PAPER ID: 1162
DOI: 10.18462/iir.gl.2020.1162

Field data of CO_2 integrated refrigeration, heating and cooling systems for supermarkets

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1. ABSTRACT

The EU H2020 project MultiPACK has given the opportunity of installing three state-of-the art CO_2 systems for supermarkets in South Europe, able to supply all the required thermal energy needs of the site, i.e. refrigeration, heating, cooling and hot water production. The MultiPACK units include parallel compression, ejectors for expansion work recovery and liquid recirculation and evaporator overfeeding, together with full monitoring of operation and performances. After more than one year of operations, field data of two supermarkets installed in Italy are presented and operating conditions and performance are illustrated; KPI indicators are evaluated to prepare for comparison with traditional solutions. A maximum monthly average COP of 4.2 was measured in central Italy in March 2020. The average specific energy consumption, due to Refrigeration, AC and heating, referred to the shopping area, was found to be 111 and 146 kWh $m^{-2}year^{-1}$ for the two sites.

Keywords: Commercial Refrigeration, Carbon Dioxide, Heat Recovery, DHW, Energy Efficiency.

2. INTRODUCTION

Following the F-gas Regulation and the Kigali amendment to the Montreal Protocol, Commercial Refrigeration has been forced to rapidly consolidate alternative, eco-friendly solutions to traditional systems. CO_2 has confirmed to be a reliable and sustainable alternative and an available solution for supermarkets after the 2020 and 2022 F-gas deadlines. The last trend proposes the complete integration of HVAC and Refrigeration system, so that a single, natural based refrigerant unit, can totally replace the thermal energy services in food retail stores. The EU project SuperSmart (Minetto et al, 2018) has shown how non-technological barriers can hinder the diffusion of energy efficient solution in the HVAC&R sector. After SuperSmart, the EU funded project MultiPACK wants to assure the market about the reliability and efficiency of CO_2 integrated systems by installing, monitoring and disseminating results of fully integrated state-of-the art systems in the South European Climate. The MultiPACK units include parallel compression, recovery of expansion work and liquid recirculation by ejectors, as described in Gullo et al, 2019, together with AC and heat pump functionalities. MultiPACK units are scalable and adaptable to different requirements from the building HVAC system.

In this paper, two systems developed and installed in Italy within the project MultiPACK are presented; daily operations are shown in typical winter, mid-season and summer operations, while one year energy results are disclosed.

3. INSTALLATION SITES AND SYSTEMS LAY-OUT

The selected installations are typical Italian neighbourhood supermarkets; they are located in Rome and in the Trentino region, North Italy, thus representing different climatic areas. According to EN ISO 15927-6:2008, the Rome location (urban site) has 1415 Heating Degree Days. For the Rome site, it was possible to log the actual external temperature of the installation site, as a temperature and humidity sensor was located at the inlet of the external air to the AHU; the recorded values are then representative of outdoor conditions. The Trento location has 3001 Heating Degree Days; temperature and humidity values adopted in this manuscript were taken from an official meteo station, close to the supermarket (http://storico.meteotrentino.it). The total shopping areas are 1450 m^2 and 1750 m^2 respectively in Rome and Trento, as reported in Table 1, while the Trentino building is a single-floor, isolated industrial-type construction, dedicated to commercial purposes. The installation of the MultiPACK units is part of refurbishment plans, which includes the entire HVAC&R system, display cabinets and cold rooms. According to the MultiPACK design, the units are providing full thermal energy services to the sites, i.e. Refrigeration, Heating and Cooling, while adopting the state-of-the art technologies for CO_2 units in warm climates, which include parallel compression, two-phase ejectors and optimal evaporator use by superheat minimisation. All the MultiPACK units are fully instrumented, to monitor operations and energy performance in the field. The Rome layout is illustrated in Figure 1, where also the major measuring instruments are represented (squares for temperature sensors, circles for pressure sensors, M mass flow rate, L liquid level, P_{el} power input to each compressor rack and total input to the compressors and gas cooler). The detailed description of system operations and measurement instruments accuracy can be found in Minetto et al., 2019. Temperature is measured with NTC 10 kΩ ±1% at 25 °C Beta 3435 sensors, whose declared precision is ±0.5 °C at 25 °C and ±1.0 °C in the range -40 °C to +90 °C. Pressure is measured with six commercial type piezoresistive pressure transmitters, with accuracy ranging from ± 1%FS to ±4 %FS (FS=60 10^5 Pa and 150 10^5 Pa on high pressure side) depending on temperature level pressure.

