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ABSTRACT

Offering the possibility of environmental friendly operation, several alternative refrigeration technologies are emerging aiming to substitute current refrigerant fluids and even current vapor compression technologies. Among such technologies are the Stirling machines, CO_2 cycles, Magnetocaloric, Thermoacoustic and Thermoelectric systems besides a broad range of other options. In most cases when comparing the performance aspects of such technologies with the current technologies some basic concepts are not taken into account. Statements such as " .... presenting the same performance level of current compressors ....", for example, are easily found in the open literature. Considering performance is a broad concept including aspects related to e.g. efficiency level, environmental impact, reliability issues, etc it is clear that a fair performance comparison among different technologies is not an easy task. This paper does not intend to present a unique and complete methodology to compare alternative technologies however will provide some key information and boundary conditions to make this comparison more realistic. As far as environmental impact is a concern, a Total Equivalent Warming Impact (TEWI) analysis is proposed, looking at both the direct and indirect global warming potential, presenting real data for different regions (North America, Europe and Asia) and different applications into both household and commercial refrigeration. A sensitivity analysis is performed for each world region and for each kind of application. The aim is to identify the critical contribution for obtaining a better environmental operation. The study is grounded on information available on technical literature and experimental data.

1. INTRODUCTION

Global cooperation for the protection of the environment began with the negotiations of the Vienna Convention for the Protection of the Ozone Layer, concluded in 1985. The details of the international agreement were defined in the Montreal Protocol on Substances that Deplete the Ozone Layer. The Montreal Protocol was signed in September 1987 and became effective in 1989. At a meeting in London in 1990, the Parties to the Montreal Protocol agreed to a phase out of controlled substances and since them several other meetings and other bodies such as the U.S. Environmental Protection Agency and the European Community have imposed still more strict regulations and accelerated the phase out schedules of those substances including (CFCs, HCFCs, halons, carbon tetrachloride, methyl chloroform, etc). Table 1 outlines the phase out schedule for CFCs under the different revisions of the Montreal Protocol as well as other U.S. and European regulations.

The production and consumption of ozone depleting substances has been reduced more rapidly than that required by the Montreal Protocol. Focused efforts of industry have enabled the progress to date on phasing out ozone depleting substances to surpass national and international efforts (AFEAS, 2002).

Having the ozone layer issue addressed, the environmental focus changed to Global Warming. Most of the sun's energy reaches the earth as visible light. After passing through the atmosphere, part of this energy is absorbed by the earth's surface and converted into heat energy. The earth, now warmed by the sun, radiates heat energy back into the atmosphere. Naturally occurring gases, such as carbon dioxide, water vapor, and ozone, absorb and thus retain some of the outgoing heat energy. This process slows the heat loss, maintaining the earth's surface temperature around 33°C warmer than it would be if this heat energy had passed unobstructed through the atmosphere into space. Increasing concentrations of gases from man-made sources (e.g., carbon dioxide, methane, CFCs, HCFCs, HFCs, etc) that absorb the heat radiation could lead to a slow warming of the earth. This phenomena is commonly referred to as Global Warming and is currently an issue of much political, social, economic and scientific interest.

Table 1 – CFC Phase Out Schedules: Allowed Production and Consumption for Developed Countries (percent of baseline in 1986)

	Original Montreal Protocol	London Montreal Protocol	U.S. Air Act Amendments	Copenhagen Montreal Protocol	European Community Schedule
Year	**1987**	**1990**	**1990**	**1992**	**1994**
1990	100%				
1991	100%	100%	85%		
1992	100%	100%	80%		
1993	80%	80%	75%		50%
1994	80%	80%	25%	25%	15%
1995	80%	50%	25%	25%	0%
1996	80%	50%	0%	0%	
1997	80%	15%			
1998	80%	15%			
1999	50%	15%			
2000	50%	0%			

Source: Alternative Fluorocarbons Environmental Acceptability Study (AFEAS, 2002)

In December, 1997, more than 160 nations met in Kyoto, Japan, to negotiate binding limitations on greenhouse gases for the developed nations, pursuant to the objectives of the Framework Convention on Climate Change of 1992. The outcome of the meeting was the Kyoto Protocol, in which the developed nations agreed to limit their greenhouse gas emissions, relative to the levels emitted in 1990. The Protocol is subject to ratification, acceptance, approval or accession by Parties to the Convention. Due to the "voluntary" characteristic of the Protocol some countries have no targets under the Protocol, but the Protocol reaffirms the commitments of the Framework Convention by all Parties to formulate and implement climate change mitigation and adaptation programs.

