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EFFICIENT R744 TECHNOLOGY FOR SUPERMARKET HEATING, COOLING AND REFRIGERATION – A THEORETICAL ASSESSMENT OF ENERGY ADVANTAGES IN VARIOUS SPANISH CITIES

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ABSTRACT

Various appealing expedients aimed at enhancing the energy efficiency of transcritical CO_2 (R744) supermarket refrigerating systems have been recently developed. The concurrent adoption of these could lead such hydrofluorocarbon (HFC)-free technologies to become standard even in the South of Europe. Consequently, these solutions have drawn an enormous interest in the Spanish food retail industry as this features very severe regulations with the purpose of substantially mitigating ongoing climate change.

In this theoretical work the performance of a state-of-the-art transcritical R744 supermarket refrigerating system, i.e. a solution including medium (MT) and low temperature (LT) overfed evaporators, parallel (or auxiliary) compression and "all-in-one" (or fully integrated) concept, was exhaustively investigated. This was compared to that of a baseline (i.e. "old" solution relying on R404A-based units to satisfy the refrigeration loads and a R410A reversible heat pumping unit) and to that of another alternative complying with the environmental legislative acts in force (i.e. solution based on a R134a/R744 cascade arrangement to provide the refrigeration demands and a R1234ze(E) reversible heat pump unit). The study was carried out by considering an average-size food retail store located in the Spanish climate context. The outcomes obtained revealed that the fully integrated R744 refrigeration plant offers total energy conservations between 1% (in Tenerife) and 33% (in Burgos) over conventional separated HFC-based units. In addition, the investigated transcritical R744 system brought the total annual electricity consumption down by at least 39% compared to HFC-based arrangements in heating mode.

Keywords: Air Conditioning, Commercial CO_2 Refrigeration System, Overfed Evaporator, Parallel Compression, System Integration, Transcritical CO_2 Refrigeration System

1. INTRODUCTION

Fluorinated gases (i.e. HFCs) have a dramatic greenhouse effect as these refrigerants are released into the atmosphere. The phase-down of these working fluids is part of the EU's commitment under the EU F-Gas regulation 517/2014 (European Commission, 2014). As for multipack centralized refrigerating units with rated capacity above 40 kW, this legislative measure imposes a global warming potential (GWP) limit of 150 since 2022. However, an exception was introduced only for the primary circuit of cascade systems, whose GWP limit was set to 1500 (e.g. R134a). In addition, at the 28th Meeting of the Parties to the Montreal Protocol 197 countries committed to bring the production and consumption of HFCs down by more than 80% over a 30-year period. A further push towards the use of low-GWP refrigerants in Spain is offered by the Law 16/2013, which introduced a tax rate corresponding to 20 € per tonnes of CO_2 equivalent (with a maximum value of 100 €) on fluorinated gases with a GWP above 150. Due to the approval of these climate-friendly regulation acts, the need for the Spanish food retail industry to move from man-made to natural refrigerants has become mandatory. In fact, it is easily predictable that the whole refrigeration sector in Spain will be dramatically influenced by the cost (including new refrigerants, e.g. R448A, R449A, R422D, R438A, R422A) and the availability of synthetic working fluids with a consequent considerable impact on the prices of air conditioning and refrigeration units. For climate reasons, the air conditioning (AC) reclaim as well as the refrigeration demand play a pivotal role on economic, energy and environmental perspectives in Mediterranean area.

However, the future-proof candidates for large applications (e.g. supermarkets) are additionally limited in Spain due to the adoption of the Royal Decree 138/2011, which prohibits the use of hydrocarbons for medium and large stores. To avoid future complications and unnecessary extra cost, a state-of-the-art transcritical R744 refrigeration systems relying simultaneously on parallel compression, overfed evaporators and “all-in-one” concept could be successfully implemented in the Spanish food retail industry. Also, the new subsidy recently announced by the Environment Ministry could be a further doorway to the adoption of these solutions in Spain (www.r744.com). However, although these HFC-free technologies are supposed to become standard even in Southern Europe and to the best of authors’ knowledge, only two investigations on their performance assessment have been carried out. Karampour and Sawalha (2015) claimed that a fully integrated transcritical R744 refrigerating arrangement with parallel compression is a suitable HFC-free alternative for cold regions. At a later time, this conclusion was also supported with the aid of some field measurements (Karampour and Sawalha, 2017). In order to bridge this scientific gap, in this paper the performance of an “all-in-one” R744 refrigerating arrangement outfitted with MT and LT overfed evaporators as well as parallel compression has been compared to that of two separated solutions employing synthetic refrigerants in an average-size food retail located in different Spanish locations.