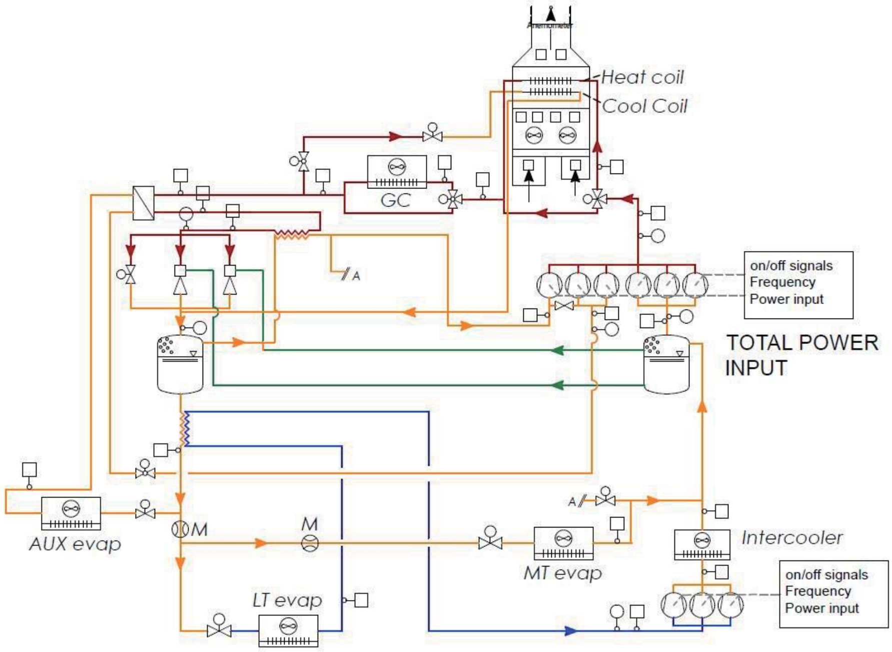

Figure 1: Rome site Layout

The three-phase electric power meters, located before each compressors rack, measure the power input to Low Temperature ($P_{el,LT}$), Medium Temperature ($P_{el,MT}$), and Auxiliary ($P_{el,AUX}$) compressors, with ±0.5 % FS accuracy (FS is 24 kW for LT compressor rack and 120 kW for MT and AUX). The accuracy of the Coriolis mass flow meters is 0.1 % of the actual flow. A hot wire anemometer (accuracy ±0.2 m/s +3 % of measured value) is located on the main air duct. The accuracy of the RH probes is ±3 % and of the reading (temperature range 0 °C to -40 °C, RH up to 90 %) and ±0.5 °C for temperature from +10 °C to +30 °C.

The unit installed in the Trentino region is presented in Figure 2. The operations of the unit are fully described in Tosato et al, 2020; the same instruments as in the Rome site are used. While the layout is basically the same, the main difference between the two systems is the type of terminals selected for heating and cooling of the indoor space. In Rome, HVAC are demanded to an AHU, while in Trento, shop ceiling indoor units are distributed in the shopping area; they provide heating and cooling by direct flow of CO_2 inside the ventilated coils. In addition, in the Trento shop a centralized Air Handling Unit (AHU) is activated only for summer dehumidification. This specific layout, with indoor ceiling units, can provide a practical option in those refurbished sites with limited ceiling height. Table 1 reports the design capacities of both systems, together

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with the area of the total areas of each site. The goal is to provide common basis to define specific KPI for the two installations.

Table 1. Design characteristics the sites

	Rome	**Trento**
$Q_{MT,D}$	50 kW @ -4°C	90 kW @ -4°C
$Q_{LT,D}$	19 kW @ -30°C	22 kW @ -30°C
$Q_{H,D}$	75 kW @ 10°C external temp.	200 kW @ 10°C external temp.
$Q_{AC,D}$	110 kW @ 30°C external temp.	280 kW @ 30°C external temp.
Shopping area	1450 m^2	1750 m^2
Total area	1900 m^2	2200 m^2

