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PERFORMANCE TEST METHODOLOGY FOR THE LCCP DETERMINATION OF SUPERMARKET AND OTHER INTEGRATED SYSTEMS

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ABSTRACT

A new flexible supermarket R-744 refrigeration unit has been implemented in the laboratories at NTNU/SINTEF. The unit is fully equipped with real display cabinets for both medium and low temperature, as well as seven large volume counter flow glycol heat exchangers to simulate the entire load of a supermarket. The entire range of alternative system architectures can be experimentally investigated, from a simple booster system, parallel compression towards ejector supported parallel compression. Various air conditioning (AC) loads can also be handled, to demonstrate the performance and potential of integrated R-744 systems.
Life Cycle Climate Performance (LCCP) tools are commonly applied to compare different system architectures. These tools are very detailed, accounting for most of the Greenhouse Gas (GHG) releases from CO_2 emissions due to energy usage (indirect) and CO_2 equivalent emissions from other operations (direct CO_{2equ}) from “cradle” (refrigerant and product manufacturing), through use, to “grave” (recycling and disposal) for a product. The results of LCCP investigations are mainly dependent on the energy usage, i.e. the energy demand for different load conditions at various ambient conditions, often expressed as the Seasonal Energy Efficiency Rating (SEER) of the refrigeration unit.
Several options are proposed in the literature for the determination of the LCCP in systems such as mobile air conditioning (MAC), heat pumps or refrigeration systems, but there is no approach for integrated units, i.e. equipment that meet simultaneously more than one load. This paper addresses this issue and suggests a possible way to deal with these cases.

1. INTRODUCTION

Heating, ventilation and air conditioning (HVAC) and refrigeration systems are responsible for a significant part of the GHG emissions that contribute to global warming and climate change nowadays. The Montreal Protocol set the mechanisms to reduce the use of CFC and HCFC refrigerants, which caused the ozone layer depletion. Now the focus is on phasing out HFC refrigerants, which cause global warming and climate change. The Kyoto Protocol included this fluid family in the list of GHG, and their use should decrease in Europe as stated in the Regulation (EU) No 517/2014 on fluorinated greenhouse gases. However, HFCs are only responsible for the direct share of greenhouse gases associated with refrigeration and HVAC units. The indirect emissions, due to the production of the electricity used by these units during operation on one side as well as the energy usage related to the manufacture of both the units and the refrigerant, should also be taken into account.

There are different indicators to show the contribution of a refrigeration system to global warming. The most common approach is to focus on the global warming potential (GWP) of the refrigerant applied in a refrigeration system. This view is incomplete, as aforementioned, and thus the Total Equivalent Warming Impact (TEWI) index was developed earlier, which also takes into account the GHG emissions related to the energy usage of the refrigeration system. The lately further adopted LCCP approach is a holistic indicator since it considers all the different factors involved in GHG emissions, from the manufacturing of refrigerants and components to the disposal of the unit,

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including its power consumption and refrigerant leakages during the lifetime of the unit. The LCCP is the indicator proposed by the International Institute of Refrigeration (IIR) in order to evaluate the footprint of refrigeration systems, and for that purpose they have recently launched the Guideline for life cycle performance (IIR, 2016).