2. INVESTIGATED REFRIGERATION SYSTEMS

2.1 “Old” solution (baseline)

The selected baseline describes three separated HFC-based systems relying on the predominant refrigerants which used to be adopted in the European food retail industry (i.e. R404A, R410A). In particular, two R404A centralized units which separately provide the LT and MT refrigeration loads were chosen. A schematic and an exhaustive description of such a technology was presented by Sharma et al. (2014) and Gullo et al. (2017a). As regards AC, space heating and domestic heat water (DHW) production, a conventional R410A reversible heat pumping unit was selected (Gullo and Hafner, 2017a). These man-made refrigerants will be bound to be abandoned due to the aforementioned legislative acts.

2.2 Alternative 1

The term “Alternative 1” refers to two separated HFC-based units, i.e. a R134a/R744 cascade arrangement to meet the refrigeration loads and a R1234ze(E) reversible heat pumping unit to provide the AC, space heating and DHW needs. A schematic and an in-depth description of such a cascade solution was presented by Gullo et al. (2016a).

2.3 Alternative 2

Refrigeration systems based on R744 as the only refrigerant are perceived to be future-proof alternatives to today’s employed systems, even in high ambient temperature countries (e.g. Spain). As a result of the recent technological development, in fact, these HFC-free technologies can attain competitive energy efficiencies even at severe operating conditions. According to Girotto (2012) and Gullo et al. (2016c, 2017b), such an achievement can be accomplished by concurrently adopting parallel compression (AUX) (Karampour and Sawalha, 2015, 2017; Gullo et al., 2016a, 2016b, 2017a; Gullo and Hafner, 2017b; Polzot et al., 2016; Javerschek et al., 2016) and overfed evaporators (Minetto et al., 2014; Girotto, 2017), as sketched in Figure 1. The overfeeding of the MT evaporators is achieved with the aid of the liquid ejectors (LEJ) (Hafner et al., 2014). As regards the LT heat exchangers, the use of an internal heat exchanger (IHX in Figure 1) located downstream of the intermediate pressure (IP) receiver (RC(IP)) and upstream of the low stage (LS) compressors is necessary to accomplish this target (Minetto et al., 2015). The consequence increase in MT and LT related to the adoption of such expedients can be attained all year round (Hafner and Banasiak, 2016). The heat recovery has become standard in transcritical CO_2 supermarket refrigeration plants, being an energetically advantageous (Sawalha, 2013) and cost-effective (Reinholdt and Madsen, 2010) technique. The heat recovery is performed by using two de-superheaters, i.e. DS1 and DS2 in Figure 1. These are respectively employed for DHW production and providing space heating. An air-cooled gas cooler/condenser (GC) is located downstream of these heat exchangers to enhance the overall energy efficiency depending on the running mode (Sawalha, 2013). A 3-way valve is used upstream of DS1, DS2 and GC to permit possibly by-passing these components (Sawalha, 2013) with respect to the operating conditions as well as the space and tap water heating demands. Furthermore, satisfying the heating, cooling and refrigeration needs via only one system (i.e. “all-in-one” solution) is expected to considerably bring the total investment, maintenance and running costs down

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(Hafner et al., 2015), besides offering other benefits (Karampour and Sawalha, 2017). As depicted in Figure 1, the AC request can be met with the aid of an additional evaporator (HX_AC), whose refrigerant mass flow rate is then drawn by one (or more) of the parallel compressors being isolated from the others with the aid of a valve (Figure 1).