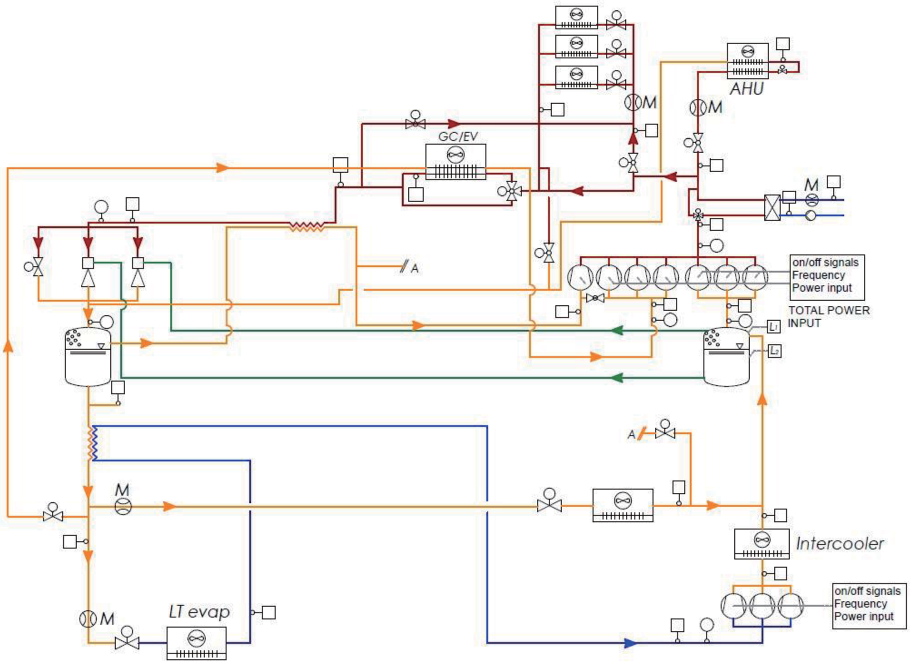

Figure 2: Trento site Layout

4. OPERATING CONDITIONS

In the following figures, the working conditions of the Rome and Trentino units are presented, in three representative days of the year. These days where chosen in order to highlight the thermal loads and electrical consumption profiles, as well as the pressure levels of the units during the hottest and coldest period of the year, when the demand of heating and AC cooling reaches the peak, together with a day when in both sites only refrigeration is required. The selected days are August 13th, January 15th and September 20th. When considering the pressure trend, it clearly emerges that the p_{gc} value achieves much higher values in Rome (Figure 3a) in the summertime, than in Trento (Figure 4a), corresponding to a much higher gas cooler outlet temperature for CO_2, due to the gas cooler different location and fan speed. On the other end, p_{MT} and p_{LT} are respectively 2.5 bar and 1.4 higher in Rome than in Trento. The thermal loads are represented in Figures 3b and 4b: the load ratios (Q_{MT}/Q_{LT}) are extremely different between the two sites, resulting in about 2 in Rome during the daytime and near 5 in Trento. These different values, partially visible in the design loads (Table 1), obviously depend on the different cabinet mix in the two supermarkets (in Trento there are plug-in LT units, which are not connected to the refrigerating unit) and they affect the global performance of the system. The AC load is extremely higher in Trento than it is in Rome, despite the maximum temperature during the day is nearly the same: this behaviour derives from the type of buildings (ground floor in one case, single floor “industrial” building in the other case).

The winter operating conditions are represented in Figures 5 and 6. In the wintertime, the Rome AHU is ON only during the day; therefore transcritical operations only occur for a limited number of hours (Figure 5a),; on the contrary, the heating system is always on in Trento (Figure 6a), with full time transcritical operations at about 90 bar. While in Rome the heating demand is limited (Figure 5b), it results much higher in Trento

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(Figure 6b), thus activating the heat pump functionality and resulting in relevant power input to the auxiliary compressors.

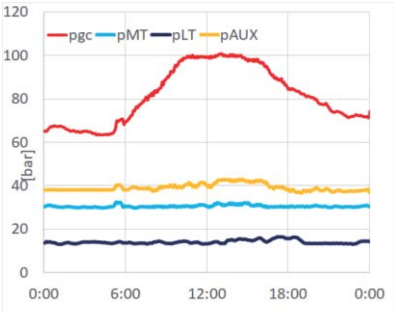

Figure 3a: 24h Pressures of Rome Unit (13th August)

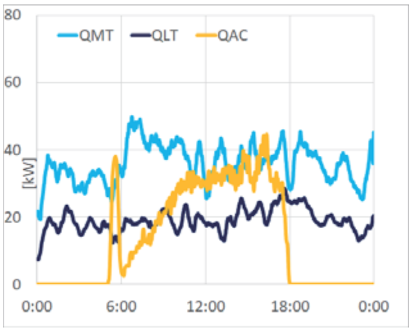

Figure 3b: 24h Thermal loads of Rome Unit (13th August)

