Combined refrigeration, heating and air conditioning systems in supermarkets: seeking energy efficient solutions

Manuscript ID: 771
DOI: 10.18462/iir.icr.2019.771

Combined refrigeration, heating and air conditioning systems in supermarkets: seeking energy efficient solutions

Paola D'AGARO, Michele A. COPPOLA, Giovanni CORTELLA
DPIA – University of Udine
Udine, 33100, Italy
giovanni.cortella@uniud.it

ABSTRACT

A deep synergy between the refrigeration and the HVAC plants is a viable solution to reduce the energy use of supermarkets. Not only heat recovery can be performed from the refrigerating plant in favour of space heating and hot water production, but also provision of AC capacity.
A model based on TRNSYS and in-house types, validated with field data gathered from a fully instrumented plant in an active supermarket, allows to seek the optimal coupled solution. The model has been used to predict its feasibility and energy use at different climate conditions, for a reference supermarket. An energy saving of about 9% was predicted, regardless of the climate conditions, if the energy performance quality of the building envelope is kept constant.
The integration of the refrigeration and HVAC systems shows to be effective in terms of energy use. Significant reductions can also be obtained in the investment costs, space occupied by the plants and amount of refrigerant charge.
Keywords: Carbon dioxide, Commercial building, Commercial refrigeration, Heat recovery, Modelling, Supermarket

1. INTRODUCTION

The efficiency of CO_2 plants in supermarkets is a critical issue at warm climate conditions, when yearly energy consumption can be higher than that of conventional HFCs plant, thus contrasting the efforts to reduce the greenhouse gas emission. This drawback is partially overcome by employing one or more improved system configurations, such as parallel compression, overfed evaporators, compression work recovery (Gullo et al, 2016). A key role in making CO_2 systems attractive can be played by heat recovery, which can take advantage of the high discharge temperature and properties of the transcritical carbon dioxide and turn the use of this natural refrigerant into an advantage (Polzot et al 2016, 2017a, Sawalha 2013, D'Agaro et al 2018). In the view of reducing substantially the investment cost and increasing the compactness of the system, the integration between the refrigerating and the HVAC systems can be extended also to the air conditioning function, which can be assigned to the commercial refrigerating unit. Different solutions have been investigated, with similar or even slightly lower energy use (Karampour and Sawalha 2017, 2018; D'Agaro et al. 2019; Pardiñas et al, 2018). Modelling the whole system is the main tool when looking for the best solution, possibly with validation by comparison from field data (Minetto et al. 2014; Karampour and Sawalha 2017; Cortella et al. 2018).
A small supermarket (1200 m^2 selling area) located in Modena (Italy) has been considered as case study for this work. It was recently refurbished in the framework of the FP7 European Project CommONEnergy, involving several aspects such as plants, envelope, solutions for both artificial and natural lighting and the refrigeration system, which is fully integrated with the HVAC one. A comprehensive model has been setup in the Trnsys environment, and validated with field data. With such model the performance of the integrated system is estimated at various climate conditions, to help identifying a design rule when replicating this installation in other sites.

2. REFRIGERATION AND HVAC COUPLING

The commercial refrigeration system considered supplies cooling capacity to 14 m of new refrigerated display cabinets for the low temperature level (LT) and 40 m of closed cabinets and 23 m of serve-over or open ones for the medium temperature level (MT). The commercial refrigeration unit coupled with the

HVAC plant is sketched in Fig. 1. It is a transcritical CO_2 booster system with receiver at the intermediate pressure p_{INT} and parallel compression for the flash gas, which is expanded to MT pressure in subcritical operation or is compressed to the high stage (HS) pressure p_{HS} in transcritical operation. The evaporating temperature is -35 °C and -10 °C for the MT and LT application respectively. The system performs waste heat recovery at two temperature levels at the exit of HS compressors: heat exchanger HR1 recovers heat for DHW production (70 - 55 °C) and heat exchanger HR2 supplies lower temperature water for space heating purposes (50 - 40 °C). In order to increase the amount of heat recoverable in wintertime, the refrigeration system is forced to operate in transcritical regime, at a p_{HS} value higher than the subcritical one which would be driven by the outdoor temperature.
An evaporator at p_{INT} pressure (AC supply) may be used to provide cooling capacity for air conditioning system. Both compressor racks, LS and HS, are composed of two compressors, distinguished as master and slave compressor. The master is controlled by an inverter and the slave is an ON/OFF type.

