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REFRIGERANTS WITH LOW ENVIRONMENTAL IMPACT FOR REFRIGERATION APPLICATIONS

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ABSTRACT

Commercial refrigeration systems worldwide predominantly use high global warming potential (GWP) refrigerants such as R404A. However, these refrigerants are under an agressive phase out process in several countries through strict CO2 regulations. One widely implemented strategy to reduce CO2 emissions is to retrofit existing systems to lower GWP refrigerants such as R448A, while improving the system efficiency at same time. For new installations, there is opportunity to further reduce CO2 emissions by designing system architectures that enable the use of very low-GWP refrigerants. In this paper, two new concepts of distributed system architectures using ultra-low GWP fluids are proposed. In the first concept system, refrigeration at both low and medium temperature levels is provided using R1234yf based hermetic self-contained units while a two phase heat transfer fluid based secondary loop in combination with R1234ze(E) based chiller removes the heat from self-contained units to ambient. In the second concept, a low-GWP refrigerant is used in both medium temperature cases and to provide cooling to low-temperature self-contained cases through cascade heat exchangers. We will show that both new systems can signifanctly reduce emissions and energy consumption.

Keywords: HFO-Refrigerants, LCCP, Commercial Refrigeration, Supermarkets

1 INTRODUÇÃO

A common strategy to reduce CO2 emissions in existing supermarket refrigeration systems is to retrofit the currently used high GWP refrigerants with low GWP alternatives. R448A (GWP of 1273) is one such non-flammable retrofit option for existing R404A systems leading to reduction in direct emissions and about 11% improvement in energy efficiency (Abdelaziz and Fricke, 2014). Baba and Yamagushi (2014) showed that in comparison to R404A adoption of R448A in both low and medium temperature condensing units can yield up to 16% higher coefficient of performance (COP) and a near match in refrigeration capacity. Alternatively, Petersen et al., 2018 revealed that the system with refrigerant having lowest GWP does not automatically lead to the lowest emissions. Rather, overall emissions of refrigeration system depend on energy efficiency as well as on GWP of refrigerant. Hence, a new holistic approach is required to design and modify the existing system architectures to enable the adoption of low GWP fluids.

In the first section, the thermodynamic performance of low-GWP refrigerants such as R1234yf, R1234ze(E) and R515A are compared to the baseline refrigerant R134a. In the following step two new distributed system architectures using R1234yf, R1234ze(E) and R515A are proposed and their performance in terms of energy efficiency and CO2 emissions is compared with those of traditional systems as well as with current retrofit and other low-GWP alternative systems. Using a comprehensive analysis approach, the proposed new distributed system architectures with low GWP refrigerants R1234yf, R1234ze(E) and R515A are shown to be energy efficient leading to a significant reduction in both direct and indirect emissions compared to other systems.

2. LOW GWP ALTERNATIVES

In this session we will briefly describe three low-GWP refrigerants, R1234yf, R1234ze(E) and R515A, that are used in the new system architectures proposed in this paper. All three refrigerants are known to be "R134-like", with lower pressures and around 40-50% lower volumetric capacity than R404A. Thermodynamic analysis is carried out to compare the performance of these three low GWP alternatives in contrast to R134a in terms of cooling capacity and COP. The analysis is conducted at evaporation temperature of -7°C, evaporator superheat of 5.5°C, condensing temperature of 40.5°C, condenser sub cooling of 5.5°C, compressor isentropic efficiency of 65% and compressor volumetric efficiency of 100%. Table 1 summarizes the results obtained using thermodynamic data from the NIST property database REFPROP 9.1 (Lemmon et al., 2013). In comparison to R134a, all three alternatives show a close match in efficiency as well as reduced compressor discharge temperatures. R1234yf also has similar capacity. The reduction in capacity for R1234ze(E) and R515A in comparison to R134a can be compensated in new system architectures by increasing the compressor displacement.

Table 1 - Comparison of thermodynamic properties of R134a with low GWP alternatives.