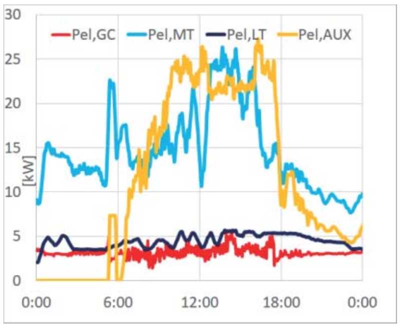

Figure 3c: 24h Electrical Power of Rome Unit (13th August)

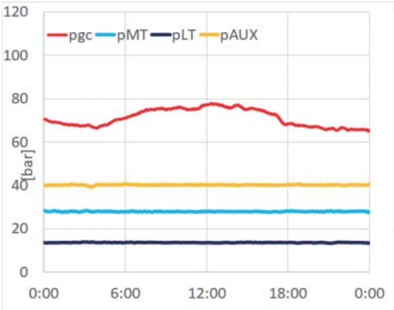

Figure 4a: 24h Pressures of Trento Unit (13th August)

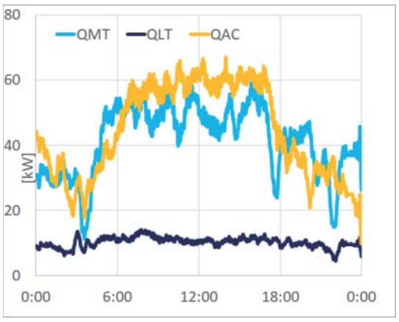

Figure 4b: 24h Thermal loads of Trento Unit (13th August)

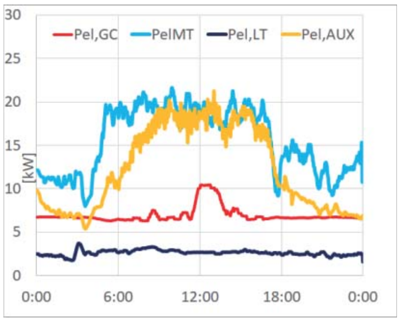

Figure 4c: 24h Electrical Power of Trento Unit (13th August)

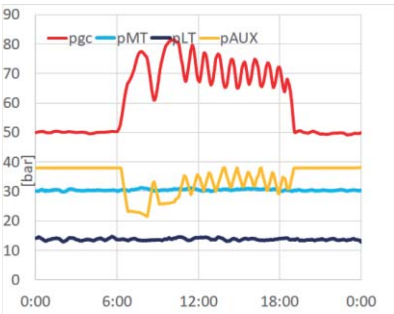

Figure 5a: 24h Pressures of Rome Unit (15th January)

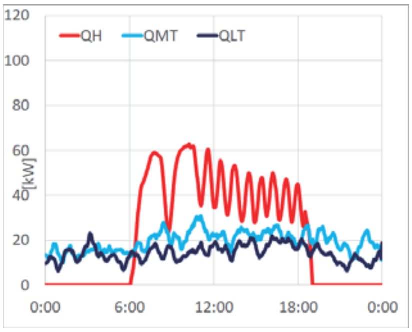

Figure 5b: 24h Thermal loads of Rome Unit (15th January)

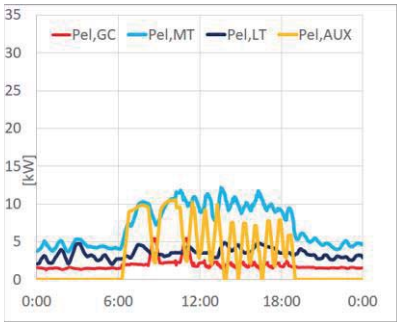

Figure 5c: 24h Electrical Power of Rome Unit (15th January)

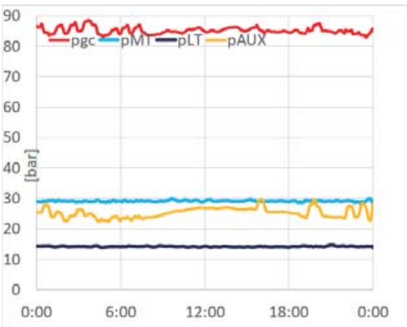

Figure 6a: 24h Pressures of Trento Unit (15th January)