LCCP tools have been utilized in several occasions for the analysis of systems and of different alternatives for a certain application. Dieckmann and Magid (1999) prepared a thorough report on the calculation of LCCP for different kind of HVAC and refrigeration systems, including automotive air conditioning, commercial refrigeration, etc. They analysed also different alternatives for each system, however, some results might be outdated. In particular, the authors did not evaluate transcritical CO_2 systems for commercial refrigeration applications, which were just introduced by that time. An interesting conclusion of their work is that direct GHG emissions due to the refrigerant itself account for a small share of the total LCCP of each solution. Papasavva and Andersen (2011) presented the GREEN-MAC-LCCP model, which is used for the evaluation of the impact of mobile air conditioning units. In this work, they evaluated systems with alternative refrigerants to R-134a, such as R-1234yf and R-744, from the point of view of LCCP and applying their LCCP tool and controversial system performance input values. They stated that CO_2 was not a convenient solution with the technologies available to them at that moment. In contrast, Hafner et al. (2004) and Wieschollek et al. (2007) demonstrated that a CO_2 MAC system could outperform R134a in terms of COP under ambient temperatures as high as + 45 °C, particularly with the vehicle in movement. Therefore, the LCCP associated with the R-744 system could be up to 49% lower than with an R134a unit, depending on the location/region. Zhang and Muehlbauer (2012) developed a tool for the calculation of the LCCP of residential heat pumps which calculated the annual energy consumption based on the operating conditions defined in the AHRI 210/140 standard, with two ambient conditions for cooling and three ambient conditions for heating (AHRI, 2008). They also proposed a simpler method, which used the nominal Seasonal Energy Efficiency Rate (SEER) and Heating Seasonal Performance Factor (HSPF). This method appeared to be inaccurate when results were compared with the more detailed studies. Lee et al. (2016) analysed also the LCCP of different systems for residential heat pumps, each of them operating with several refrigerants and in different locations. For the calculation of the annual energy consumption they also considered the conditions included in AHRI 210/140 standard (AHRI, 2008) in their simulations of different systems (the baseline system had been successfully validated with experimental data) and studied eight temperature bins for cooling and 15 for heating.

It has been pointed out that Dieckmann and Magid (1999) did analyse the LCCP of commercial refrigeration systems, but ignored transcritical CO_2 systems. Beshr et al. (2015) considered such system, as well as four other options for supermarket refrigeration units, and evaluated their LCCP in different climate areas in the USA. The annual energy consumption, related to the indirect emissions included in the LCCP calculation, was determined hour by hour with the weather data, the energy load of the supermarket and the energy consumption, which is calculated with a simulation tool and with the ambient conditions at rated capacities. Thus, part load inefficiencies are ignored.

To the best of our knowledge, there are systems which have not been considered both in the existing case studies and in the guideline of the IIR (IIR, 2016): integrated units. These systems meet different loads simultaneously and efficiently, and can fulfil the needs that otherwise required two or more units. There is a need and tendency for integration in application areas such as supermarkets (commercial refrigeration), hotels or gyms, and it desires to be discussed how to evaluate the energy consumption of such systems in order to determine the LCCP. In this paper, an approach is proposed for these integrated units that allows to obtain the LCCP with an acceptable number or experimental tests or validated simulations. It is also a flexible solution that should be applicable independently of the type of loads the system meets.

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2. IIR Guideline for life cycle performance

This section describes the main issues discussed in the Guideline for life cycle performance (IIR, 2016) created by the IIR LCCP Working Group. In the first place the components that are considered for the calculation of the LCCP are summarised, thereafter focus is given to the determination of the emissions associated with the annual energy consumption, which normally account for the largest share in the total of the LCCP. Consequently, it is crucial that the focus is placed on its calculation.

2.1. LCCP

LCCP groups the emissions associated with a HVAC or refrigeration system in direct and indirect emissions (Figure 1). On the one hand, direct emissions include the effect of refrigerant leakages during the lifetime of the unit and any consequence caused by the products of the degradation of the refrigerants leaked. On the other hand, indirect emissions comprise the emissions associated with the manufacture of the HVAC or refrigeration system and of the refrigerant used, the emissions due to the generation of the electricity consumed by the system and due to the disposal of the system and refrigerant at the end of the lifetime of the unit.