It is of interest to the Air Conditioning and Refrigeration (AC&R) industry to formulate and implement such programs since some of the refrigerants used, chemicals such as CFCs, HCFCs and HFCs, are known to be strong greenhouse gases. Also the process of generating electricity (or burning fuel) to run AC&R equipment produces carbon dioxide, which is also a greenhouse gas. Therefore, the AC&R industry has a large stake in the ongoing worldwide debate regarding global warming.

Global warming effect can be determined using different methodologies. The widely used Total Equivalent Warming Impact (TEWI) concept was adopted in the present work. TEWI is the sum of the direct (chemical) and indirect (energy) emissions of greenhouse gases from a certain equipment during its useful life.

The following sections will present more details about this methodology and also real application of this concept considering typical refrigeration system and different market regions. A sensitivity analysis will also be performed in order to identify the direct and indirect emission contributions for each application and market region aiming to orient the research activities to the most important factors influencing the environmental performance of a certain technology.

2. METHODOLOGY

As mentioned before the Total Equivalent Warming Impact (TEWI) concept will be employed in an attempt to identify possible paths in technology development that could mitigate the environmental impact of a certain technology in the market.

TEWI is calculated in accordance with equation (1):

$$TEWI = GWP \cdot L \cdot n + GWP \cdot m \cdot (1-\alpha) + n \cdot E \cdot \beta \quad (1)$$

where,

GWP - Refrigerant Global Warming Potential (equivalent to CO_2) [kg CO_2/kg refrigerant]
L - Annual leakage rate [kg/year]
n - System operating life time [years]
m - Refrigerant charge [kg]
α - Recycling factor [%]
E - Annual energy consumption [kWh/year]
β - CO_2 emissions on energy generation [kg CO_2/kWh]

In order to understand direct and indirect contributions impact on the greenhouse gases emissions typical household and light commercial refrigeration systems (cooling capacity below 1kW @ LBP ASHRAE conditions) were chosen for 3 representative market regions around the world (North America, Europe and Asia). Each system was tested following the energy consumption standards of each region and the results are presented in Table 2. For comparative purposes Table 2 also includes data for refrigerant type, refrigerant charge and internal volume or storage capacity.

Table 2 – Typical refrigeration equipment per market region

Region	Application	System Model	Internal Volume Capacity	Refrigerant		Energy Consumption	
				Type	Amount [g]	KWh/month	Ambient Temperature [C]
North America	Household	Top Mounted	600 liters	HFC 134a	110	40	32
		Side by Side	800 liters	HFC 134a	150	50	32
		Chest Freezer	500 liters	HFC 134a	150	45	32
		Vertical Freezer	500 liters	HFC 134a	120	55	32
	Light Commercial	Glass Door Merchandiser	600 cans	HFC 134a	330	210	32
		Vending Machine	600 cans	HFC 134a	400	300	32
Europe	Household	Small Refrigerator	250 liters	HC 600a	30	15	25
		Combined Refrigerator	430 liters	HC 600a	60	30	25
		Vertical Freezer	200 liters	HC 600a	40	25	25
	Light Commercial	Chest Freezer (Ice Cream)	200 liters	HFC 134a	120	100	30
		Display Case (Ice cream)	550 liters	HFC 404a	500	480	30
Asia	Household	Compact Refrigerator	80 liters	HC 600a	25	20	25
		Combined Refrigerator	350 liters	HC 600a	50	25	25
	Light Commercial	Vending Machine	600 cans	HFC 134a	400	300	32

Source: Embraco experimental data

Annual average leakage rate stipulated by appliance manufacturers of household refrigerators is around 2-3%. In commercial systems, like supermarket cabinets, leakage rates are around 8-10%. For calculation purposes a leakage rate of 3% and 5% was adopted for household and light commercial applications, respectively. (an intermediary value was used for light commercial applications).