Refrigerants	R134a	R1234yf	R1234ze(E)	R515A
ASHRAE Safety Classification	A1	A2L	A2L	A1
Composition	R134a (100%)	R1234yf (100%)	R1234ze(E) (100%)	R1234ze(E)/ R227ea (88%/12%)
GWP (AR5)	1300	<1	<1	402
Capacity [% of R134a]	100%	96%	74%	73%
Efficiency [% of R134a]	100%	96%	100%	100%
Suction pressure [kPa]	225	247	166	166
Discharge pressure [kPa]	1017	1018	767	767
Pressure ratio [% of R134a]	100%	91%	102%	102%
Difference in compressor discharge temperature vs. R134a [K]	0.0	-13	-8.8	-10

3. NEW AND EXISTING SYSTEM ARCHITECTURES FOR SUPERMARKETS

The R404A centralized Direct Expansion (DX) system is the most common architecture used in supermarket refrigeration. It has a centralized machine room consisting of compressor racks for both medium and low temperature cases. Its long reftrigerant lines typically require large refrigerant charge and lead to higher refrigerant emissions due to higher leak rates associated with more connections. Long connecting lines also yield higher pressure drop and heat gains which cause increase in compressor suction temperature.

In contrast to centralized systems, distributed refrigeration architectures are gaining popularity in recent years. In these systems, refrigerant tubing lenght is significantly reduced owing to adoption of distributed compressor racks located closer to both medium and low temperature cases, typically located in the back room of the supermarket, rather than in a remote machine room. In addition, condensers are typically located in the roof immediately above the racks, reducing the lenght of liquid lines. This leads to reduction in refrigerant charge and losses due to shorter connecting lines, which leads to higher efficiency, lower leak rates and consequently lower CO2 emissions.

New system architectures facilitate adoption of low GWP alternatives. One example is the R744 booster system which is essentially a two-stage system. R744 booster system can achieve comparable energy efficiency to R404A centralized systems at low ambient temperature operation. However, owing to the low critical temperature (31°C), the booster system operates in a trans-critical mode at ambient conditions above around 25°C, which leads to significant drop in energy efficiency. Adoption of parallel compressor (Karampour and Sawalha, 2016) and dedicated mechanical sub-cooling (Llopis et al., 2016) are two prominent modification strategies to improve performance of R744 booster system in high ambient conditions.

Fig. 1 introduces the first new low-GWP system architecture, called micro-cascade refrigeration system. This configuration uses R515A in medium temperature stage and R1234yf in the low temperature stage. R515A being non-flammable is employed in a traditional DX configuration to satisfy medium temperature load in store as well as to remove heat from the low temperature self-contained systems, using multiple cascade heat exchangers. R1234yf, although being mildly flammable, can be employed safely in low temperature stage owing to use of multiple low refrigerant charge hermetic units, as shown in Fig. 1. The choice of R1234yf in low temperature stage is favored over the highly flammable A3 refrigerants such as R290 which has lower allowable refrigerant charge.

The second proposed system architecture, called micro-distributed system, is show in Fig. 2. In this configuration, R1234yf is used in both low and medium temperature self-contained hermetic units, while a two phase Heat Transfer Fluid (HTF) secondary loop, in conjunction with a R1234ze(E) based chiller, removes the heat from all self-contained stages to outside ambient. Here, the choice of a two-phase HTF reduces the temperature difference in the cascade heat exchangers in comparison to single-phase heat transfer fluids such as water or water/glycol mixtures, improving consequently energy efficiency. The three-way valve, as shown in Fig. 2, allows use of free cooling of HTF in low ambient temperature operation, in which the R1234ze(E) Chiller would not be turned off. Thermodynamic optimization based on cooling temperature of two phase HTF and onset of free cooling depending on ambient temperature is therefore required for best performance. Another distributed configuration investigated is R290/water micro-cascade system which is being adopted in supermarkets in recent years. In this architecture, R290 is employed in self-contained low temperature and medium temperature cases. Water is used as secondary fluid to remove the heat from the self-contained units, while heat from water can be removed either directly to the outside ambient or by using a chiller.