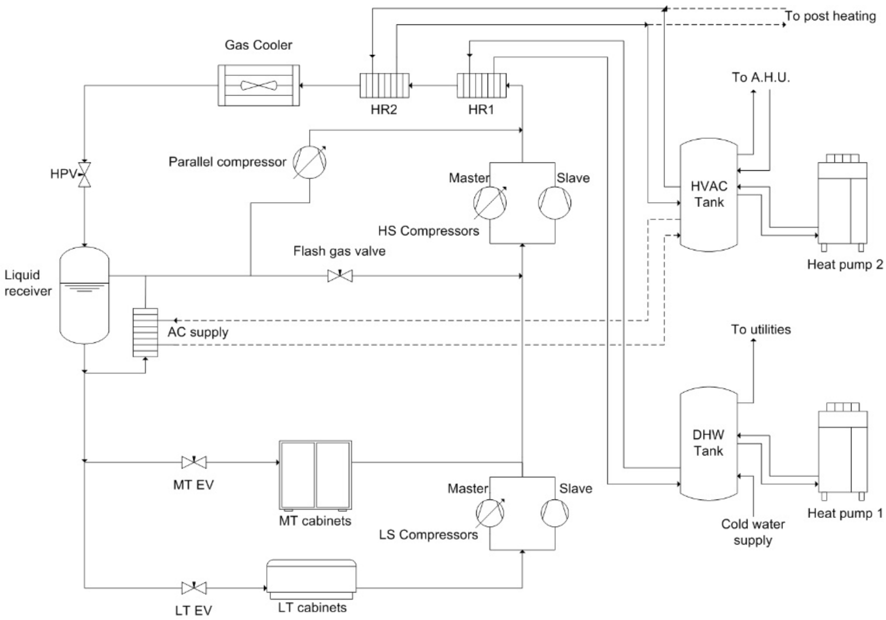

Figure 1: Schematic of the CO_2 refrigeration system with heat recovery and evaporator for AC supply

The comprehensive model of the entire refrigeration system, which includes the operation of the display cabinets, cold rooms and of the refrigerating unit has been implemented in the TRNSYS environment, developing in-house routines for each component. In particular, the sub-hourly cooling load profiles at the two evaporating levels are predicted by adjusting the cooling capacity at rated condition of each display cabinet in accordance with time-dependent operating conditions in the supermarket as described in detail in Polzot 2017b. Regarding the refrigerating unit, the thermodynamic and thermophysical properties of the refrigerant are calculated by linking our in-house routines in the TRNSYS environment to the CoolProp libraries (Bell et al., 2014). The compressors are described through correlations provided by the manufacturer in accordance with the Standard EN12900:2013.
The values of the main design parameters are reported in Table 1.
The control rules implemented in the model are described in D'Agaro et al (2019). If there is no heating demand from the HVAC system in the supermarket (q_{HEA} = 0), the high stage pressure p_{HS} is driven by the outdoor temperature as in Polzot 2017b; otherwise, when there is heating demand ($q_{HEA} \neq 0$), the refrigerating unit is switched to transcritical mode at 78 bar.

$$\begin{cases} \text{if } q_{HEA}=0 \ \Rightarrow \begin{cases} \text{in transcritical operation: } p_{HS} = \max(75;1.75 t_{GC\_out} + 22.13) \text{ [bar]} \\ \text{in subcritical operation: } p_{HS} = \max\left(p_{sat}(t_{cond,\min}); p_{sat}(t_{GC\_out} - \Delta t_{sc})\right) \text{ [bar]} \end{cases} \\ \text{if } \ q_{HEA} \neq 0 \Rightarrow \ p_{HS} = 78 \text{ [bar]} \end{cases} \qquad \text{Eq. (1)}$$

In the integrated system, the heat recovery in heat exchanger for both DHW and heating is active whenever the outlet water temperature (t_{w,HR_out}) is higher than the temperature in the corresponding tank

(t_{tank}). Whenever the temperature in the tank drops below the minimum value ($t_{tank,min}$), the corresponding heat pump HP (Fig.1) is activated to bring the set point value ($t_{tank,set}$) back.

$$\begin{cases} \text{if } t_{w,HR\_out} > t_{tank} \text{ and } t_{tank} < t_{tank,set} \Rightarrow \text{ HR active} \\ \text{if } t_{tank} < t_{tank,\min} \quad \Rightarrow \text{ HP active} \end{cases} \qquad \text{Eq. (2)}$$

The COP profiles for the two heat pumps used to fulfil DHW/Heating demands are shown in Fig. 2 as a function of the outdoor temperature.