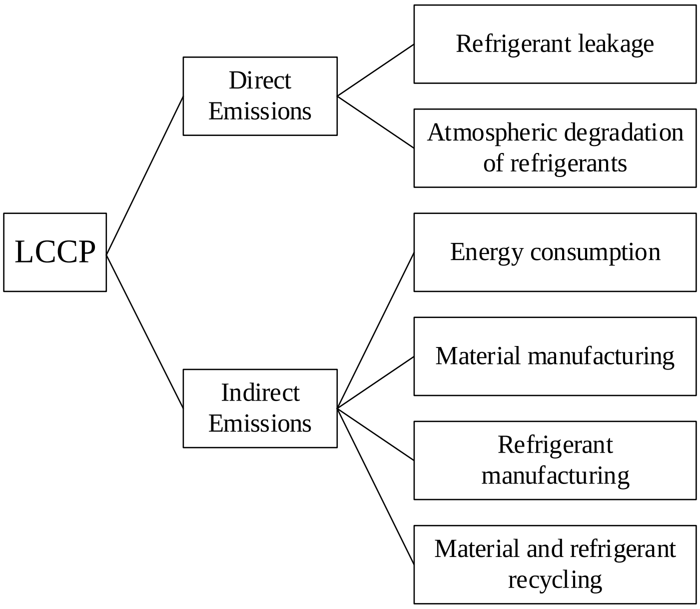

Figure 1. Categories for the calculation of the LCCP (based on the figure in the IIR (2016)).

2.2. Annual energy consumption determination

The IIR Guideline for life cycle performance (IIR, 2016) suggests the use of ISO and ASHRAE standards in order to determine the annual load model. This allows calculating the energy consumption, which depends also on the performance of the unit and the ambient conditions, which could be evaluated through a temperature bin method. When the performance of the unit is a function of the ambient conditions, the Guideline suggests that a minimum of four temperature bins should be considered for cooling and other four for heating. Therefore, the load and energy consumption of the unit are calculated for each bin, weighted with the number of hours the system operates in that temperature bin in that particular location, and added in order to determine the total energy consumption. In addition, the power in standby or due to compressor crankcase heaters should be considered.

The contribution to the LCCP due to the energy consumption is the result of multiplying the annual energy consumption by the lifetime in years that the refrigeration unit should be in operation and by the emissions due to the electricity generation in the particular location. The Guideline indicates that it

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might be necessary to correct the obtained value in case the performance of the unit is deteriorated by refrigerant leakages not solved with a proper maintenance (refilling of the system).

2.3. Limitations of the Guideline

As stated in the introduction of the IIR Guideline for the life cycle performance (IIR, 2016), it "provides a harmonized method to calculate the LCCP for all types of stationary air conditioning, heat pumping and refrigeration systems". However, it is limited to systems that meet one demand at a time, i.e. non-integrated systems. Thus, the methodology cannot be directly applied to integrated units, such as those ones that are becoming increasingly popular and a standard for supermarket applications worldwide. Besides, the performance of integrated units depends not only on the ambient conditions, however, could also be affected by the cooling demands at various temperature levels at each moment. As an example, the discharge pressure of a transcritical CO_2 system is not the same with only refrigeration loads as with refrigeration and heat recovery, even if the evaporation pressure is the same, which means that the power consumption is different too.

The guide proposes the use of standards for the determination of the conditions at which the power consumption of the units should be obtained. However, these standards are mainly focused on air conditioners and heat pumps, and there are no such indications for refrigeration systems or integrated units.

3. CONSIDERATIONS FOR INTEGRATED SYSTEMS

In this section different considerations for the calculation of the LCCP of integrated units, mainly for supermarket refrigeration systems, are suggested and discussed.

The first subject to be analysed is the determination of the load or loads to be met by the system. According to the IIR Guideline (IIR, 2016), the heating or cooling load should depend on the ambient conditions, i.e. on the temperature bin considered. On the other hand, with integrated systems we should also consider that heating, AC and refrigeration loads co-exists. In the particular case of supermarket refrigeration, the base refrigeration load (at different temperature levels) could co-exist with AC loads (at relevant summer ambient temperatures) or heating loads (at relevant low ambient temperatures). Besides, the loads may depend as well on the time of the day and the degree of use of the installation. As an example, with the same ambient temperature, the refrigeration and air conditioning loads of a supermarket are higher when the supermarket is open and with many customers than during the night-time.

As a summary, the determination of the load for a certain installation with an integrated system depends on the installation itself, on the ambient temperature (location), on the simultaneous existence of demands and on the hour of the day (intensity of use of the installation, building enveloped). Information is also needed about any external demand that is met by the integrated system (heat reclaim / AC of adjacent buildings or district heating/cooling system utilised for heat export, for example).