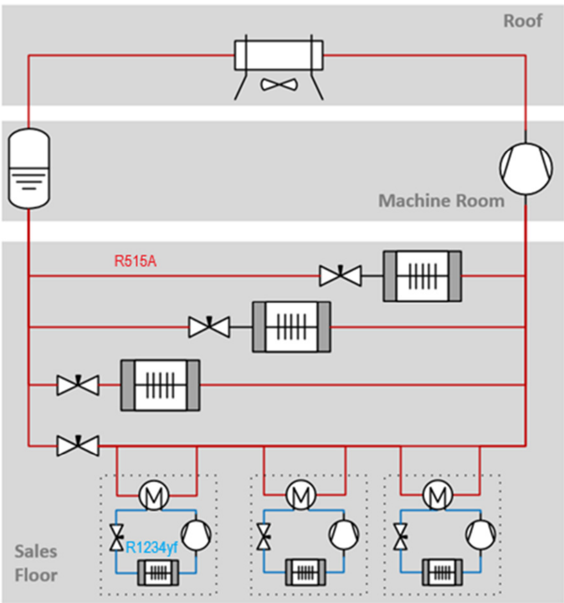

Figure 1 - R515A/R1234yf Micro Cascade Refrigeration System

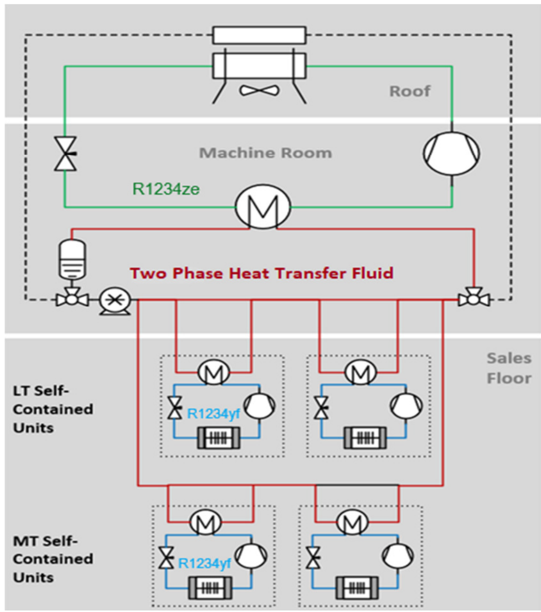

Figure 2 - R1234ze/HTF/R1234yf Micro Distributed Refrigeration System with a two-phase HTF

The energy efficiency and emissions of all abovementioned system architectures were simulated assuming a typical store size of 4180 m2. The various assumptions made for the analysis are listed in Table 2. The refrigeration load is modelled as a function of ambient temperature derived from the actual refrigeration case data as shown in Fig. 3. The design refrigeration load for medium temperature and low temperature is 138 [kW] and 87 [kW], respectively. A higher evaporation temperature is assumed for R744 in comparison to R404A and R448A due to its better heat transfer properties. Due to short connecting lines, self-contained units are assumed to operate at higher evaporation temperature owing to lower suction line pressure drop, and lower suction superheat due to fewer heat transfer infiltration losses. The compressor isentropic and volumetric efficiencies of R290 are comparatively inferior owing to reduced size of piston-displacement compressors in self-contained units. The adoption of electronic expansion valves in booster, micro-cascade and micro-distributed configurations enables lower minimum condensing temperature.

Table 2 - Refrigeration System Assumptions

Description	Unit	R404A Centralized	R448A Distributed	R744 booster	Micro-Cascade R515A/ R1234yf	Micro-Distributed R1234ze/ HTF/ R1234yf	R290/ Water cooled
GWP (AR5)	[-]	3943	1273	1	402/<1	<1	3
Refrigerant charge	[kg]	1450	750	1000	750	750	750
Leak rate	[%]	15%	10%	15%	10%	10%	10%
MT Evaporation temperature	[°C]	-6.7	-6.7	-6.1	-6.7	-5.5	-5.5
LT Evaporation temperature	[°C]	-28.9	-28.9	-28.3	-27.8	-27.8	-27.8
LT/MT Cooling Load (Design Load)	[kW]	87/138					
Evaporator superheat	[°C]	5.5					
Suction superheat LT	[°C]	27.7	22.2	22.2	5.5	5.5	5.5
Suction superheat MT	[°C]	13.8	8.3	8.3	5.5	5.5	5.5
Isentropic efficiency LT	[-]	0.67			0.6	0.6	0.52
Isentropic efficiency MT		0.70					0.55
Volumetric efficiency LT/MT		0.95					0.90
Approach temperature Cascade Condenser	[K]	-	-	-	5.5	5.5	6.6
Approach temperature Condenser	[K]	5.5	5.5	5.5 SC, 2.8 TC	5.5	5.5	5.5
Minimum condensing temperature	[°C]	21.1	21.1	10	15.5	15.5	15.5

