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LCCP vs. Eco-Efficiency

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ABSTRACT

The contribution of anthropogenic greenhouse gases to global warming has become one of today's most urgent environmental issues. International treaties endeavour to achieve a reduction of the most relevant greenhouse gases.
Concerning refrigeration technology, CO_2 from energy production and direct emissions of f-gases used as refrigerants (HCFCs and HFCs) can contribute to global warming. These indirect and direct emissions are interdependent.
Different assessment approaches are used to identify the most effective solutions for refrigeration systems and refrigerants with respect to a reduced environmental impact.
Simplistic models consider only the global warming potential of the used refrigerant together with releases during operation of the system. The TEWI concept (Total Equivalent Warming Impact) extends the scope of the assessment to the CO_2 arising from energy supply required during operation of the system.
The LCCP (Life Cycle Climate Performance) evaluates the complete environmental impacts from cradle to grave, from manufacture of the refrigeration system, to the use of the system and finally to the end-of-life management.
All these assessment approaches aim to describe the environmental impact of refrigeration systems. However, a conclusion about the optimally achievable result in terms of environmental impact cannot be derived unless the economic aspect of limited financial resources is taken into consideration. Therefore the concept of eco-efficiency complements the LCCP with this crucial aspect.
Using the example of a supermarket refrigeration system we show how the input data for the different environmental assessment methods are obtained. The notably different results of the different tools are discussed.
The outlook considers other areas of refrigeration, e.g. MACs and stationary A/C systems, where the concept of eco-efficiency can also provide valuable insights.

1. INTRODUCTION

The emission reduction of greenhouse active substances is currently one of the overriding goals of national and international politics. Against this background, also fluorinated hydrocarbons (HFC's) and their use within cooling devices have been drawn into the focus of the public debate especially in Europe. This debate has been often based on a stringent material view, taking only the physical properties of the substances class into account. It has neither considered the whole applications the HFC's are used in, nor the costs that are related to the substance substitution. Such a narrow focus could end up in misleading results as e.g. the application might have a worse performance with a substitute substance. To step forward from a solely material based discussion to the useful dialogue about substances in their respective applications, a broad investigation of the relevant systems has to be carried out in a global approach. This global examination should consider the whole life cycle of the application, from the exploration of the raw materials to production of components, from the operation of the application until the end of service life and the recycling. LCCP and LCA are examples of environmental indexes that carry out cradle to grave analyses. Beside the ecologic aspects, also the economic aspects should be taken into account always bearing in mind that a reduction of greenhouse gases must be achieved in the cheapest way possible. A possible approach to attain this goal is the eco-efficiency concept. Based on the obtained results, pros and cons of a technology can be globally balanced, optimization potentials can be uncovered and recommendations for politics and industry can be deduced.

2. LCCP

To carry out a Life Cycle Climate Performance assessment means essentially to count the Global Warming emissions of a technology from its cradle to its grave. All the direct and indirect contribution to Global Warming is taken into account from the production of systems to their disposal, passing through their use. The idea has been successful and it is the natural broadening of the TEWI index, which focused on systems during their life. LCCP is indeed a complete and complex index to evaluate the global warming performance of a technology, and in fact it has been the reference for many studies. As an example, all different technologies for the Mobile Air Conditioning and Supermarket Refrigeration have been analysed through the LCCP. The method complexity enhances the grades of freedom of the applicant, so that it is not rare to find contradictory studies on the same topic. In fact, if we want to evaluate the global impact of a system, we need to define its production method, how it is used and how it is wasted: something that cannot be univocal. On the other hand, a complex situation needs a complex analysis method to obtain complete and reliable results that are flexible and applicable to different realities (markets) where any system is run. Indeed, in order to have a useful tool to the environmental discussion, it is essential to define a standard that transparently, upon the same hypothesis, leads to the same results.