Figure 2 exemplifies the daily load profiles in an assumed supermarket located in Trondheim (Norway), as a function of the time of the day. The graphs at the top and at the bottom represent the different loads for a day in winter and a day in summer, respectively. It can be seen that the loads at medium temperature (MT) and low temperature (LT) would increase during the opening hours (from 7 a.m. to 23 p.m.) and particularly more when there is a high level of activity in the supermarket (reception of product, peak of attendance of customers).

Concerning the heating demand (green solid line in Figure 2), it comprises space heating and heating for domestic hot water production. The share of space heating depends on the temperature outdoors

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(and on the envelope of the building or buildings covered by the facility), and that is the reason why it appears only in the graph at the top. However, the domestic hot water production part is present in both cases (and throughout the year). For the conditions assumed in this example there are two periods at which domestic hot water is demanded, one in the morning and one in the evening. Even though, this contribution to the heating load will depend on the actual profile of the installation (building). Air conditioning demand in this assumed installation occurs only in summer (purple solid line in Figure 2 bottom).

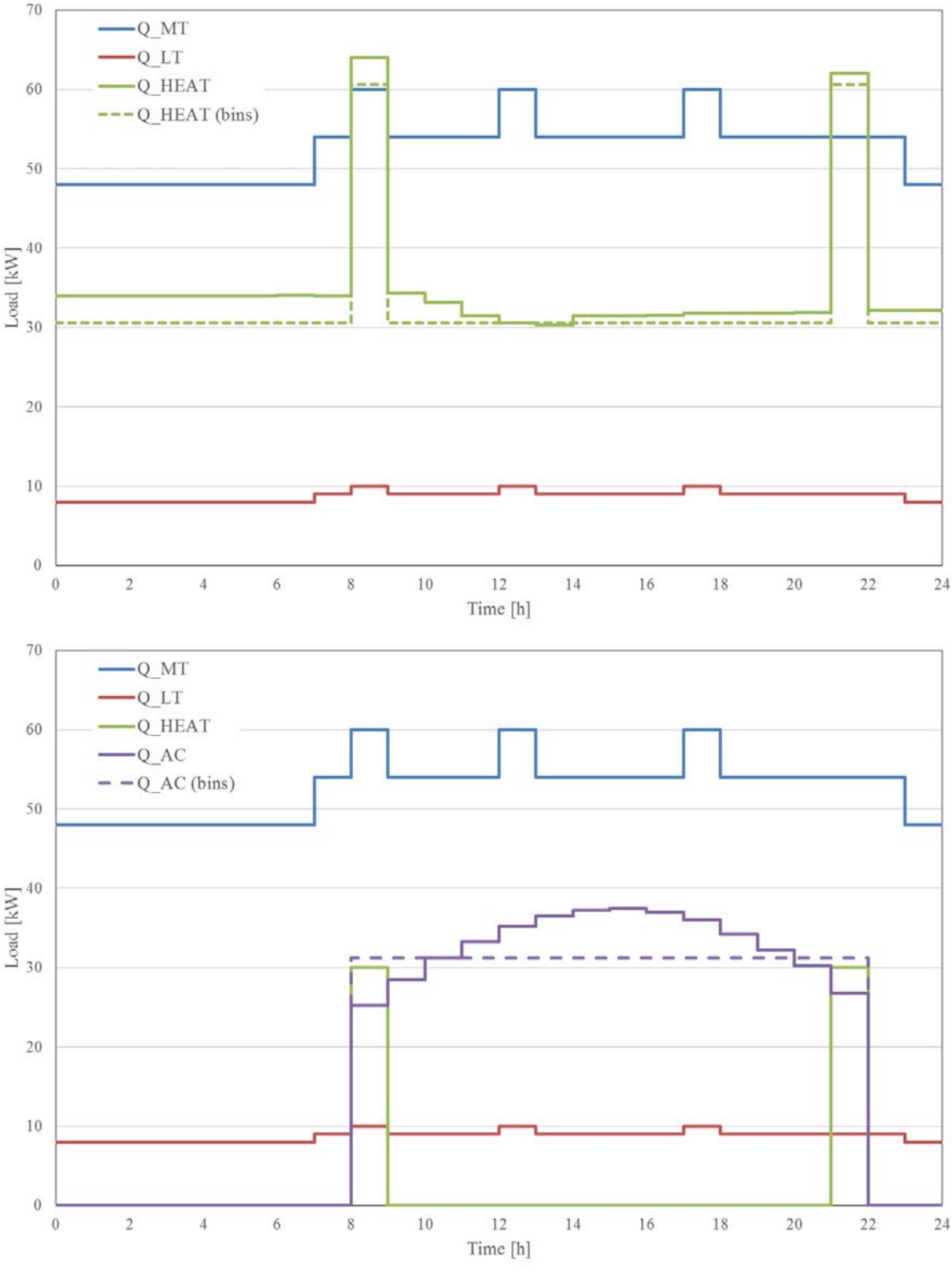

Figure 2. Example of daily load profiles for a supermarket located in Trondheim (Norway). Top, loads for a day in winter; bottom, loads for a day in summer.

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In addition, the heating and air conditioning demands depend on the ambient temperature, and therefore they could vary from one hour to the next. The determination of the energy consumption for each of this individual temperatures for its implementation in the LCCP calculation requires an experimental/simulation effort which cannot be addressed. Therefore, an acceptable simplification is to group those ambient conditions in temperature ranges (of 5 °C, for example) and determine the heating load and the energy consumption for the central value of each temperature range. The dashed lines in Figure 2 represent the heating and air conditioning loads assuming this approach.