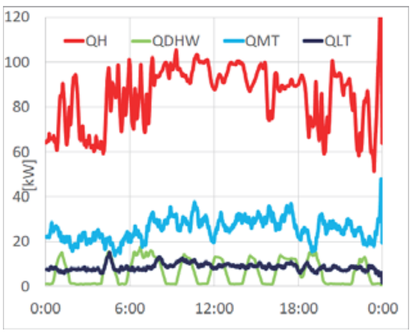

Figure 6b: 24h Thermal loads of Trento Unit (15th January)

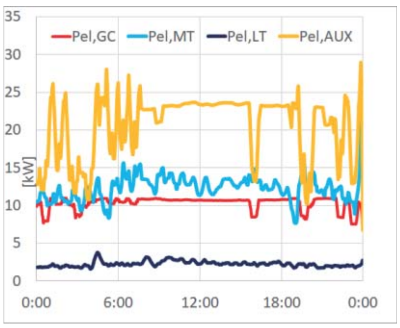

Figure 6c: 24h Electrical Power of Trento Unit (15th January)

Electrical power inputs to the different units are reported in Figures 3c and 4c. AHU fans and indoor coil fans electrical consumption is not accounted for.
The suction pressure of the auxiliary compressor operating for the heat pump functionality (p_{AUX}, Figure 5c) is low, due to the low ambient temperature; the power input ($P_{el,AUX}$ in Figures 5c and 6c) accounts for total power input to the auxiliary compressors. During the wintertime, the Trento evaporation pressure of the MT

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compressors p_{MT} is increased, with respect to summer operations, by 1.5 bar, while p_{LT} is kept at the summer value. Finally, a day when no HVAC is on was selected, to show operations of the Rome unit (Figure 7) and of the Trento unit (Figure 8).

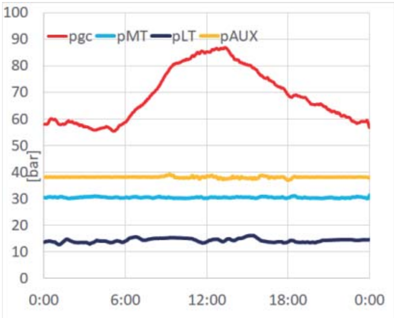

Figure 7a: 24h Pressures of Rome Unit (20th September)

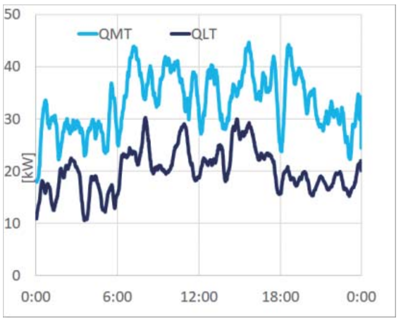

Figure 7b: 24h Thermal loads of Rome Unit (20th September)

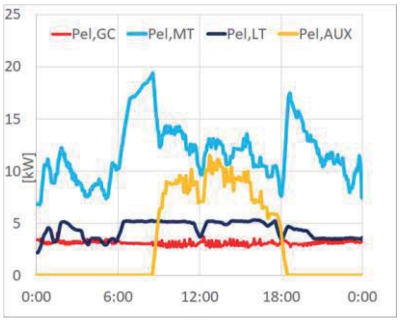

Figure 7c: 24h Electrical Power of Rome Unit (20th September)

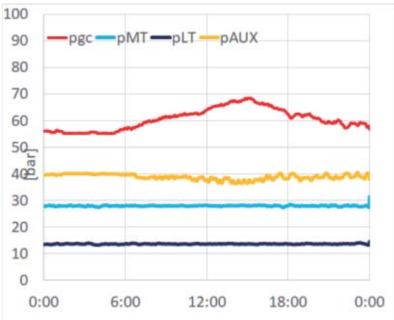

Figure 8a: 24h Pressures of Trento Unit (20th September)

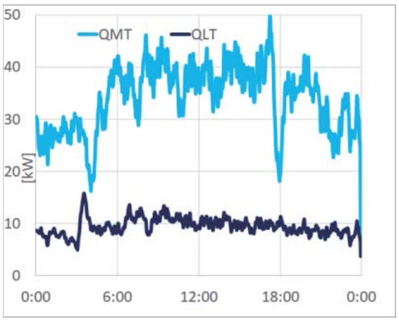

Figure 8b: 24h Thermal loads of Trento Unit (20th September)

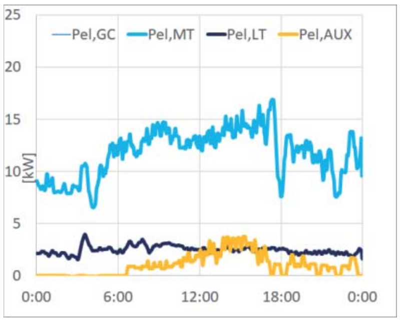

Figure 8c: 24h Electrical Power of Trento Unit (20th September)