3. LCA [1,2,3,4]

Life Cycle Assessment extends the LCCP approach to the other relevant aspects that concern the environmental impact of a technology. Together with the Global Warming Impact, also the eutrophisation potential, the acidification potential and the ozone depletion potential are taken into account. The approach is conceptually identical, considering all the respective source of pollution from the production to the disposal. Taking account of the greenhouse emissions only, LCA and LCCP should lead to same results. The advantage of LCA is in its standardization: LCA is ruled under ISO standards. Thus, it is possible to affirm that the Life Cycle Assessment, in the part concerning the Greenhouse emissions, is the most accurate description of how to calculate the Life Cycle Climate Performance of a technology.

Even though LCA considers exhaustively the different aspects of the environmental impact of a technology, it does not offer any procedure to compare them. In fact, it is not possible to state if a technology that shows a lower greenhouse impact but a higher eutrophisation potential is better or vice versa. The different phenomena act on different scale, and, also form a physical point of view, they are measured with different units. A global evaluation of a technology is not a mere computation and the role of the politic is binding and essential.

The limit of LCA is its exclusive focus on accounting environmental impacts. Comparing different technologies only through their environmental impacts under-evaluates all their economic and social impacts. In the case of refrigeration, this aspect is particularly important because it does not only involve the working places of 2 millions people worldwide [5], but it impacts also the essential standard of life of the whole humanity. However, even by focussing our attention only on the environmental aspect, the cost of a technology is a parameter that must be taken in consideration. Financial resources are limited and a cheap technology offers the chance to pay for its technological improvements. It is fair, and scientifically correct, to compare technologies with comparable costs.

4. LCCA [6]

As for the environmental impact, it is important not to restrict the cost analysis of systems simply to their price. The price is only a component of the total cost of ownership. A coherent approach takes into account all the costs from cradle to grave, considering so the system price together with the capital costs, the energy costs and the costs of disposal at the end of life. The complexity of such an analysis is evident and it is comparable with the one of the Life Cycle Assessment we have previously discussed. Every market has specificities that can lead to results with substantial differences. The legislations on waste disposal, for example, involve different costs, even though it is presumable that the most significant discrepancies arise from energy costs. In fact, the 15% of the total energy produced in the industrialised world is spent to run refrigeration systems. Indeed, the energetic factor is the most strongly under-evaluated by the over-simplified analysis that take into account only the GWP of the refrigerants and the costs of systems. This is particularly sinful because energy contributes significantly both to the cost of ownership and to the greenhouse emissions. LCCA is a standardised IEC method, being this a fundamental contribute to the comparability of the different results that are obtained for different markets or under different hypothesis of work.

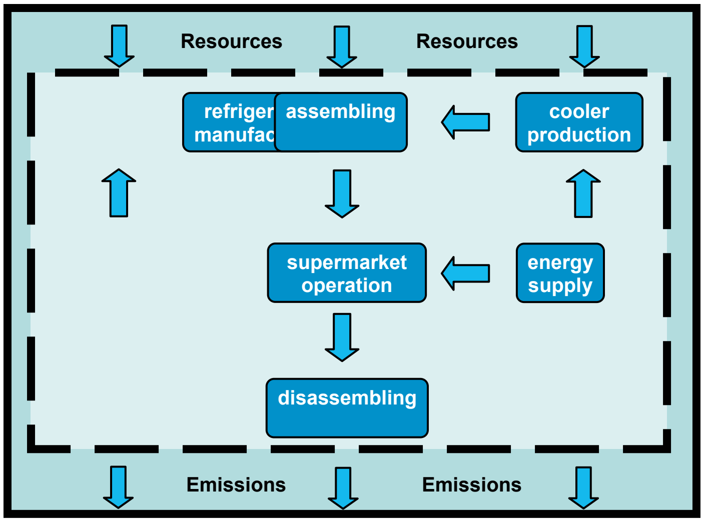

Fig. 1 - Example of cradle to grave approach for LCCA and LCA analysis for Supermarket refrigeration