Life expectancy for refrigeration equipment in household applications was considered to be 15 years. For light commercial applications 10 years life expectancy was adopted. This is due to more severe operating conditions and constant transportation of such equipment from one sales point to another.

The improvement on refrigerant containment and recovery practices due to increasing pressure from regulations and increasing awareness about environmental issues has caused the recycling factor to rise. A recycling factor of 75% was considered for both household and light commercial applications. This means that 75% of the refrigerant charge is recovered at the end of the equipment useful life.

When evaluating a refrigeration system using the proposed methodology both the working fluid and the fluid used as a blowing agent for the cabinet insulation have to be taken into account. The purpose of this paper is to present a methodology to compare alternative refrigeration technologies. With this in mind the effect of the blowing was not considered in this study. The premise behind this simplification is that alternative insulation technologies will be available regardless of the refrigeration concept being adopted in the equipment.

2.1 Global Warming Potential (G.W.P.)

Considerable uncertainty exists about the climate change responses to greenhouse gas emissions due to an incomplete understanding of sources and sinks of greenhouse gases, clouds, oceans, polar ice, and interactive climate feedback mechanisms. "Radiative forcing" (factors that can perturb the radiative balance of the Earth-atmosphere system) or direct heat trapping effect involves less uncertainty and is used by atmospheric scientists to assess relative impacts of different gases.

Many of the indices that have been used as measures of relative contributions of the various greenhouse gases are based on past concentration changes in the atmosphere. A simplified mean of describing the relative ability of each greenhouse gas emission to affect future radiative forcing, and thereby, the global climate change, is provided by an index termed Global Warming Potential (GWP). The extent to which a greenhouse gas contributes to the global warming calculation depends on the emission amount, the period of time which elapses before it is purged from the atmosphere and the infrared energy absorption properties of the gas. GWP enable chemical emissions to be converted to their equivalent emissions of carbon dioxide so that there is a common basis for comparing impacts.

The period or time considered for the GWP calculation is termed Integration Time Horizon (ITH). If the ITH is set as 100 years, the whole of the potential effect of a short-lived HCFC or HFC would be counted, but a substantial part of the effect of carbon dioxide - a long lived gas in the atmosphere - would be excluded. Thus, the 100-year time horizon does not give a true measure of the equivalence between any other gas and carbon dioxide. Even though this paper uses GWP at the 100-year time horizon as listed in Table 3 to allow common basis of comparison since most of the technical literature consider this value. Table 3 also presents data on Ozone Depletion Potential (ODP) for the refrigerants used in this study.

Table 3: Refrigerant Data (GWP, ODP)

Refrigerant	GWP (100 years)	ODP
CFC 12	8,500	1
HFC 134a	1,300	0
HFC 404a	3,260	0
HC 600a	3	0
CO_2	1	0

2.2 CO_2 emissions on electricity generation (β)

When a fuel is burnt, energy is produced and carbon dioxide (CO_2) and other chemicals, mostly water, are produced. The ratio of CO_2 emitted to the electricity generated differs according to the type of fuel used. Electricity is generated from a range of fuels including nuclear, gas, oil and coal and in some cases waste. Besides burning a fuel there are several other alternatives to produce electricity like hydroelectric plants, wind power, geothermal energy sources, tidal power, wave energy, photovoltaic panels, etc.

The relationship between CO_2 production and electricity generation may vary significantly, depending on the approach to be followed. Some sources consider a Life Cycle approach what means that not only the amount of CO_2 generated during the energy conversion is taken into account, but also the amount emitted during the fuel transportation up to the electricity generation plant and during the construction of such plant. Some methodologies also consider the equivalent mass of CO_2 related to other greenhouse gases such as CH_4 and N_2O. Table 4 (Vate, 1998) shows minimum and maximum values of equivalent CO_2 emissions per electricity consumption considering several primary energy sources and a Life Cycle approach. For calculation purposes the average value given in Table 4 illustrated in Figure 1 have been used.