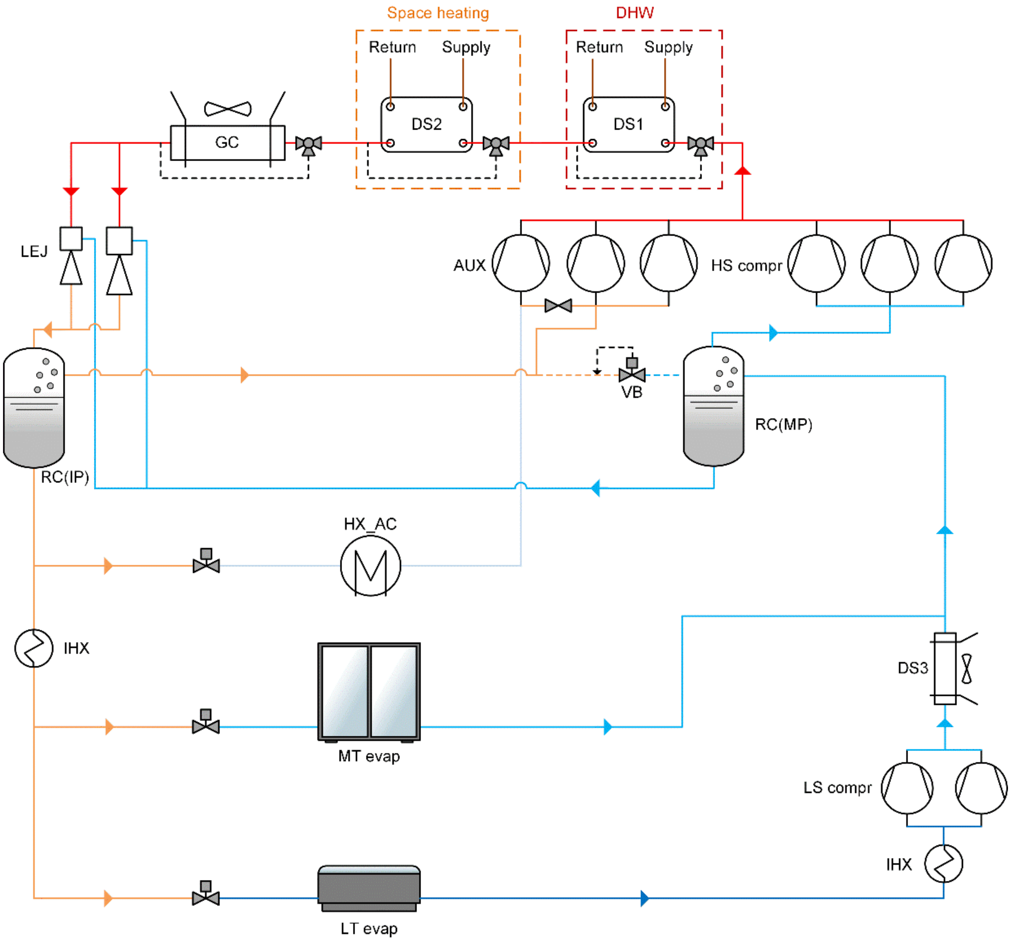

Figure 1: Schematic of the investigated all-in-one transcritical R744 supermarket refrigeration system.