5. THE ECO-EFFICIENCY CONCEPT

Eco-Efficiency offers a procedure to balance the environmental and the socio-economic impacts of different technologies in a global approach.
The fundamental approach of eco-efficiency can be put in a nutshell as follows: »create more value with less impact«. The term was coined in 1992 by the World Business Council for Sustainable Development (WBCSD) as an essential contribution to sustainable development. Since then, the WBCSD has developed it into a strategy and management concept.
»The WBCSD defines eco-efficiency as being achieved by the delivery of competitively priced goods and services that satisfy human needs and bring quality of life, while progressively reducing ecological impacts and resource intensity throughout the life cycle, to a level at least in line with the Earth's estimated carrying capacity.«[7]
Since both natural resources and financial resources are scarce and subject to competition, a more generic definition is reasonable. Thus, eco-efficiency (E/E) can be represented by the following simplified formula:

$$\frac{E}{E} = \frac{\Delta\ Added\ Value}{\Delta\ Total\ Burden} \tag{1}$$

In this equation, the increased added value (numerator) comprises both the functional unit (e.g. refrigeration of a defined supermarket) and possibly further added value (e. g., profitability, reduced external costs). The incremental total burden (denominator) encompasses both the environmental impact and the total cost of ownership of a technology.
Eco-efficiency therefore comprises a number of aspects which allow the development of sustainable product strategies:

- Customer or societal view: eco-efficiency can be increased by providing added value to the consumer or society at large, i.e. improving the functionality, while avoiding stepping up the associated environmental burden.
- Corporate view: eco-efficiency can also be increased by providing added value to the company, e. g. by higher incomes and profits, again at the same or lower environmental burden.
- Environmental view: finally, a higher eco-efficiency can be accomplished by mitigating the environmental impact of the product system, i.e. achieving the same function with a lower ecological footprint.

5.1 Implementing ECO-EFFICIENCY

An Eco-Efficiency study can be carried out comparing systems that have the same added value, as for example the same refrigerating capacity for a supermarket or the same comfort standard for a mobile air conditioner. This is equivalent to consider the variable *Δ added value* in formula (1) as being constant. The most complete procedure to measure the *Δ Total Burden* at the denominator is to sum the LCA index and the LCCA index as respective evaluations of the environmental burden and the financial burden, as we have outlined in the previous chapters. Both indexes follow a cradle to grave approach, but they lead to results that inevitably are measured with different units. The best eco-efficient system maximises the function (2) here below.

$$\frac{E}{E} = \frac{1}{\mathrm{LCCA} + \mathrm{LCA}} \qquad (2)$$

As LCA encompasses the different contributes to pollution, the best system is the best compromise between cheapness, low greenhouse impact, low acidification impact etc… Surely, today the attention of the public debate is focalised on the Greenhouse effect, which is a global threat of tremendous magnitude. Limiting the analysis to this is equivalent to maximise the equation (3), where only the greenhouse addendum of the LCA study is considered. That is, as we have outlined, the best method to follow in order to carry out an LCCP analysis.

$$\frac{E}{E} = \frac{1}{\mathrm{LCCA} + \mathrm{LCCP}} \qquad (3)$$

The best eco-efficient system minimises both costs and environmental impact or, in other words, maximises both the environmental advantage and the cost advantage. It is possible to represent the results through a 2 axis diagram, like the one here below, where the abscissa represents the environmental burden of the LCCP function and the ordinate represents the financial burden of LCCA study. To overcome the fact that the two functions have different scales and different units, both axes are normalised to 1 by the average of the values obtained by the LCCP and LCCA analyses.

