) are even more stringent. These restrictions are forcing the shift to a fourth generation of refrigerants with both ODP and GWP regulations [14].

In the field of the mobile refrigeration systems, the European Parliament already set a regulation of F-Gases phase out [15] that bans the use of refrigerants having GWPs exceeding 150. Such regulation is in effect since 2011 [16].

Vapour compression plants produce both a direct and an indirect contribution to global warming. The former depends on the GWP of refrigerant fluids and on the fraction of refrigerant charge which is released into the atmosphere during operation and maintenance, or is not recovered when the system is scrapped. The indirect contribution is energy-related. In fact, a vapour compression refrigerator requires electrical energy produced by a power plant that typically burns a fossil fuel releasing $CO_2$ into the atmosphere. The amount of $CO_2$ emitted is a strong function of the COP of the vapour compression plant. The Total Equivalent Warming Impact (TEWI) index takes into account both contributions to global warming.

* Corresponding author. Tel.: +39 0817682289; fax: +39 0812390364.
*E-mail address:* adriana.greco@unina.it (A. Greco).

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**Nomenclature**

*Symbols*

| | |
|---|---|
| $CO_{2,dir}$ | direct contribution to global warming ($kg_{CO2}$) |
| $CO_{2,indir}$ | indirect contribution to global warming ($kg_{CO2}$) |
| COP | coefficient of performance |
| GWP | global warming potential ($kg_{CO2}$ $kg_{refrigerant}$) |
| $H$ | annual operating hours (h/years) |
| $h_{in,ev}$ | refrigerant enthalpy at the evaporator inlet (kJ/kg) |
| $h_{out,ev}$ | refrigerant enthalpy at the evaporator outlet (kJ/kg) |
| IHX | internal heat exchanger |
| $\dot{m}$ | refrigerant mass flow rate (kg/s) |
| ODP | Ozone Depletion Potential |
| $P_L$ | accidental refrigerant leaks per year (% refrigerant charge/year) |
| $P_R$ | recycling rate (% refrigerant charge) |
| $Q_{ref}$ | refrigerant power (kW) |
| RC | refrigerant charge (kg) |
| $T_{air,inlet}$ | air temperature at the inlet of the condenser/gas-cooler (°C) |
| $T_{amb}$ | external ambient temperature (°C) |
| $T_{ev}$ | evaporating temperature (°C) |
| TEWI | Total Equivalent Warming Impact ($kg_{CO2}$) |
| $TEWI_{woIHX}$ | Total Equivalent Warming Impact of R744 plant without the internal heat exchange ($kg_{CO2}$) |
| $TEWI_{wIHX}$ | Total Equivalent Warming Impact of R744 plant with the internal heat exchange ($kg_{CO2}$) |
| $V$ | plant useful life (years) |
| $\dot{W}$ | compression power (kW) |

*Greek symbols*

| | |
|---|---|
| $\alpha$ | $CO_2$ emission from power conversion ($kg_{CO2}$/kWhe) |
| $\beta$ | compression ratio |
| $\Delta$TEWI | TEWI difference |

R134a is an HFC with zero ODP and a GWP of 1300. According to the above mentioned European regulation on F-Gases, the use of R134a will be banned in mobile systems. R134a will be replaced with a low GWP fluid [17,18]. R744, with negligible direct contribution to global warming, can be a substitute of R134a. In this study, the impact of the substitution of R134a with R744 on global warming was studied through experimental evaluations of the TEWI index under different operating conditions.

The experimental tests discussed in this study compare a commercial R134a refrigeration plant subjected to a cold store and a prototype R744 system working as a classical spit-system to cool air in a trans-critical cycle.

## 2. The TEWI concept

The concept of total equivalent warming impact (TEWI) was developed to combine the effect of direct refrigerant emission with those due to energy consumption and the related combustion of fossil fuels for the electric energy production. TEWI provides a measure of the environmental impact of greenhouse gases originating from operation, service and end-of-life disposal of the equipment. TEWI is the sum of the direct contribution of the greenhouse gases used to make or to operate the systems and the indirect contribution of carbon dioxide emissions resulting from the energy required to run the systems along their normal lifetime [19].

The TEWI is calculated as [20–24]:

$$\begin{aligned} \text{TEWI} &= CO_{2,\text{dir}} + CO_{2,\text{indir}} \quad [\text{kg } CO_2] \\ CO_{2,\text{dir}} &= \text{RC}\left[P_L + \left(\frac{1-P_R}{V}\right)\right] V \cdot \text{GWP} \quad [\text{kg } CO_2] \\ CO_{2,\text{indir}} &= \alpha \cdot \frac{\dot{Q}_{\text{ref}}}{\text{COP}} \cdot H \times V \quad [\text{kg } CO_2] \end{aligned} \tag{1}$$

The direct global warming effect of refrigerant fluids, stemming from the absorption they produce of long-wave radiations, depends on their GWP and on the fraction of refrigerant charge released into the atmosphere. The last is mainly due to leakage during the plant operational life time ($P_L$) and to the residual amounts which, according to the current state of technology, are not recyclable and thus are released into the atmosphere when taking the plant out of operation ($1 - P_R$).

As already stated, the indirect contribution to TEWI consists in the so-called energy-related contribution. Indeed, an electrical refrigerator requires electrical energy from a $CO_2$ releasing power plant that typically burns a fossil fuel. The amount of $CO_2$ emitted is a function of the refrigerator COP, of the power plant efficiency and of the fuel used in the conversion plant that affect the emissions per unit energy converted. The typical power-plant technology adopted varies from one country to another. The literature provides some indicative, average levels of $CO_2$ release per KWh of electrical energy for various countries [25–28]. For Italy, the value is 0.6 kg $CO_2/kWh_e$.

The annual operating hours in the TEWI simulation are 8760. These correspond to a commercial refrigerator cold store according to Dir.94/2/CE [29].

Table 1 reports the parameters adopted for the TEWI evaluation.

## 3. Experimental equipment

### 3.1. Refrigeration plant working with carbon dioxide

Fig. 1 shows a sketch of the experimental plant. Basically, there are two single-stage hermetic reciprocating compressors, an oil separator, an air gas-cooler, a liquid capacity, an air evaporator, an electronic expansion valve (EEV) and an electronically-regulated back pressure valve (BPV). The main compressor is a semi-hermetic one. At evaporation temperatures of 5 °C and of 30 °C at the gas-cooler exit, when the pressure is 80 bar, the refrigerating power is about 3000 W. An internal heat exchanger (IHX) between the refrigerant flow at the compressor suction and at the exit of the gas-cooler is provided. The lamination occurs thanks to the back-pressure valve and to the electronic expansion one. An auxiliary circuit can be used to by-pass the back-pressure valve, in order to vary the evaporation temperature. The air temperature on the condenser is regulated by an air-flow driven by a blower in

**Table 1**
Parameters for TEWI evaluation.

| Parameter | Value |
|---|---|
| $H$ | 8760 h |
| PL | 5% year |
| PR | 95% |
| $V$ | 10 years |
| $\alpha$ | 0.6 kg $CO_2/kWh_e$ |