In addition to the factors listed before each region inside each country has its own mix of primary sources for electricity generation. This mix can change significantly from country to country and even from one region to another in the same country. Table 5 provides a weighted mix for some countries in the world and also an average value per continent.

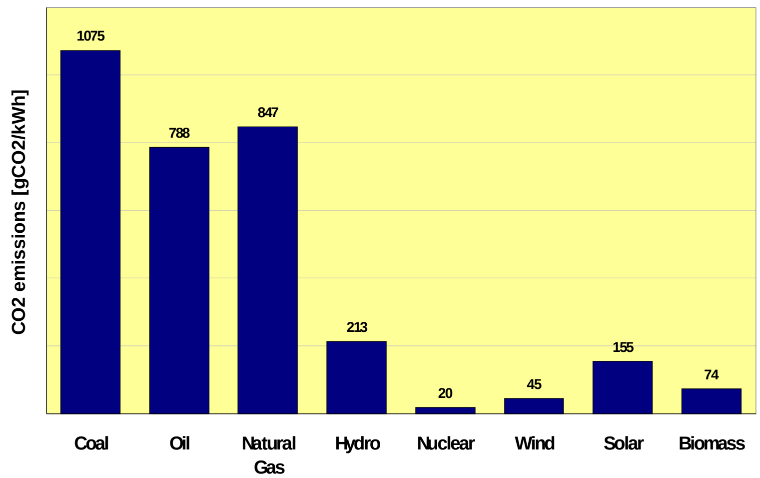

Figure 1: Average CO_2 emissions by primary energy source

Table 4: CO_2 emissions by primary energy sources

Source	CO_2 emissions[gCO_2/kWh]		
	Min	Average	Max
Coal	860	1075	1290
Oil	686	788	890
Natural gas	460	847	1234
Hydro	16	213	410
Nuclear	9	20	30
Wind	15	45	75
Solar	30	155	279
Biomass	31	74	116

Due to the previously mentioned reasons it is very important when selecting "β" factor (in gCO_2/kWh) for a certain region to understand the methodology and considerations being applied. Different sources of information and different methodologies can supply completely different values for the same factor. The "β" factors used in this work are the average values given in Table 5.

Table 5: "β" factor - CO_2 emissions on energy generation expressed in gCO_2/kWh

Continent	Country	Energy Mix by Primary Source(*)				Total Electricity Production(*)	CO_2 emissions [gCO_2/kWh]		
		Thermal	Hydro	Nuclear	Renewables	[billion kWh]	Min	Average	Max
Africa	South Africa	93%	1%	7%	0%	196	620	840	1,060
	Egipt	81%	19%	0%	0%	72	543	770	998
	Average	90%	5%	5%	0%	287	604	827	1,049
South America	Argentina	59%	34%	7%	0%	85	402	608	814
	Brazil	6%	89%	1%	4%	339	56	248	440
	Average	17%	78%	3%	3%	431	125	320	514
North America	Canada	28%	58%	13%	1%	566	198	380	562
	Mexico	79%	14%	4%	3%	199	530	745	960
	USA	71%	6%	21%	2%	3,719	481	663	846
	Average	66%	13%	19%	2%	4,484	447	631	815
Europe	Germany	62%	4%	30%	4%	545	418	577	736
	Spain	50%	18%	27%	4%	223	344	504	663
	France	8%	14%	77%	1%	520	64	120	175
	Italy	79%	18%	0%	3%	259	529	752	974
	United Kingdon	74%	1%	24%	2%	361	496	675	853
	Sweden	4%	51%	43%	2%	153	39	154	270
	Average	45%	18%	34%	3%	2,382	309	457	604
Asia	China	82%	17%	1%	0%	1,288	548	773	999
	India	83%	14%	3%	0%	512	555	777	1,000
	Japan	60%	8%	30%	2%	1,037	405	567	729
	Russia	66%	19%	15%	0%	835	447	641	835
	Average	72%	15%	12%	1%	3,788	487	688	888
Pacific	Australia	91%	8%	0%	1%	198	609	839	1,069
	New Zeland	32%	58%	0%	11%	38	223	418	613
	Average	81%	16%	0%	2%	236	547	772	996

(*) *Source: The Energy Information Administration (EIA) - U.S. Department of Energy*

3. RESULTS

Considering the experimental data given in Table 2 and the premises listed in Section 2 for expected life time, leakage rate, recycling factor, GWP and "β", the TEWI values for each equipment and market region, were then calculated using Equation (1) . The results are shown in Figure 2 and Table 6.