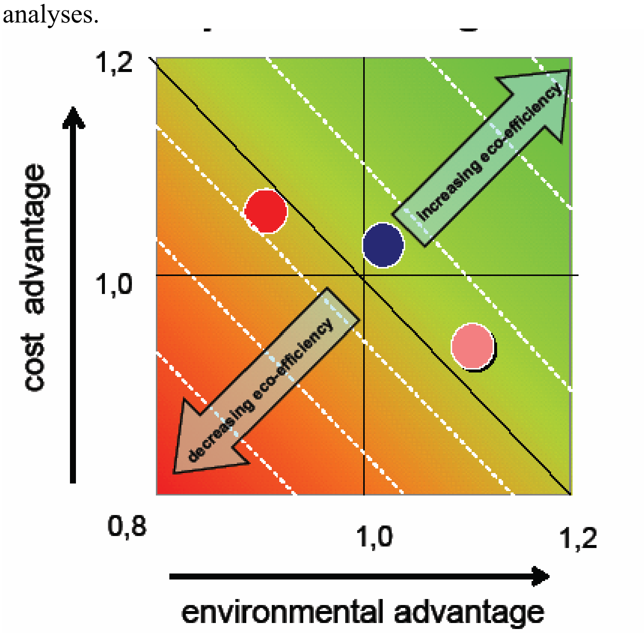

Fig. 2 - Example of an Eco-Efficiency diagram

4. THE ECO-EFFICIENCY CONCEPT FOR MAC

The eco-efficiency concept is an important tool also to carry out a-priori analyses on technologies that are in fast evolution. As an example, an analysis on the mobile air conditioning (MAC in acronym) is discussed, which is an overriding topic of today, mainly in Europe, where the new regulation will impose to use fluids with a GWP lower than 150, banning R134a.

Mobile Air Conditioning systems are the example of not tight systems, because the compressor is shaft-driven with inevitable losses at the lip gasket. Other losses are due to the flexible connecting tubes that must be produced with porous materials.
The EU commission estimated [8] in 2001 for the European vehicle fleet average losses as per the attached table.

Tab. 1 - European estimation of MAC emissions

	Low hypothesis	*High Hypothesis*	*Average*
Regular R134a emissions occurring during normal operation of a vehicle	53 g/y	53 g/y	53 g/y
Irregular R134a emissions from accidents, stone hits etc…	16 g/y	20 g/y	18 g/y
R134a emissions during service	100 g per service	200 g per service	150 g per service
R134a emissions at end of life	20 %	50%	35%

According with these hypotheses, the eco-efficiency of two theoretically identical systems is estimated here below, one running with R134a and the other with R744, with a life of 13 years. To do this, the following simplifications have been assumed:
1. Only the TEWI index is evaluated, because no data are available on the impact of systems production and waste management. However, it is reasonably to consider comparable their impacts for the two systems, so that the most appropriate LCCP analysis would lead to more precise results, but with about the same delta.
2. Few data are available on which is the exact fuel consumption of a MAC system in a car. It is considered here a rough estimate of the 5% of a vehicle that consume 12l/km for 15000 km/y: meaning 60l/y. [9]
3. It is assumed that the CO_2 MAC systems will be the 20% more expensive than the R134a one. It is an assumption recently confirmed by AUDI [10].
In the here below example, it has been supposed that one service every four year is necessary, when 284 g of refrigerant charge will be lost in average.