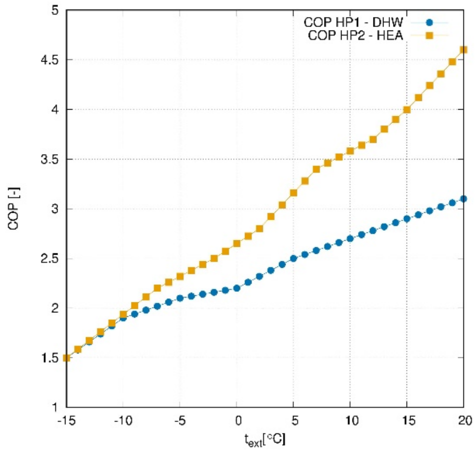

Figure 2: Coefficient of Performance of the heat pumps for DHW and heating

As regards the AC capacity, the evaporator at p_{INT} pressure (AC supply) supplies cooling capacity up to a limiting value imposed by the maximum compressor displacement, aiming at reaching the setpoint value. Whenever the temperature in the tank raises above the maximum value, the corresponding unit (HP2 in Figure1) is activated to bring the set point value back. The EER of this chiller unit is given by:

$$EER = 5.629 - 0.0886\ t_{ext} \qquad \text{Eq. (3)}$$

The set point and minimum/maximum temperature values are reported in Table 1.
The model has been validated with data from a whole year of monitoring (D'Agaro et al, 2019).

Table 1. Main design parameters for the commercial refrigeration unit

Parameter	Unit	Value
Nominal cooling capacity at MT	kW	70.5
Nominal cooling capacity at LT	kW	10.8
MT evaporating temperature	°C	-10
LT evaporating temperature	°C	-35
Minimum condensing temperature $t_{cond,min}$	°C	6
Liquid receiver pressure p_{INT}	bar	35
Degree of subcooling at subcritical conditions ΔT_{sc}	K	3
Gas Cooler/Condenser approach ΔT	K	4
Superheat at LS/HS suction	K	30/20
DHW tank setpoint temperature / min temperature	°C	70/55
HVAC tank setpoint temperature / min temperature (heating use)	°C	45/35
HVAC tank setpoint temperature / max temperature (AC use)	°C	7/12

3. SUPERMARKET BUILDING AND HVAC DEMANDS

The supermarket, which was a democase in the EU CommONEnergy project, has a selling area of 1200 m^2. It is rectangular in plan and occupies the ground floor of a building. The north-east façade of the building is visible in the picture of Fig. 2 (marked 1 in the plan sketch of the supermarket in the right). The supermarket is in the lower glazed part, shaded by a porch and it is just 3.16 meters high; the upper floor is entirely occupied by a gym and a warehouse area is located in the underground. The other external façade (marked 2) is mainly opaque, as just 2% of its surface is glazed. A gallery runs along the two other façades. The thermal transmittance of the opaque elements as well as the thermal and the solar energy transmittance of the transparent elements of the envelope are provided in Table 2.

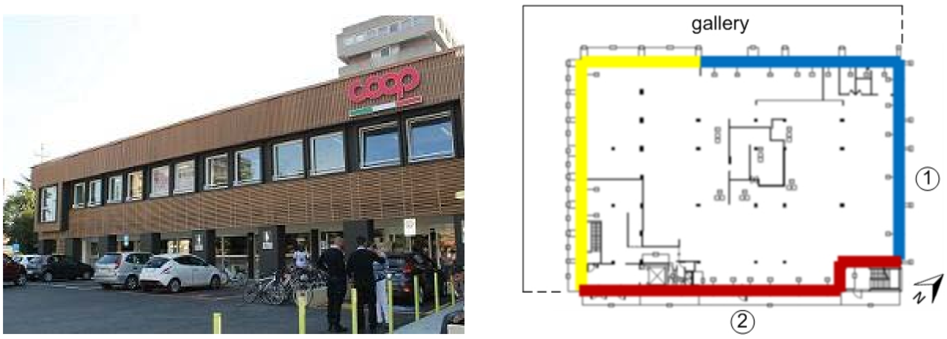

Figure 2: Case study supermarket: main façade after retrofit (left) and sketch of the plan (right)