Table 1 represents a first approach for such an ‘integrated temperature bin’ for an integrated supermarket refrigeration system. It is proposed to split up the temperature bins with a matrix of the number of hours that system will operate within a range of ambient temperatures, with a degree of usage (load) of the installation (intensity) and with the combination of loads in the location. This example takes into account the temperatures in Trondheim (Norway). Please mind that the simultaneous existence of heat reclaim and AC is justified by the need of producing DHW also in summer. This matrix could have more cases if the installation meets regional loads/demands, such as snow melting.

Table 1. Example of matrix of the number of hours that the system operates in a certain outdoor temperature range, with a degree of use (intensity) and combination of loads in a certain location.

		Number of hours with each combination of existing loads [h]			
$T_{amb,bin}$ [°C]	Intensity [-]	REF. only	REF. + HEAT	REF. + AC	REF. + AC + HEAT
-25/-20	High	0	0	0	0
	Medium	0	0	0	0
	Low	0	0	0	0
-20/-15	High	0	11	0	0
	Medium	0	43	0	0
	Low	0	29	0	0
-15/-10	High	0	7	0	0
	Medium	0	31	0	0
	Low	0	50	0	0
-10/-5	High	0	54	0	0
	Medium	0	219	0	0
	Low	0	302	0	0
-5/0	High	0	115	0	0
	Medium	0	502	0	0
	Low	0	835	0	0
0/5	High	0	207	0	0
	Medium	0	946	0	0
	Low	0	940	0	0
5/10	High	0	236	0	0
	Medium	0	995	0	0
	Low	0	867	0	0
10/15	High	0	195	0	0
	Medium	0	846	0	0
	Low	0	538	0	0
15/20	High	66	32	0	0
	Medium	284	129	0	0
	Low	113	52	0	0
20/25	High	0	0	16	0
	Medium	0	0	72	2
	Low	0	0	24	2

As it can be seen in Table 1, the number of conditions that need to be considered for the calculation of the LCCP of an alternative to be used in an installation is still too high. In order to reduce them, statistics could be applied in order to determine which cases are more significant in terms of their contribution to the total energy consumption. Another simpler approach would be to focus on those cases (bins) that have a larger share on the total of number of hours during a year.

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Once determined the matrix with the number of hours at each condition/combination and the loads associated with each case, it is possible to obtain the energy consumption for each of them. The IIR Guideline (IIR, 2016) does not indicate a specific method to determine this power consumption. Hafner et al. (2004) or Papasavva and Andersen (2011) based their LCCP calculations on experimental data. In contrast, Zhang and Muehlbauer (2012), Beshr et al. (2015) and Lee et al. (2016) utilized results from their simulations instead. Both experimental and numerical determination of the energy consumption are valid options provided that the experimental facility or numerical models are properly validated.