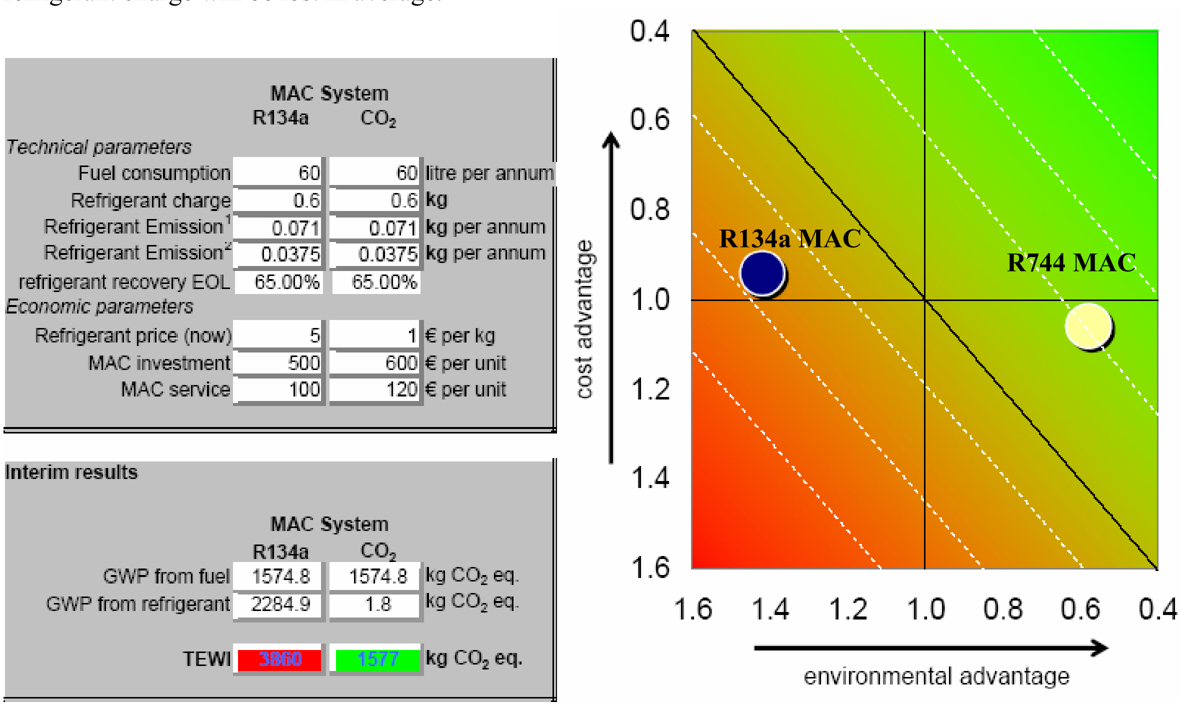

Fig. 3 - Eco efficiency analysis of 2 MAC systems

The R134a system has an impact of 3860 kg CO_2 eq., which the 59% of is due to DIRECT emissions. A theoretical R744 system, which is able to offer the same efficiency than an R134a one, may cut the green-house emissions by

half and shows the best eco-efficiency. This analysis explains the reasons which lead the EU to ban R134a systems from cars.
Recently, more accurate data on actual leakage rate of MAC systems [11] are available. Measured actual average losses on today's European vehicle fleet are in the range of 10 g/y. A consortium, in the US, is developing a so called 'Improved Mobile Air Conditioning system (I-MAC)', working with 134a, which declares the following targets [12]: improving in performance (COP) +30%, servicing and end-of-life losses -50%, leakage rate -50%. Those targets are considered feasible by the international scientific community. Consequently, it has been analysed here the eco-efficiencies if the I-MAC project will be successful. The technical improvements of I-MAC technology are extended to R744 systems. With a leakage rate of 5 g/y, it is assumed also that no service at all will be necessary for MAC systems, because after 13 years of life only the 10% of the original charge will be lost. 18g/y of accidental release have been kept constant.

Tab 2 - 134a MAC emissions according to new data and I-MAC hypothesis

	New measurements	*I-MAC Hypothesis*	*Our Hypothesis*
Regular R134a emissions occurring during normal operation of a vehicle	10 g/y	5 g/y	5 g/y
Irregular R134a emissions from accidents, stone hits etc…	---	---	18 g/y
R134a emissions during service	---	75 g	---
R134a emissions at end of life	---	10 - 25%	17,5%

Under this scenario, the cars running an I-MAC system would have an impact of 2144 kg CO_2 eq.; cars running a CO_2 system would have an impact of 1576 kg CO_2 eq., having the first one the lower eco-social impact.