The model for the building energy simulation, which was realized using multi-zone building Type 56, derives from the outcomes of the EU CommONEnergy project. Antolin et al. (2016) report the full data set for the simulation model, in Table 2 just the main values of building loads and the heating and cooling temperature set point values are summarized. The building was subject to a deep renovation, which included the wall insulation and new glazed façade, Load from lighting have been substantially reduced by massively using LED lamps and solar light tubes. It should be underlined that the sensible and latent contributions from the display refrigerated cabinets to the HVAC system are dynamically calculated: the heat and mass transfer between the refrigerated volumes and the indoor environment are assessed, for each cold room and display cabinet typology, as a function of the indoor air temperature and humidity.

Table 2. Main input data for the simulation model of the building for the actual building (climate 4)

Building envelope	U (W m^{-2} K^{-1})	g
Exterior wall (marked in yellow in Fig.2)	0.275	-
Exterior wall (marked in red in Fig.2)	0.290	-
Ceiling/interior floors	0.930	-
Ground floor	1.73	-
Exterior glazed façade (marked in blue in Fig.2)	1.80	0.6
Building loads and set points		
Lighting (W/m^2)	12	
Appliances (W/m^2)	10	
Occupancy in the selling area (persons/m^2)	0.2	
Heating set point temperature (°C)	22	
Cooling set point temperature (°C)	26	

In this study, 5 locations representative of different Italian climate conditions are considered. The weather files for the simulation of both the commercial refrigeration unit and the building are the Typical Meteorological Year (TMY) which derive from the Meteonorm database (Meteonorm, 2017). In order to perform a fair comparison among the loads on the HVAC system at different climate conditions, the energy performance quality of the building, with reference to the winter performance, has been keep constant. The thermal characteristics of the building envelope at each location have been corrected to attain approximately the same ratio as the actual building at climate 4:

$$\frac{EP_{H,nd}}{EP_{H,nd,\lim}} = 0.35 \quad \text{Eq. (4)}$$

between the annual heating energy need per unit area $EP_{H,nd}$ (EN ISO 13790) and its benchmark value $EP_{h,nd,lim}$ calculated, as indicated by the Italian National Decree of June 26th, 2015, assuming the prescribed thermal transmittances values for the elements of the building envelope.

4. SIMULATION RESULTS

Table 3 reports the locations, identified with an increasing number from the warmest (1) to the coldest (5) one, the value of Heating Degree Days and Cooling Degree Days (estimated from the weather data for 18 °C indoor temperature and outdoor temperature lower than 15 °C for HDD according to EUROSTAT; for 21°C indoor temperature and outdoor temperature higher than 24 °C for CDD according to JRC/MARS), the climate zone classification according to Italian regulation, the annual energy need for heating $EP_{H,nd}$ and for cooling $EP_{C,nd}$, both per unit area.

Table 3. Reference Italian cities, climatic region, annual energy need per unit volume for heating $EP_{H,nd}$ and for cooling $EP_{C,nd}$

Climate	HDD	CDD	Climate zone	$EP_{H,nd}$ [kWh m^{-2}y^{-1}]	$EP_{C,nd}$ [kWh m^{-2}y^{-1}]
1	606	380	A/B	20.61	22.66
2	1112	237	C	31.65	13.50
3	1600	248	D	51.39	13.08
4	1837	395	E	55.19	16.66
5	2438	65	E	76.08	5.60

The simulations performed on the building at the various climate zones gave rise to different distributions of heating and cooling loads, which are summarized in terms of monthly energy values in Fig. 3. The heating load for DHW has been assumed constant for all climates, given the commercial use of the building. Also the LT and MT cooling loads at the display cabinets have been assumed not to be affected by outdoor conditions, and their monthly values are shown in Fig. 4.