3. INVESTIGATED RUNNING MODES

Refrigeration capacities for full load conditions were taken as 25 kW for the LT load and 83 kW for the MT demand. An air-cooled de-superheater downstream of the LS compressors was adopted for both the cascade arrangement and the R744 system (DS3 in Figure 1). The R744 outlet temperature coming out of this heat exchanger was selected equal to 30 °C for outdoor temperatures up to 28 °C and to 35°C at the more severe operating conditions (Javerschek et al., 2016). The approach temperature of GC and the temperature difference of the cascade condenser were assumed as 5 K (Karampour and Sawalha, 2015; Gullo et al., 2016a). Furthermore, in the implemented simulations LEJ were replaced by a high pressure (HP) expansion valve to properly control the heat rejection pressure as well as by a pump characterized by an efficiency of 0.5 to overfeed the evaporators (Gullo et al., 2016c, 2017b; Girotto, 2012). This assumption is justifiable by considering that such a pump involves a negligible amount of electricity to be run (Minetto et al., 2014) and the main energy benefit ascribable to LEJ is associated with the increase in the evaporation temperature (Minetto et al., 2014). The evaporating temperatures were assumed equal to -8 °C at MT and -34 °C at LT for dry-expansion evaporators (Wiedenmann, 2015). These were respectively increased by 6 K and 8 K for overfed evaporators (Gullo et al., 2017a). As regards the cascade arrangement and the R404A-based units, the minimum condensing temperature and the approach temperature of the condenser were respectively chosen equal to 25 °C and 10 K (Gullo et al., 2016a, 2017a).

Heat recovery was performed between the outdoor temperatures of 15 °C and -10°C with a linear heat demand increasing from 50 kW to 100 kW (Javerschek et al., 2016). The heat demand, which was satisfied in accordance with the strategy recommended by Sawalha (2013), was assumed to be the sum between DHW reclaim and space heating load. It is worth remarking that the DHW need is commonly constant over the year (Karampour and Sawalha, 2017) and negligible in comparison with the other reclaims (Karampour and Sawalha, 2017). In heating operating conditions, the condensing temperature and the pinch point temperature of the evaporator were taken as 40 °C and 9 K for the heat pump units, respectively. Air conditioning was implemented for outdoor temperatures between 24 °C and 30 °C with a linear growth from 90 kW to 120 kW, becoming constant above this value (Gullo et al., 2017a). The reversible heat pumping technologies presented an evaporating temperature and an approach temperature of the condenser as 3 °C and 10 K in AC mode, respectively. Also, the transcritical R744 alternative featured an evaporating temperature of about 1 °C to guarantee a proper feeding of HX_AC. The heat pumping units and HX_AC were simulated similarly to the investigations by Gullo and Hafner (2017a) and Gullo et al. (2017a), respectively.

Finally, the performance of all the compressors was simulated by employing some manufacturer's software and an internal heat exchanger with an effectiveness of 0.5 (Gullo et al., 2017a) was supposed to be part of all the investigated solutions. It is important to mention that the same refrigeration, AC and heating loads were assumed in all the investigated locations (Karampour and Sawalha, 2017). However, significant differences can be observed in real applications, depending on building design and insulation, load ratio, etc. (Karampour and Sawalha, 2017).

4. INVESTIGATED CLIMATE CONTEXT

The investigation was based on six representative cities (Figure 2) so as to appropriately evaluate the majority of the Spanish climate context.