It is evident how strong is the influence of indirect effect due to energy consumption on total CO_2 emissions. In the North American market the indirect effect contribution to the TEWI is around 98% for both household and commercial applications. In Europe due to the use of Hydrocarbons as refrigerant in household applications, indirect effect has practically no contribution to the TEWI. Meanwhile light commercial applications in Europe present indirect contribution ranging from 95% to 98%, the lower value associated to the refrigerant with higher GWP. The situation in Asia for household applications is very similar to Europe due to the progressive penetration of Hydrocarbons. Light commercial applications in Asia are similar to other regions regarding indirect contribution for TEWI at the range of 98%.

Regardless of the market region and type of refrigeration system indirect effect will always represent a major contribution to Global Warming.

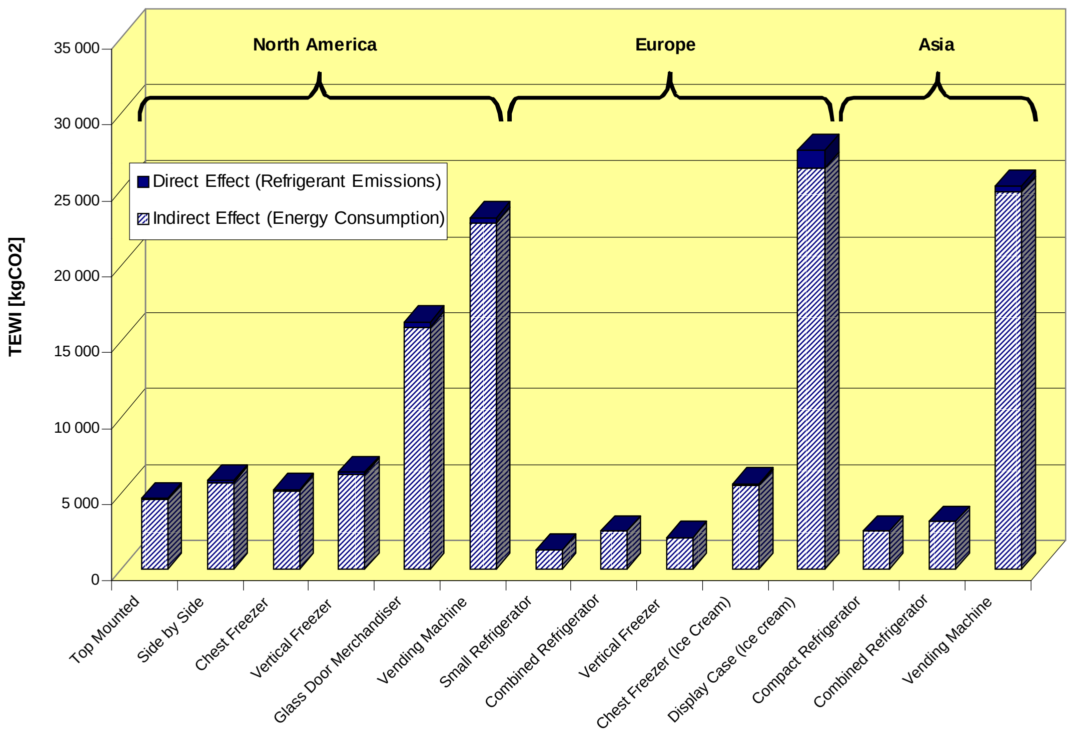

Figure 2: TEWI calculated data in kilograms of CO_2

It is also interesting to compare the TEWI values for household and light commercial refrigeration systems. Of course this comparison is not entirely fair because of the system differences and in some cases slightly different test conditions, but despite of that some comparisons will be made based on equipment with equivalent storage capacity. In the North American market, for example, the TEWI value for a Glass Door Merchandiser is 2.8 times higher than the one for a Side by Side refrigerator. The same difference but using an Ice Cream Chest Freezer and a residential Freezer was found in the European market. As mentioned before both applications have their own characteristics and requirements such as products advertisement using stronger lightning systems that contribute to TEWI degeneration. On the other hand more stringent regulations on energy consumption for household applications strongly contributed to the performance improvement of these equipment allowing a significant reduction on the Global Warming impact in the last decade.