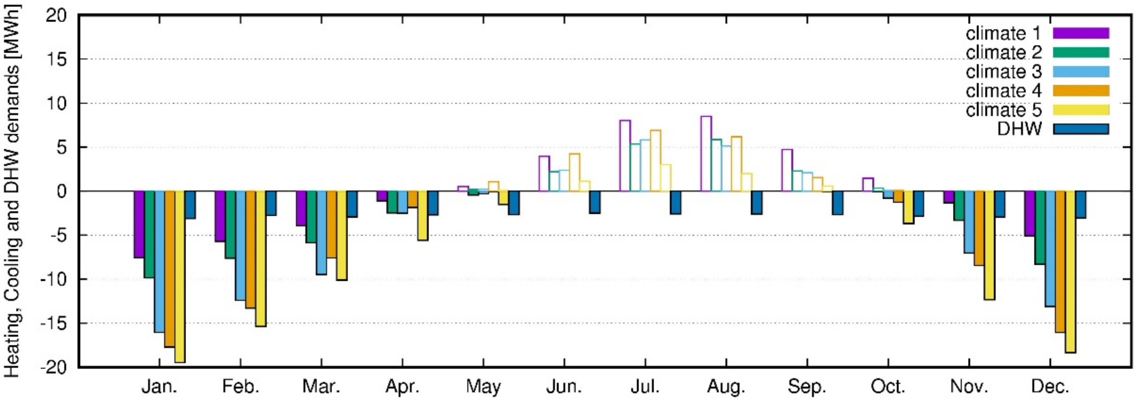

Figure 3: Heating, cooling and DHW demands

Although the building envelope has been adapted to face the various climates, the great influence of outdoor conditions on both the heating and cooling demands appears clearly.

A slight oversizing of the commercial refrigeration unit, especially of its parallel compressor, with the control rules described above allows the load coverages reported in Figure 5. Coverage of the heating demand by heat recovery is from 70 to 76% depending on the climate. Hot water production is guaranteed up to 97 %. Similarly, air conditioning is fully covered at the coldest climate, and almost fully covered at all climates with the exception of climate 4 (coverage: 94%), which is not the warmest.

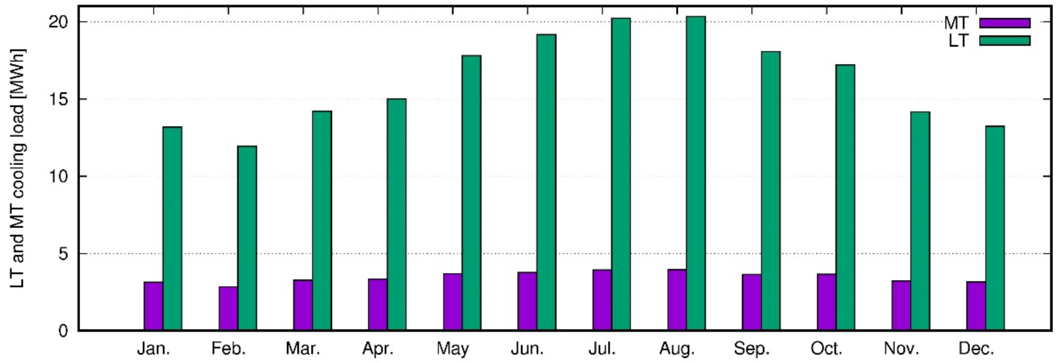

Figure 4: LT and MT cooling load of the display cabinets

This is due to the distribution of outdoor temperature values (and consequently cooling load) which is characterized by higher temperature values for shorter periods in climate 4 when compared to climate 1, typical of Mediterranean seaside location. This can also be seen in Fig. 6, where the number of hours of operation of the parallel compressor is given as a function of its fractional capacity for climates 1 and 4. For climate 4 the parallel compressor works at its nominal capacity for a larger number of hours.

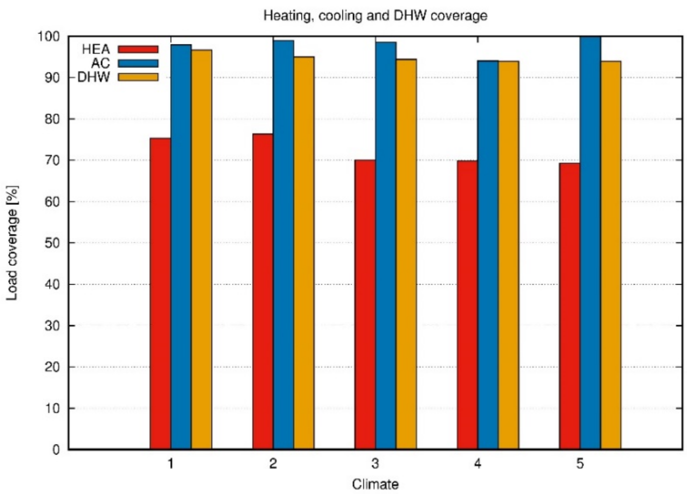

Figure 5: Load coverage of the energy need for space heating (HEA) and cooling (AC) and of the energy demand for DHW production