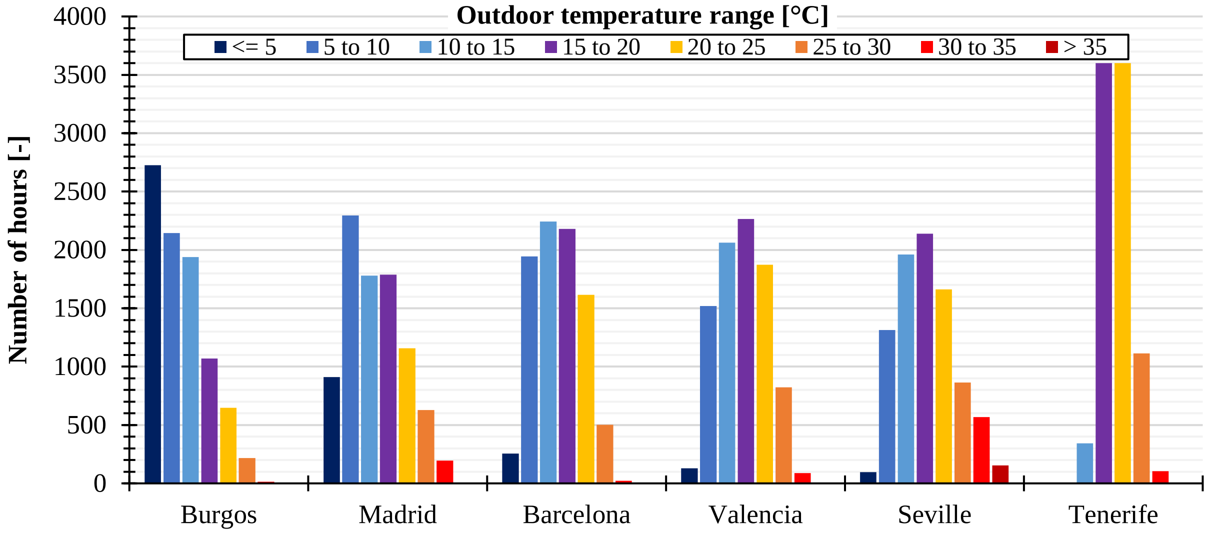

Figure 2: Temperature bins for the investigated cities (EnergyPlus).

5. RESULTS

5.1 Results in heating mode

The favorable properties of R744 in heat recovery are highlighted in Figure 3, in which the $COP_{heating\ mode}$ values of all the investigated systems are compared. As regards Alternative 2, these were computed according to Eq. (1):

$$COP_{heating\ mode} = \frac{\dot{Q}_{DS1}+\dot{Q}_{DS2}}{[\dot{W}_{total\ for\ integrated\ sytem}-\dot{W}_{total\ for\ only\ refrigeration}]} \quad (1)$$

It was found that the heat pump unit relying on R1234ze(E) slightly outperforms that using R410A at outdoor temperatures between -5 °C and -10 °C. As regards the "CO_2 only" solution, this offered $COP_{heating\ mode}$ values on average about 83% higher than those shown by the R1234ze(E)-based system over the investigated range of outdoor temperatures. It is worth remarking that the energy benefits related to AUX were not considerate in this operating condition as the activation of these compressors is generally associated with the AC demand (Karampour and Sawalha, 2017).