The data given in Table 6 are the results of a sensitivity analysis, employing two different scenarios. In the first one the refrigerants were replaced by a new refrigerant with GWP equal to 1 and the energy consumption was held constant. In the second one the energy consumption was reduced by 15% and the refrigerant was not changed. (15% energy consumption reduction is just a hypothetical value – its feasibility must be carefully evaluated for each equipment).

Table 6: TEWI calculations and Sensitivity Analysis

Region	CO_2 emissions [gCO_2/kWh]	System Model	Lekage Rate [%]	Life Time [years]	Refrigerant		Energy Consump.	Original Situation			New Refrigerant GWP = 1		Energy Consumption reduction by 15%	
					Type	Amount [g]	KWh/month	TEWI	Direct Effect	Indirect Effect	TEWI	Reduction	TEWI	Reduction
North America	631	Top Mounted	3%	15	HFC 134a	110	40	4643	2.2%	97.8%	4543	-2.2%	3962	-14.7%
		Side by Side			HFC 134a	150	50	5816	2.3%	97.7%	5679	-2.3%	4964	-14.6%
		Chest Freezer			HFC 134a	150	45	5248	2.6%	97.4%	5111	-2.6%	4481	-14.6%
		Vertical Freezer			HFC 134a	120	55	6356	1.7%	98.3%	6247	-1.7%	5419	-14.7%
		Glass Door Merchandiser	5%	10	HFC 134a	330	210	16223	2.0%	98.0%	15901	-2.0%	13838	-14.7%
		Vending Machine			HFC 134a	400	300	23106	1.7%	98.3%	22716	-1.7%	19699	-14.7%
Europe	457	Small Refrigerator	3%	15	HC 600a	30	15	1234	0.0%	100.0%	1234	0.0%	1049	-15.0%
		Combined Refrigerator			HC 600a	60	30	2468	0.0%	100.0%	2468	0.0%	2098	-15.0%
		Vertical Freezer			HC 600a	40	25	2057	0.0%	100.0%	2057	0.0%	1748	-15.0%
		Chest Freezer (Ice Cream)	5%	10	HFC 134a	120	100	5601	2.1%	97.9%	5484	-2.1%	4778	-14.7%
		Display Case (Ice cream)			HFC 404a	500	480	27546	4.4%	95.6%	26324	-4.4%	23597	-14.3%
Asia	688	Compact Refrigerator	3%	15	HC 600a	25	20	2477	0.0%	100.0%	2477	0.0%	2105	-15.0%
		Combined Refrigerator			HC 600a	50	25	3096	0.0%	100.0%	3096	0.0%	2632	-15.0%
		Vending Machine	5%	10	HFC 134a	400	300	25158	1.6%	98.4%	24768	-1.5%	21443	-14.8%

In the North American market the replacement of the refrigerants by a unitary GWP refrigerant decreases TEWI in household applications from 1.7% to 2.6% and from 1.7% to 2.0% for household and light commercial applications, respectively. On the other hand keeping the current refrigerants but improving energy efficiency by 15% decreases the TEWI by 14.7% for both household and commercial applications.

In the European market due to current use of hydrocarbons in household applications the replacement of refrigerants does not provide any additional benefit. However by improving the energy efficiency in 15% the same level of reduction in TEWI was observed. Replacing current refrigerants in light commercial application can reduce TEWI by only 4%.