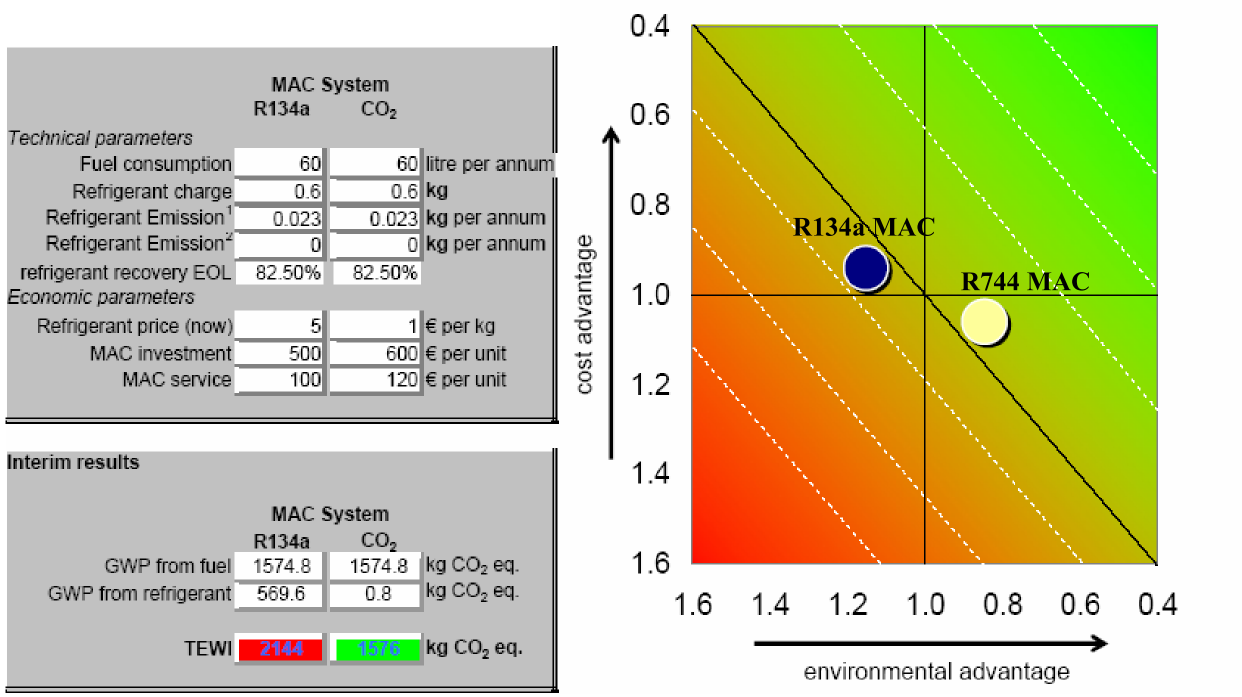

Fig. 4 - Eco efficiency analysis of 2 MAC systems

It is of interest to abandon the hypothesis that the two technologies offer the same performance in terms of efficiency. In fact, the two thermodynamic cycles differ deeply from each other because R744 is in supercritical conditions at temperature above 31°C. This is a very common situation for condensers that work prevalently in summer in the hood of cars.

In this example, the eco-efficiency concept is not exploited to compare two actual technologies, but to evaluate a priori under which circumstances a technology is better than others. The analysis that is carried out in *fig. 5* aims to establish till which difference in performance the R744 MAC system shows the best eco-efficiency. It is estimated that the two technologies present the same eco-efficiency if the 134a MAC system saves 9l of gasoline per year, or, in other words, if the R744 system consumes 9l of gasoline more per year. The gasoline consumption can be considered as an indirect measurement of the COP of the respective cycles, because it is an indirect measurement of the energy needed to run the compressor.

	MAC System R134a	MAC System CO_2	
Technical parameters			
Fuel consumption	60	69	litre per annum
Refrigerant charge	0.6	0.6	kg
Refrigerant Emission[1]	0.023	0.023	kg per annum
Refrigerant Emission[2]	0	0	kg per annum
refrigerant recovery EOL	82.50%	82.50%	
Economic parameters			
Refrigerant price (now)	5	1	€ per kg
MAC investment	500	600	€ per unit
MAC service	100	120	€ per unit

Interim results

	MAC System R134a	MAC System CO_2	
GWP from fuel	1574.8	1811.0	kg CO_2 eq.
GWP from refrigerant	569.6	0.8	kg CO_2 eq.
TEWI	2144	1812	kg CO_2 eq.