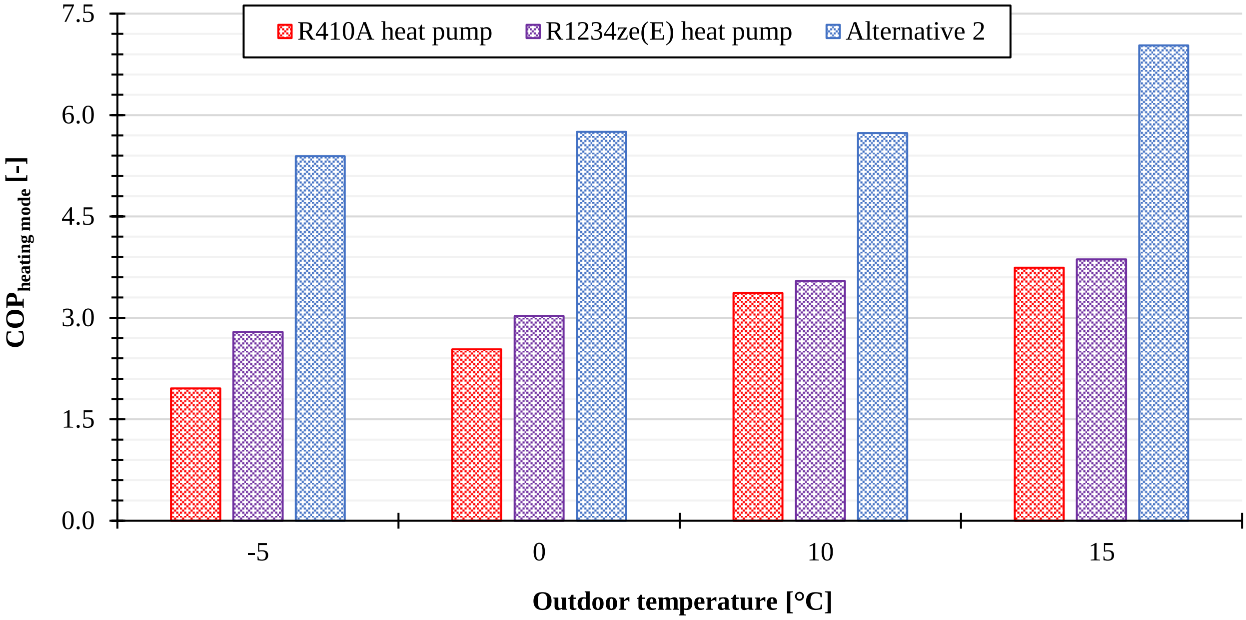

Figure 3: $\mathrm{COP}_{\text{heating mode}}$ of the investigated solutions at different outdoor temperatures.

5.2 Results in AC mode

Figure 4 depicts the results in term of $\mathrm{COP}_{\text{AC mode}}$ of the selected technologies at outdoor temperatures from 25 °C to 40 °C, being calculated through Eq. (2) as for Alternative 2:

$$COP_{AC\ mode} = \frac{\dot{Q}_{HX\_AC}}{[\dot{W}_{total\ for\ integrated\ sytem} - \dot{W}_{total\ for\ only\ refrigeration}]} \qquad (2)$$

The R1234ze(E)-based solution featured slightly better performance than the unit using R410A in AC mode as well. The HFC-free technology had from about 26% to 42% poorer energy efficiencies than the “old” solution over the investigated range of external temperatures. This could be ascribable to the high relative load between AC and refrigeration.

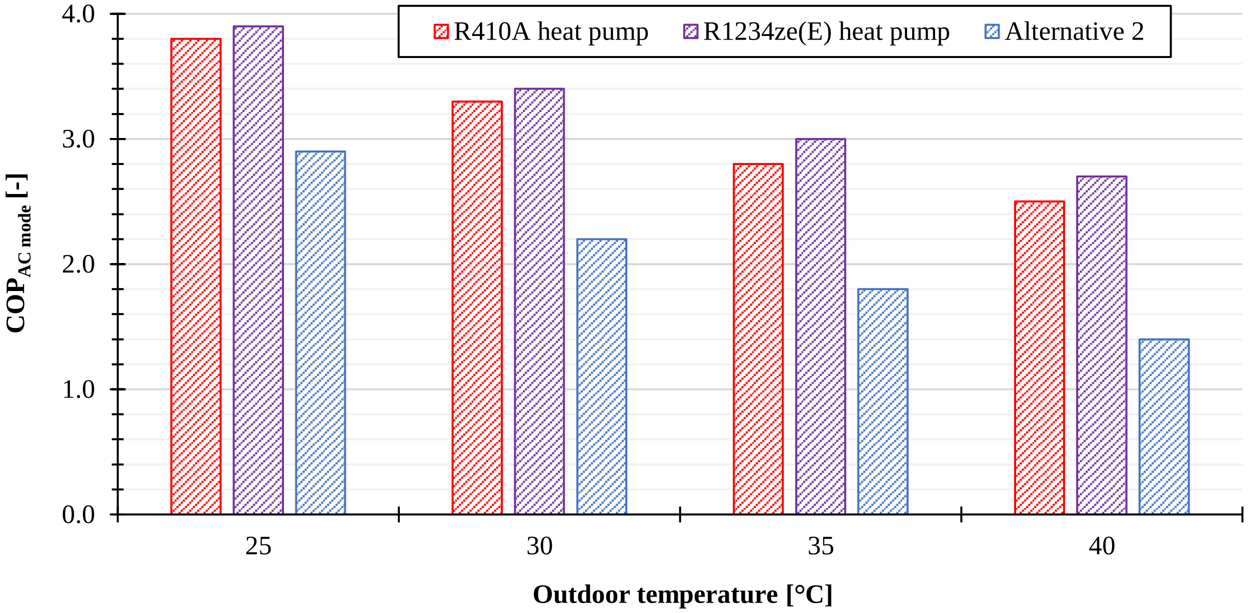

Figure 4: $\mathrm{COP}_{\text{AC mode}}$ of the investigated solutions at different outdoor temperatures.