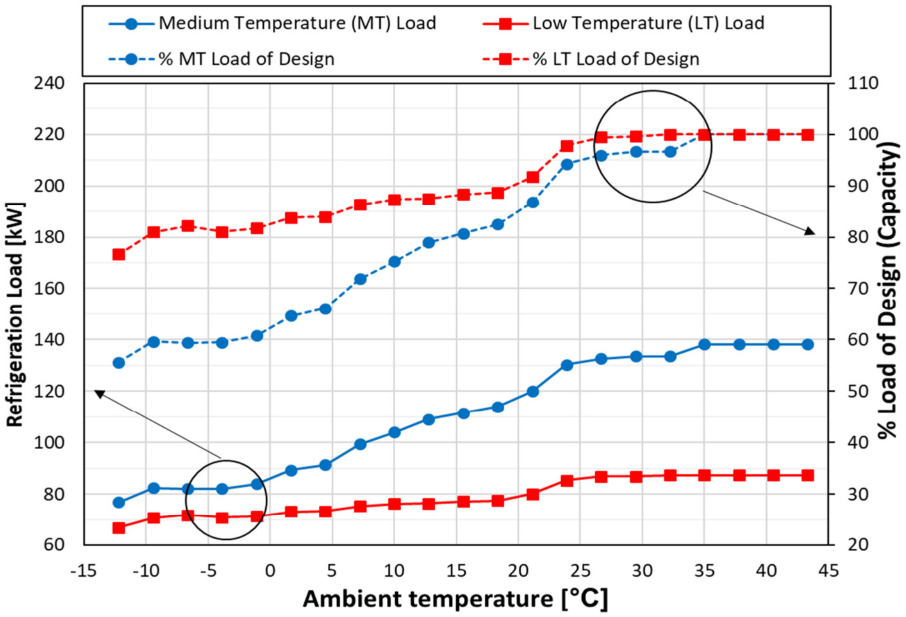

Figure 3 - Refrigeration Load [kW] vs Ambient Temperature

4. ENERGY EFFICIENCY ANALYSIS

In this section, we carry out a comparison of all above mentioned system architectures in terms of energy efficiency, for different ambient temperatures and geographical locations.

In the proposed micro-distributed system, the two-phase HTF, removes the heat from the self-contained units either directly to the ambient, as "free cooling", or to a R1234ze chiller dependent on the ambient temperature conditions. The power consumption of self-contained units increases with increase in temperature of HTF in the secondary loop while the power consumed by R1234ze chiller is reduced. Likewise, the power consumed by self-contained units decreases while that of R1234ze chiller increases with decrease in secondary loop HTF temperature. This leads to a trade-off and an operating temperature of 4.4°C is found optimal which maximizes the energy efficiency for different ambient temperatures. Further, the availability of free cooling depending on ambient condition provides additional advantage. Fig. 4 depicts the optimization of the operation of micro-distributed configuration with respect to availability of free cooling. The dotted green line represents the operation of cycle with fixed HTF temperature of 4.4°C. While, the solid green line depicts the optimized operation of cycle with respect to availability of free cooling where the HTF temperature floats with the ambient temperature when the free cooling operation increases the overall energy efficiency. Use of two phase HTF in place of single phase (liquid) HTF such as water or ethylene glycol in the secondary loop leads to reduction in the temperature difference for a given cascade heat exchanger heat transfer area. In addition, the lower bulk density of two phase HTF and the higher enthalpy difference across the cascade heat exchanger offers lower pressure drop and pumping power.

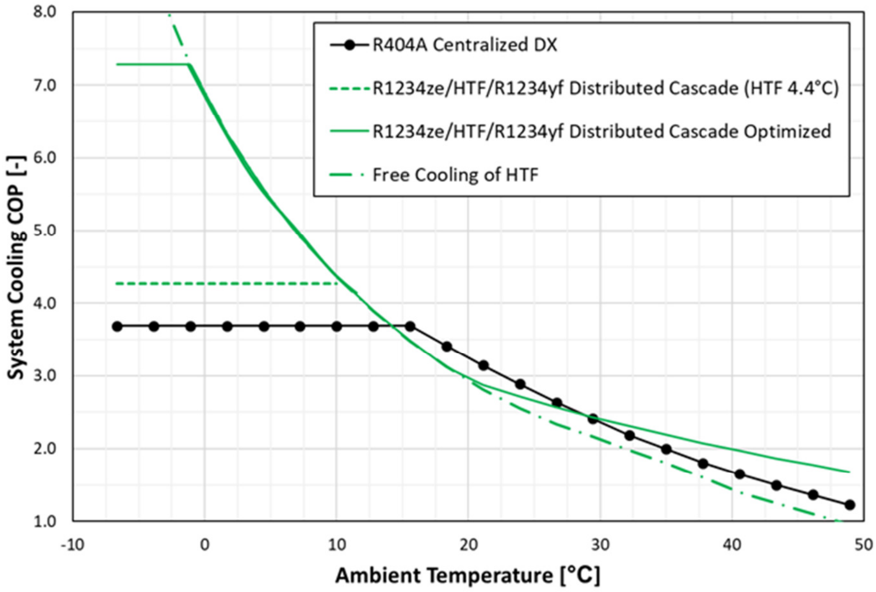

Figure 4 - Cooling COP at different ambient temperatures for micro-distributed configuration