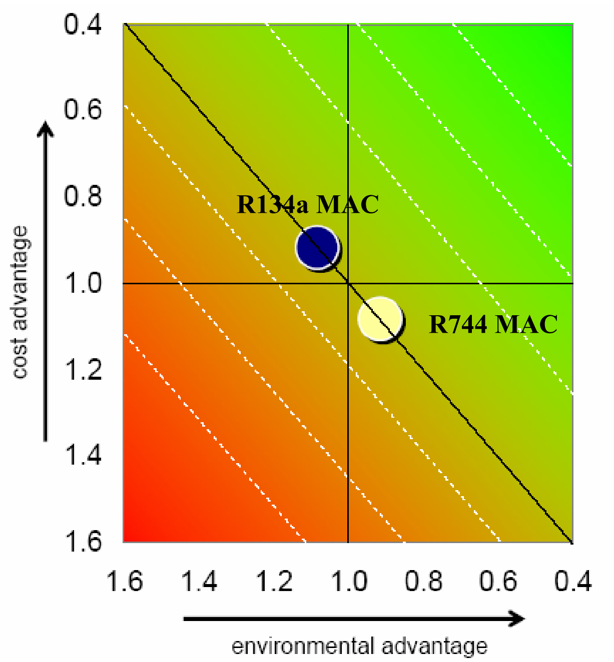

Fig. 5 - Eco efficiency analysis of 2 MAC systems

Thus, the 134a technology and the R744 technology have the same eco-efficiency if the R-134a cycle has a better COP of + 13%.

Simple thermodynamic calculations can show that the R744 cycle with a condensing temperature of 40°C and an evaporation temperature of 1°C has a theoretical COP of -50% compared with the equivalent 134a cycle. There are many technological reasons to presume that the actual distance between the two cycles is not as high as the 50%, but it is also true that a delta of 13% is not a high margin, even with all the approximations here considered. It is however reasonable to presume that this target is feasible for cars produced for northern Europe, but difficult for cars produced for warmer climate markets like the South of Europe. It is doubtful that the R744 systems will obtain good COPs in the hot climates typical for markets like south US or Singapore, or growing markets like India, Brazil.

4. DISCUSSION

The environmental debate on greenhouse effect in HVAC cannot be restricted to the GWP values of the fluids exploited in the different technologies, because it is essential to take into consideration all the aspects that contribute to the environmental impact. Among the indexes that have been proposed to measure this global impact, the LCCP philosophy is the most convincing. Unfortunately, there is a lack of standardisation that makes often this type of measurements not clearly comparable. ISO 14000 provides a reliable standard for Life Cycle Assessments, which under the same global approach evaluates all the different environmental impacts of a technology. Referring to this standard and limiting the analysis to the greenhouse emissions is the best method for carrying out LCCP analyses. It is also very important to include in the debate the economical aspect of the issue. This is not only true for the simple economic principle to purchase the cheapest technology, but also because the cheapest technology leaves financial opportunities to pay those technical developments that can lead to improve the environmental performance. Moreover, the economic impact is indelibly linked to the social impact in a sector which employs 2 million people worldwide and offers essential standard of life to humanity. The concept of ECO-EFFICIENCY has been introduced to this purpose. As an example of ECO-EFFICIENCY analyses, interesting results about Commercial Refrigeration are presented by IZW [13]. In this paper, the ECO-EFFICIENCY concept is exploited to analyse the strong technological changes of the Mobile Air Conditioning, which are influenced by political constrains. It is analysed the reasons behind the new European legislation that bans the R134a systems and the reasons why the new R744 technology hardly sees its sunrise.

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