5.3 Results of annual energy consumption

The annual energy consumption of the investigated solutions in various Spanish locations are shown in Figure 5. As regards the investigated transcritical R744 solution, this was calculated in accordance with Eq. (1) and Eq. (2) for the parts associated with heating and AC mode, respectively. Also, the electricity intake referring to the heating mode was related to the total demand, i.e. sum between DHW production and space heating need.

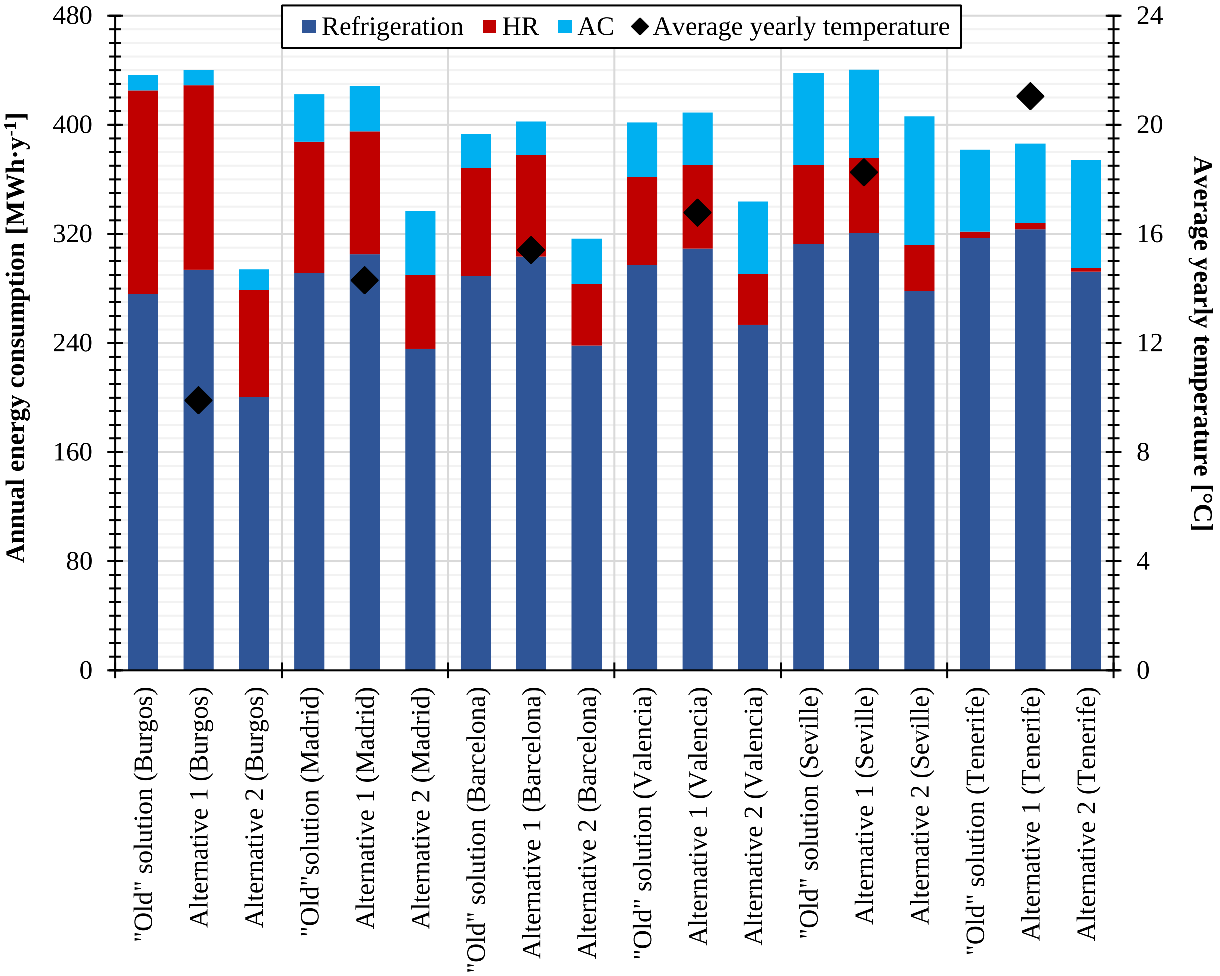

Figure 5: Annual energy consumption of the investigated systems in various Spanish climate context.