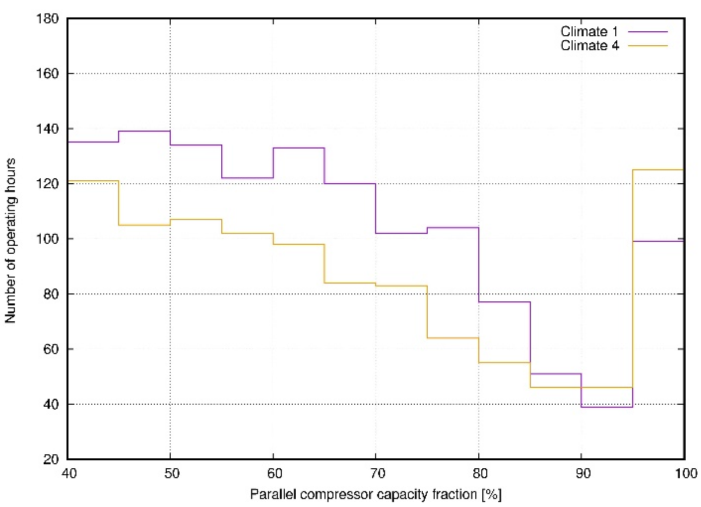

Figure 6: Number of operating hours of the parallel compressor in each capacity fraction range

The annual energy use has been evaluated for all the climates, and compared to the solution with separate refrigerating, heating, cooling and how water production systems (Table 4). In the integrated system the residual portion of loads not covered by the CRU relies on heat pumps. In all cases the integrated system leads to an energy saving around 9 %, with the highest value at the coldest climate, where heat recovery can be effectively exploited. Uniformity in energy saving values could be due to the high quality of the envelope, which damps the influence of outdoor conditions, and to some oversizing of the CRU, which limits the operation of the auxiliary heat pumps.

Table 4. CRU and Heat Pumps yearly electrical energy demand for the integrated system

Climate	CRU [kWh y^{-1}]	HEA HP [kWh y^{-1}]	DHW HP [kWh y^{-1}]	AC HP [kWh y^{-1}]	TOT [kWh y^{-1}]	Savings [%]
1	141813	1682	403	202	144101	8.8%
2	136005	2679	633	60	139378	8.9%
3	135848	5854	733	85	142520	9.5%
4	139597	6669	807	458	147531	9.7%
5	129117	9442	832	0	139391	10.8%

5. CONCLUSIONS

Simulations have been performed with a validated model, to find a design rule for replicating integrated refrigerating systems in supermarkets at various locations with different climate conditions. A recently refurbished supermarket was chosen as reference. The thermal characteristics of the building envelope at each location have been corrected to attain approximately the same energy performance quality as the actual reference building. At such conditions, it was found that using an integrated system for commercial refrigeration, hot water production, space heating and air conditioning in replacement of separate systems with heat pumps can give an energy saving around 9 %, at every climate condition considered. Such uniformity in energy saving figures is due to the high quality of the envelope, which damps the influence of outdoor conditions, and to some oversizing of the CRU, which limits the operation of the auxiliary heat pumps. At such conditions the plants design can be easily extended to new facilities in the occasion of refurbishment, since the integration of the refrigeration and HVAC systems shows to be effective in terms of overall energy efficiency. Significant reductions can be obtained in the investment and running costs, space occupied by the plants and amount of refrigerant charge. It has to be underlined that the reference building is quite small and with limited heating and especially cooling loads. The next step in this work is to extend the investigation to other buildings with different ratios between the refrigerating, heating and cooling loads, and to evaluate the feasibility of “all-in-one” plants at such conditions.

ACKNOWLEDGEMENTS

The research leading to these results has received funding from the MIUR of Italy within the framework of PRIN2015 project «Clean Heating and Cooling Technologies for an Energy Efficient Smart Grid». EPTA Refrigeration is gratefully acknowledged for their continuous and precious assistance in gathering data, and for the fruitful discussions.