Another issue related to the determination of the energy consumption depends on whether the system considered has regulation of capacity (by using inverters, for example) or not. With fixed capacity systems, Beshr et al. (2015) suggested determining the power consumption at rated capacity and calculating the energy consumption with that value for a certain fraction of the whole period (hour). This approach ignores any inefficiency during part load operation. With units that allow capacity regulation, the calculation of the energy consumption is more accurate and convenient.

Finally, if the LCCP values of integrated system are compared with those from non-integrated alternatives, all the auxiliary units required to perform the same duty (heating, AC, domestic hot water, etc.) have to be part of the non-integrated LCCP system value. Therefore it is expected that such a comparison will document the advantages of integrated systems, since there are several components of the LCCP indicator that do not need to be taken into account twice. Of course this is a simple approach, since the integrated unit requires in principle more material, refrigerant charge, power consumption, etc. than each of the non-integrated equipment, but what matters in the end is the summation of the individual contributions of the non-integrated units.

4. CONCLUSIONS

LCCP tools are preferred for the comparison of different systems and to evaluate the GHG emission associated with those systems. LCCP is a holistic indicator since it includes CO_2 emissions due to energy usage and also those related to the manufacturing, use and disposal of refrigerant and components of the unit. The IIR launched a guideline (IIR, 2016) which clarifies the steps to follow in order to determine LCCPs of MAC, heat pumps, etc., but there is no reference to integrated units, i.e. systems that meet simultaneously more than one load. This paper proposes a methodology to obtain the LCCP of such units, focusing on how to determine the emissions due to energy consumption of the system. A bin method is suggested, being these bins a function of the ambient temperature, the loads that can be potentially met by the installation and how they co-exist, and the intensity of use of the installation. The loads and energy consumption associated with each of those bins could be obtained either with experiments or using validated simulation tools. Even though the preferred solution in terms of LCCP between two options will depend on their particularities, integrated systems are likely to outperform non-integrated systems.

NOMENCLATURE

AC	Air Conditioning	*LCCP*	life cycle climate performance
GHG	greenhouse gas	*LT*	low temperature
GWP	global warming potential	*MT*	medium temperature
HVAC	heating, ventilation and air conditioning	*SEER*	seasonal energy efficiency ratio
HSPF	heating seasonal performance factor	*TEWI*	total equivalent warming impact
IIR	International Institute of Refrigeration		

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REFERENCES

1. AHRI, A., 2008. Standard 210/240-2008. Performance Rating of Unitary Air Conditioning and Air-Source Heat Pump Equipment, AHRI, Ed.
2. Beshr, M., Aute, V., Sharma, V., Abdelaziz, O., Fricke, B., Radermacher, R., 2015. A comparative study on the environmental impact of supermarket refrigeration systems using low GWP refrigerants. International Journal of Refrigeration 56, 154-164.
3. Dieckmann, J.T., Magid, H., 1999. Global comparative analysis of HFC and alternative technologies for refrigeration, air conditioning, Foam, solvent, aerosol propellant, and fire protection applications. Arthur D. Little, Incorporated.
4. Hafner, A., Nekså, P., Pettersen, J., 2004. Life Cycle Climate Performance (LCCP) of mobile air-conditioning systems with HFC-134a, HFC-152a and R-744. Proceedings of the Mobile Air Conditioning Summit 15, Washington, DC, USA.
5. International Institute of Refrigeration, 2016. Guideline for life cycle climate performance.
6. Lee, H., Troch, S., Hwang, Y., Radermacher, R., 2016. LCCP evaluation on various vapor compression cycle options and low GWP refrigerants. International Journal of Refrigeration 70, 128-137.
7. Papasavva, S., Andersen, S.O., 2011. Green-MAC-LCCP©: Life-cycle climate performance metric for mobile air conditioning technology choice. Environmental Progress & Sustainable Energy 30, 234-247.
8. Wieschollek F. and Heckt R. (2007) Improved Efficiency for Small Cars with R744. Proceedings of the VDA Alternate Refrigerant Winter Meeting 2007, Saalfelden, Austria.
9. Zhang, M., Muehlbauer, J., 2012. Life Cycle Climate Performance Model for Residential Heat Pump Systems.

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