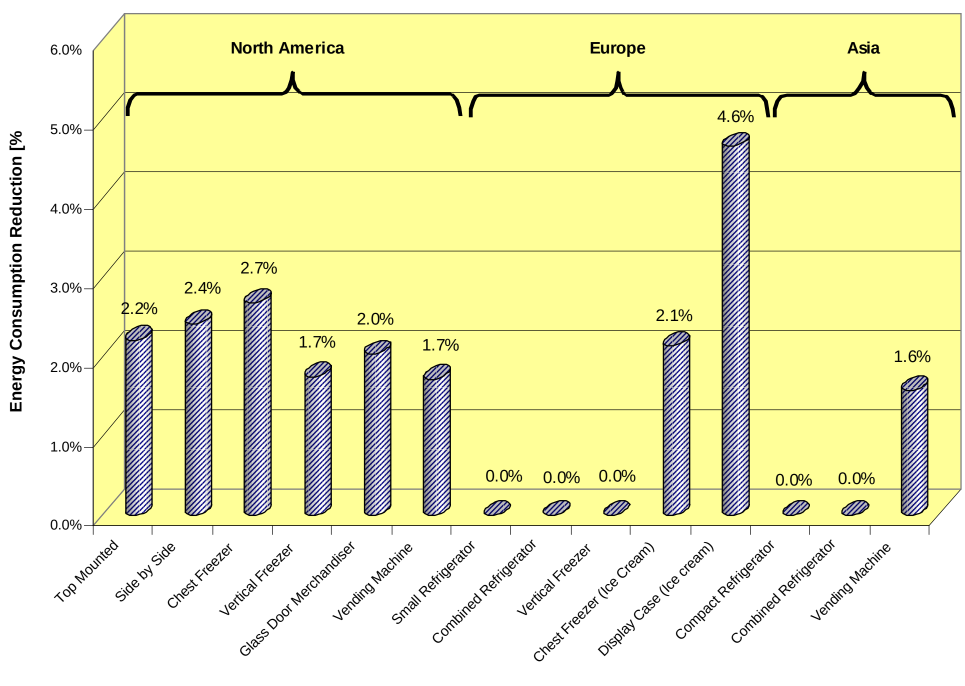

Figure 3: Energy consumption reduction required to get the same effect on TEWI give n by refrigerant replacement

In short, by replacing refrigerants, reductions up to 4% in the TEWI values can be expected, depending on the equipment. By improving efficiency in 15%, the expected reduction ranges from 14% to 15%. The influence of the indirect effect on the TEWI value is then stronger than the one imposed by the direct effect. Figure 3 shows the required energy consumption reduction to achieve the same benefit in terms of TEWI as could be achieved by replacing the refrigerant (GWP=1).

In the present analysis refrigerant type and energy consumption were treated as independent variables what means that no interaction between refrigerant replacement and energy efficiency were considered. Of course if a new refrigerant comes into the market with no direct impact on global warming (GWP=1) but introducing penalties to the equipment energy efficiency the potential benefit of the refrigerant replacement may be entirely cancelled.

The sensitivity analysis suggested and performed in this paper is very basic and does not preclude other people from performing a deeper analysis. It is possible to take into account other possible variables and combinations such as gas charge, alternative energy mix, refrigerant recovery factor, leakage rate, etc.

4. CONCLUSIONS

Total Equivalent Warming Impact (TEWI) has shown to be a strong tool for evaluating environmental contribution of technologies to the Global Warming. The methodology has a broad scope taking into account factors related to the chemical effect associated with refrigerant leakage (direct effect) and combining this effect with factors related to the emissions caused by the energy use of such equipment (indirect effect). The indirect effect is strongly dependent on the mix of primary energy sources used to produce electricity.

For reducing the TEWI of a certain equipment several measures can be taken, such as improve the energy efficiency, substitute refrigerants by new ones with lower GWP, improve refrigerant containment and recovery practices, and use of better primary energy generation mix – more use of renewable sources.

However the most effective measures should be considered. On household and light commercial applications, regardless of the market region, indirect effect represents the major contribution to Global Warming ranging from 95% to practically 100% of the total TEWI. Due to this reason it seems much more effective to the environment initiatives related to energy efficiency improvements than those focused on refrigerant replacement.

When replacing a refrigerant a special care has to be taken to avoid the TEWI degeneration due to an excessive increase in energy consumption. Incorrect decisions can be made if entire systems are not considered carefully in evaluating impacts of alternative technologies.

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