NOMENCLATURE

AC	Air Conditioning	HR	Heat recovery
CDD	Cooling Degree Days	HS	High Stage
COP	Coefficient Of Performance	HVAC	Heating, Ventilation, Air Conditioning
CRU	Commercial Refrigeration Unit	GC	Gas Cooler
DHW	Domestic Hot Water	LS	Low Stage
$EP_{H,nd}$	annual heating energy need [kWh m^{-2} y^{-1}]	LT	Low Temperature
$EP_{C,nd}$	annual cooling energy need [kWh m^{-2} y^{-1}]	MT	Medium Temperature
HDD	Heating Degree Days	p_{INT}	Intermediate pressure [bar]
HEA	Space Heating	RDC	Refrigerated Display Cabinets
HP	Heat Pump	t	Temperature [°C]

REFERENCES

Antolín J., Macía A., Samaniego J, Bujedo L. Á., Barchi G., Belleri A., Dipasquale C., Haase M., 2016. Deliverable WP6_D6.4. Energy saving results. CommONEnergy. http://www.commonenergyproject.eu [accessed 27.01.2019].

Bell, I.H, Wronski, J., Quoilin, S., Lemort, V., 2014. Pure and Pseudo-pure Fluid Thermophysical Property Evaluation and the Open-Source Thermophysical Property Library CoolProp. Ind. Eng. Chem. Res. 53(6), 2498-2508.

Cortella G., D'Agaro P., Coppola M.A., 2018. Simulations and field tests of a CO_2 refrigerating plant for commercial refrigeration, Proc. 13th IIR Gustav Lorentzen Conference, Valencia, 2018.

D'Agaro P., Cortella G., Polzot A., 2018. R744 booster integrated system for full heating supply to supermarkets, Int. J. Refrig., 96, 191-200.

D'Agaro P., Coppola M.A., Cortella G., 2019. Field Tests, Model Validation and Performance of a CO_2 Commercial Refrigeration Plant Integrated with HVAC System. Int. J. Refrig., in press, https://doi.org/10.1016/j.ijrefrig.2019.01.030.

Gullo P., Cortella G., Minetto S., Polzot A., 2016. Overfed Evaporators and Parallel Compression in Commercial R744 Booster Refrigeration Systems– an Assessment of Energy benefits, 12th Gustav Lorentzen Natural Working Fluids Conference, Edinburgh, (UK).

EN ISO 13790:2008, Energy performance of buildings -- Calculation of energy use for space heating and cooling. International Organization for Standardization, 2008.

EUROSTAT, http://ec.europa.eu/eurostat/web/energy/data/database

JRC/MARS, http://agri4cast.jrc.ec.europa.eu/DataPortal/Index.aspx

Karampour M., Sawalha S., 2017. Energy efficiency evaluation of integrated CO_2 trans-critical system in supermarkets: field measurements and modelling analysis. Int. J. Refrig. 82, 470-486.

Karampour M., Sawalha S., 2018. State-of-the-art integrated CO_2 refrigeration system for supermarkets: a comparative analysis. Int. J. Refrig. 86, 239-257.

Meteonorm - Irradiation data for every place on Earth, 2017. URL: www.meteonorm.com

Minetto S., Girotto S., Salvatore M., Rossetti A., Marinetti S., 2014. Recent installations of CO_2 supermarket refrigeration system for warm climates: Data from the field. In: 3rd IIR International Conference on Sustainability and Cold Chain, London (UK).

Pardiñas A.A., Hafner A., Banasiak K., 2018. Novel integrated CO_2 vapour compression racks for supermarkets. Thermodynamic analysis of possible system configurations and influence of operational conditions. Appl. Therm. Eng. 131, 1008-1025.

Polzot A., Gullo P., D'Agaro P., Cortella G., 2016. Performance Evaluation of a R744 Booster System for Supermarket Refrigeration, Heating and DHW, 12th Gustav Lorentzen Natural Working Fluids Conference, 21-24 August 2016, Edinburgh, (UK), paper 1022.

Polzot A., D'Agaro P., Cortella G., 2017a, Energy analysis of a transcritical CO_2 supermarket refrigeration system with heat recovery. Energy Proced, 111:648-657, 2017.

Polzot A., 2017b. Energy benefit assessment of various refrigeration systems integrated with HVAC units in shopping malls. PhD Thesis, Università degli Studi di Udine, Italy. https://air.uniud.it/handle/11390/1132161#.W8htjGgzZaQ [accessed 27.01.2019]

Sawalha S., 2013. Investigation of heat recovery in CO_2 trans-critical solution in supermarket refrigeration, Int. J. Refrig., 36, 145-156.