In all the selected locations the transcritical R744 alternative outperformed the other systems, offering total energy savings between 1% (in Tenerife) and 33.2% (in Burgos) compared to the chosen baseline. Such a HFC-free technology decreased the total energy intake by 14.4% over the “old” solution in Valencia. Compared to the latter, Alternative 1 presented comparable total electricity consumptions in the evaluated climate context. Also, it was found that the heat recovery from the “CO_2 only” solution led to reductions in the electricity input related to the heating mode at least by 39% over the arrangements using synthetic refrigerants. As regards the AC mode, the investigated R744 solution required from 31% to 46% more electricity than the systems using man-made working fluids in the selected cities.

6. CONCLUSIONS AND FUTURE WORK

The implementation of European and local regulations are making refrigerant selection a challenge for engineers and end users in the Spanish food retail industry. However, energy-efficient as well as potentially cost-effective “future-proof” technologies, such as fully integrated transcritical R744 supermarket systems, are readily available in the European market.

In this theoretical investigation the performance of a state-of-the-art transcritical R744 refrigeration plant relying on parallel compression, MT and LT overfed evaporators and “all-in-one” concept has been contrasted with that of various HFC-based systems. The evaluation has been carried out on the basis of an average-size supermarket located across Spain. The results obtained have brought to light that the investigated HFC-free technology perform much better than conventional heat pumping units in heating mode, offering energy savings by at least 39%. Despite its very poor performance in AC mode due to the substantial cooling demands, the selected transcritical R744 system consumed between 1% (in Tenerife) and 33% (in Burgos) less electricity over conventional separated HFC-based units. In order to considerably improve the performance of this solution in summertime, it is still necessary to cope with the implementation of massive experimental work aimed at assessing the energy and economic benefits related to the use of two different multi-ejector modules (i.e. one for the AC demand and the other for the refrigeration loads), of the direct cooling fan coils and air curtains and of the principle of pivoting.

Finally, it is worth remarking that the ever-growing performance enhancement of the sophisticated HFC-free solutions similar to that suggested in this manuscript is going hand in hand with their cost-effectiveness improvement, even in warm regions (Shecco, 2016). In fact, it has been noticed that their total installation price is currently at worst 10% higher than that of conventional HFC systems, depending on the market and technology (Shecco, 2016).

To conclude, the wide approval of state-of-the-art transcritical R744 supermarket refrigeration plants is currently only related to overcoming some remaining non-technological barriers, i.e. lack of knowledge and awareness, social, organizational and political barriers (Minetto et al., 2018).

NOMENCLATURE

AC	air conditioning	*AUX*	parallel (or auxiliary) compressor rack
compr	compressor rack	*COP*	coefficient of performance (-)
DHW	domestic hot water	*DS*	de-superheater
evap	evaporators	*GC*	air-cooled gas cooler/condenser
GWP	global warming potential $(\mathrm{kg}_{\mathrm{CO}_{2,\mathrm{equ}}} \cdot \mathrm{kg}^{-1}_{\mathrm{refrigerant}})$	*HFC*	hydrofluorocarbon
HP	high pressure (bar)	*HS*	high stage
HX_AC	heat exchanger for AC purposes	*IHX*	internal heat exchanger
IP	intermediate pressure (bar)	*LEJ*	liquid ejectors
LS	low stage	*LT*	low temperature (°C)
MP	medium pressure (bar)	*MT*	medium temperature (°C)
$\dot{Q}$	load (kW)	*RC*	liquid receiver
VB	vapour by-pass valve	$\dot{W}$	power input (kW)

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