Fig. 5 presents the comparison of cooling COP of various investigated supermarket configurations at different outside ambient temperatures. At high ambient operation above 40°C, R1234ze/HTF/R1234yf micro-distributed, followed by R515A/R1234yf micro-cascade and R448A distributed systems show higher cooling COPs than systems with natural refrigerants such as R290 and R744 as well as baseline R404A centralized configuration. At ambient temperature range from 10°C to 40°C, R515A/R1234yf micro-cascade followed by R448A distributed and R1234ze/HTF/R1234yf micro-distributed systems show superior performance. At ambient temperature conditions below 10°C, the R1234ze/HTF/R1234yf micro-distributed configuration followed by R515A/R1234yf micro cascade, R744 booster and R290/water cooled configurations show higher energy efficiency (COP). This is attributed to the use of free cooling in the micro-distributed and R290/water cooled systems. The lower minimum condensing temperature in micro-cascade and R744 booster configurations also make these systems more energy efficient than R404A. At higher ambient conditions the trans-critical operation of R744 configurations leads to increased losses penalizing the system performance even with adoption of parallel compressor and dedicated mechanical sub-cooler. Adoption of electronic expansion valve in R448A distributed DX configuration would lead to further improvement in energy efficiency, especially at low ambient, owing to reduction in minimum condensing temperature.

The annual weighted COP of all investigated configurations is calculated for ten different geographical locations (Table 2a and 2b). The annual weighted COP is determined based on the BIN temperatures for the locations over the course of one year. For comparatively warm locations such as Atlanta, Shanghai, Sau Paulo, New Delhi, Seville, Teheran and Athens, the

R515A/R1234yf micro cascade configuration followed by R448A distributed and R1234ze/HTF/R1234yf micro-distributed configurations show the highest annual efficiency. While the annual weighted COP is highest for R515A/R1234yf micro cascade configuration followed by R1234ze/HTF/R1234yf micro-distributed and R448A distributed configurations for comparatively colder locations such as Milan and Frankfurt. The annual weighted COP for R1234ze/HTF/R1234yf micro-distributed configuration is found like that of R515A/R1234yf micro cascade configuration for operation in extreme cold climate like Oslo due to use of free cooling. The annual weighted COP for R744 booster configurations is found inferior to R404A centralized DX configuration, except for operation in extreme cold climate condition such as in Oslo.

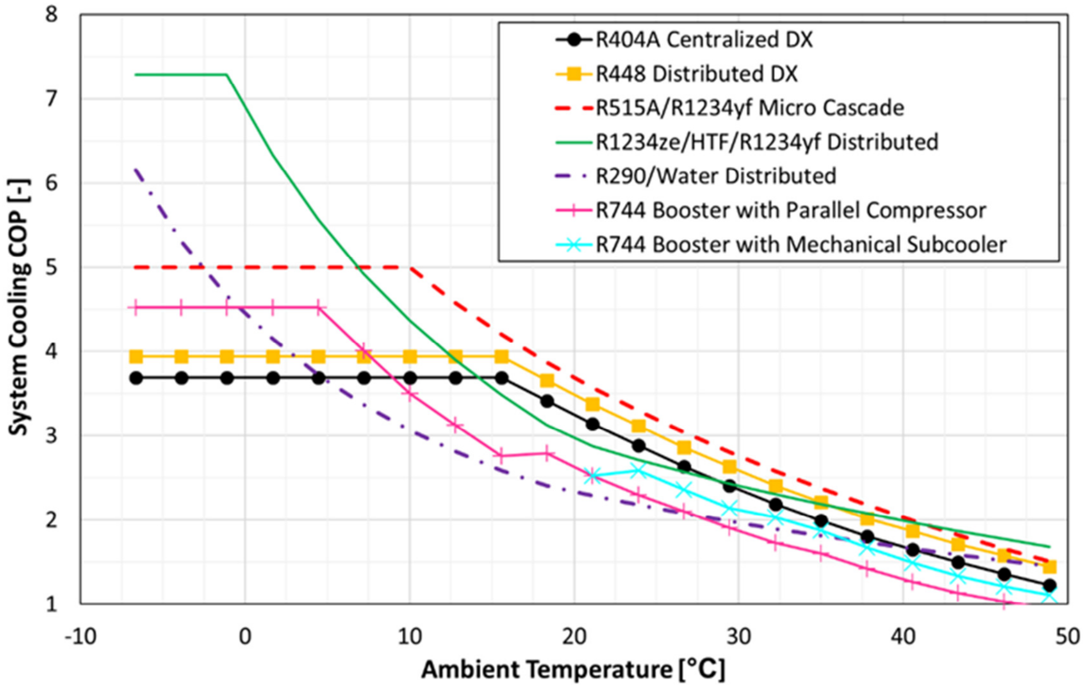

Figure 5 - Cooling COP at different ambient temperatures for investigated configurations

Table 2a: Annual Weighted COP of investigated configurations

Location	Yearly Avg. Temp. [°C]	R404A Centralized	R448A Distributed	Micro-Cascade R515A/ R1234yf	Micro-Distributed R1234ze/ HTF/ R1234yf	R744 with sub-cooler	R744 with parallel comp.	R290/ Water Cooled
Atlanta, USA	16.1	3.14	3.38	3.73	3.22	2.79	2.65	2.49
Shanghai, China	17.8	2.99	3.23	3.56	3.09	2.68	2.50	2.40
SaoPaulo, Brazil	21.6	2.99	3.23	3.43	2.84	2.54	2.38	2.25
New Delhi,	24.8	2.57	2.80	3.01	2.61	2.29	2.05	2.10

India								
Teheran, Iran	16.8	2.94	3.18	3.52	3.12	2.69	2.49	2.42
Seville, Spain	18.1	3.07	3.32	3.65	3.11	2.68	2.53	2.40
Milan, Italy	10.3	3.47	3.71	4.30	3.92	3.24	3.18	2.89
Frankfurt, Germany	8.7	3.57	3.82	4.52	4.25	3.43	3.41	3.06
Athens, Greece	16.5	3.21	3.45	3.82	3.24	2.80	2.67	2.48
Oslo, Norway	5.7	3.64	3.89	4.69	4.70	3.65	3.65	3.35

Table 2b: Annual Weighted COP of investigated configurations relative to R404A centralized Configuration

Location	Yearly Avg. Temp. [°C]	R404A Centralized	R448A Distributed	Micro-Cascade R515A/ R1234yf	Micro-Distributed R1234ze/ HTF/ R1234yf	R744 with sub-cooler	R744 with parallel comp.	R290/ Water Cooled
Atlanta, USA	16.1	100%	108%	119%	103%	89%	84%	79%
Shanghai, China	17.8	100%	108%	119%	103%	90%	84%	80%
Sau Paulo, Brazil	21.6	100%	108%	115%	95%	85%	80%	75%
New Delhi, India	24.8	100%	109%	117%	102%	89%	80%	82%
Teheran, Iran	16.8	100%	108%	120%	106%	92%	85%	83%
Seville, Spain	18.1	100%	108%	119%	101%	87%	82%	78%
Milan, Italy	10.3	100%	107%	124%	113%	94%	92%	83%
Frankfurt, Germany	8.7	100%	107%	126%	119%	96%	95%	86%
Athens, Greece	16.5	100%	108%	119%	101%	87%	83%	77%
Oslo, Norway	5.7	100%	107%	129%	129%	100%	100%	92%

5. LCCP ANALYSIS

Life Cycle Climate Performance (LCCP) is a powerful tool to conduct environmental impact analysis in which comparison of the overall equivalent carbon dioxide emissions of the refrigeration systems over its lifetime is carried out (Purohit et al. 2016). Both the direct and indirect emissions along with the emissions due to manufacturing and disposal of the system are evaluated. The direct emissions are based on the leaking refrigerant over the lifetime of the equipment. The indirect emissions are caused by the carbon dioxide that is emitted to produce the energy that is consumed over the lifetime of the equipment. The environmental impact of the investigated systems for a 15-year lifetime is determined for ten global locations.

The local electricity emission factors for different geographical locations are derived from (MCT, 2014; eGRID, 2016; IEA, 2017). The simulated direct and indirect emissions as well as average COPs for all investigated configurations operating in four locations in Frankfurt, Germany, Atlanta, USA, Shanghai, China and Sau Paulo, Brazil are shown in Figure 6. The R404A centralized system has the largest overall emissions due to the high GWP and leak rate. With a R448A distributed system, there is a significant reduction in direct emissions due to the 68% lower GWP as well as the reduced refrigerant charge amount and leakage rates of distributed systems, compared to centralized configuration. In addition, an improvement of energy efficiency due to refrigerant and system effects effectively reduces the indirect emissions. Overall emission reduction from R404A can be achieved for R448A between 79% and 53% for Sao Paulo and Shanghai respectively. The R448A distributed system achieves similar emissions compared to R744 and R290 in all four locations, due to its superior energy efficiency (lower indirect emissions), even though its GWP and direct emissions are higher. Besides CO2 emissions, the energy efficiency is especially important for the user of the equipment since it contributes directly to the energy cost. R448A shows hereby better performance than R404A centralized, R744 booster and R290/water cooled system effectively reducing the operating cost. The R744 booster system has the lowest GWP of the four investigated solutions. However, the efficiency penalty it experiences due to trans-critical operation leads to higher indirect emissions. Figure 7 shows the estimated total global CO2 emissions for all investigated configurations. The total global emissions were calculated by multiplying the number of supermarkets in each of the 10 countries considered by the CO2 emissions per system, for a representative city (Table 2a) in each country. R515A/R1234yf micro-cascade and R1234ze/HTF/R1234yf micro-distributed configurations are found to have lowest global emissions. In comparison to R404A system, those two new configurations reduce the environmental emissions by about 75%, respectively. While in comparison to R744 booster configuration with mechanical sub-cooler, the emissions are reduced by about 20% for the two new configurations. Total global CO2 emissions for R448 distributed DX configurations are found similar to both R744 booster and R290/water distributed cascade configurations.

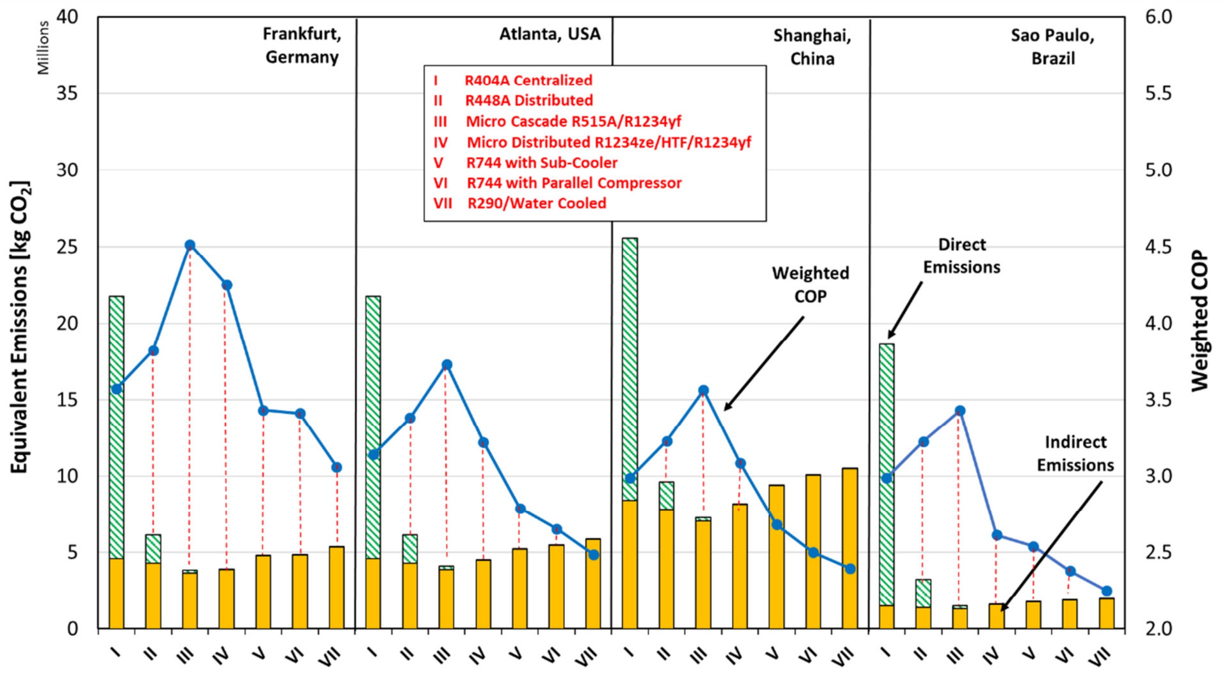

Figure 6 - Direct and Indirect Carbon Dioxide Equivalent Emissions

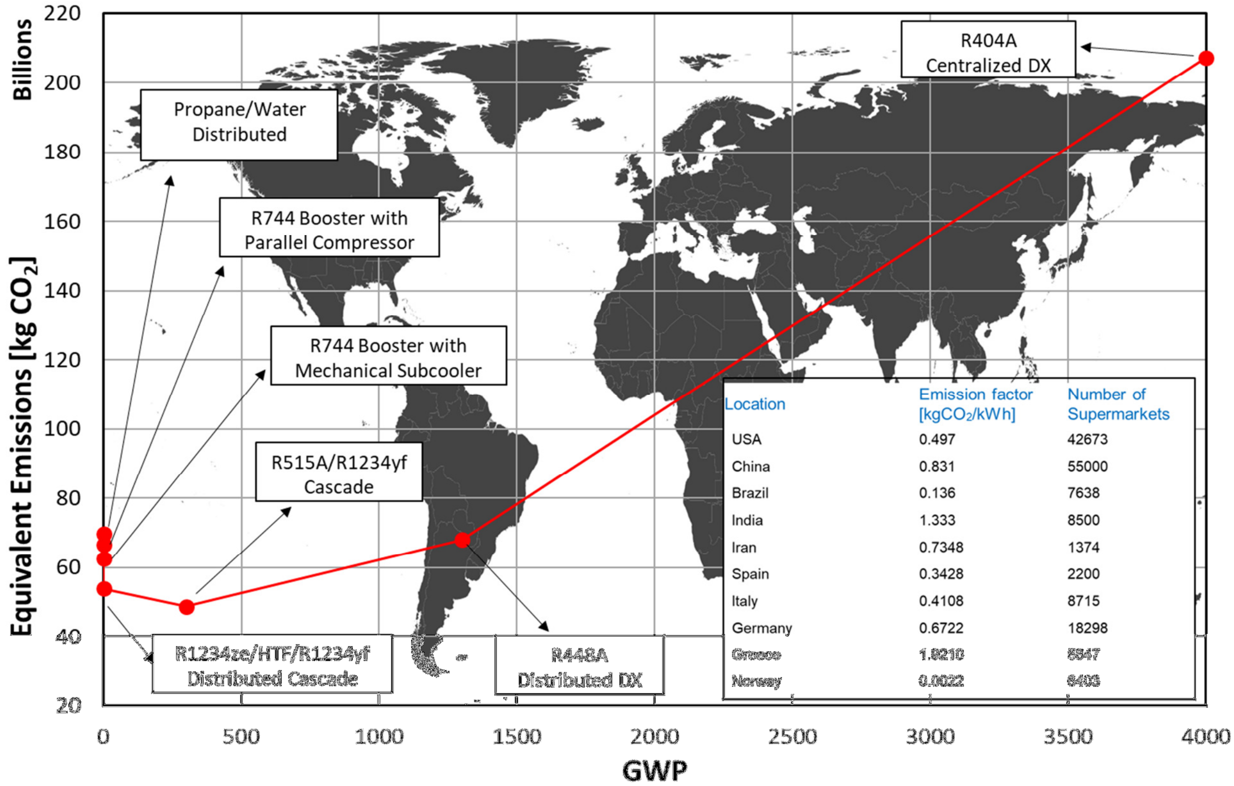

Figure 7 - Global Emissions for investigated refrigeration systems

6. CONCLUSIONS

Two new refrigeration system architectures that significantly reduce CO2 emissions and increase energy efficiency were proposed and compared to existing systems. The new systems use low-GWP refrigerants such as R515A, R1234ze and R1234yf. Both micro-cascade and micro-distributed systems show superior energy efficiency and environmental performance in several different geographical locations, both cold and warm weather, in comparison with "natural refrigerants" system configurations such as CO2 booster and water cooled with R290. In comparison to R744 and R290 systems, the R448A distributed configuration also shows higher energy efficiency with comparable global emissions, even though it has a higher GWP.

Finally, this paper demonstrates that the use of very low GWP "natural refrigerants" such as R744 and R290 does not necessarily mean lower CO2 emissions since energy efficiency plays a key role to achieve environmental performance.

NOMENCLATURE

DX	Direct Expansion	MT	Medium Temperature
GWP	Global Warming Potential	SC	Subcritical
LCCP	Life Cycle Climate Performance	TC	Transcritical
LT	Low Temperature		

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