5. ANNUAL PERFORMANCES AND KPI

Table 2. Rome site monthly performances

Rome	June 2019	July 2019	Aug 2019	Sept 2019	Oct 2019	Nov 2019	Dec 2019	Jan 2020	Feb 2019	Mar 2020	Apr 2020	May 2020
logged data [%]	23	14	97	97	63	89	91	77	53	85	45	82
E_m [kWh]	15238	20638	21239	15736	12614	10053	8930	10418	11834	10334	9141	13636
$e_{d,av}$ [kWh m^{-2} day^{-1}]	0.35	0.46	0.47	0.36	0.28	0.23	0.20	0.23	0.28	0.23	0.21	0.30
$COP_{tot,m,av}$ [-]	2.3	2.2	2.2	2.5	2.7	3.0	3.0	3.5	3.0	3.6	3.1	2.0
$COP_{m,av}$ [-]	2.7	2.4	2.5	2.9	3.3	3.7	3.8	4.1	3.4	4.2	3.8	2.3
T_{ext} [°C] max/ av	26.4/ 22.3	29.1/ 26.5	29.5/ 28.5	28.1/ 24.1	23.2/ 20.2	21.6/ 16.5	18.1/ 13.2	15.5/ 10.6	19.2/ 13.2	19.6/ 14.2	20.9/ 15.5	26.8/ 22.1

Table 3. Trento site monthly performances

Trento	July 2019	Aug 2019	Sept 2019	Oct 2019	Nov 2019	Dec 2019	Jan 2020	Feb 2020	Mar 2020	Apr 2020	May 2020	June 2020
logged data [%]	70	99	98	28	100	100	68	13	85	99	99	29
E_m [kWh]	25693	24855	17770	14038	20083	29234	32337	17599	22465	19207	17239	23261
$e_{d,av}$ [kWh m^{-2} day^{-1}]	0.47	0.46	0.34	0.26	0.38	0.54	0.60	0.35	0.41	0.37	0.33	0.44
$COP_{tot,m,av}$ [-]	2.4	2.3	2.3	2.3	2.9	2.7	2.7	2.9	2.9	2.9	1.9	2.0
$COP_{m,av}$ [-]	3.0	2.9	3.2	3.5	3.5	3.6	3.5	3.8	3.8	3.8	2.7	2.8
T_{ext} max/av[°C]	34.6/ 23.3	32.6/ 23.3	29.9/ 18.3	23.8/ 14.1	15.7/ 6.9	12.1/ 2.5	13.4/ 1.9	17.7/ 6.3	21.4/ 8.6	25.7/ 14.0	28.5/ 17.7	28.3/ 18.3

The total energy consumption month by month has been evaluated for both sites. When data were missing, due to remote connection failure, the energy consumption was evaluated by proportion with the rest of the month. In the case of the Trento unit, being the beginning of June 2020 particularly cold and having collected only the first 10 days, the rest of the month was evaluated with the same energy consumption of July 2019. For the Rome site, February 2019 replaces February 2020, when a relevant data loss occurred. E_m is the month Energy consumption due to heating, cooling and refrigeration, including gas cooler and outdoor evaporator fans, but not AHU or indoor cassettes fans. $e_{d,av}$ is the average day specific energy consumption for the given month, obtained dividing E_m by the selling area and the number of days in the month. $COP_{tot,m,av}$ has been

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evaluated dividing the total useful thermal energies (heating, cooling, refrigeration), except DHW production, by the total electrical energy input in the month, E_m, while $COP_{m,av}$ only accounts for the energy used by the compressor racks, i.e. it represents the useful thermal energy ((heating, cooling, refrigeration)) divided by the energy input to compressor racks. Table 2 reports data collected and elaborated for the Rome site, while Table 3 refers to the Trento site. With reference to annual performances, the total electrical energy used for heating cooling and refrigeration has been divided by the shopping area and the total area of the supermarket, resulting in the following specific energy consumptions , i.e. 111 kWh $m^{-2}year^{-1}$ and 85 kWh $m^{-2}year^{-1}$ in Rome and 146 kWh $m^{-2}year^{-1}$ and 116 kWh $m^{-2}year^{-1}$ in Trento. In order to get values for direct comparison with the results of Annex 44, where a supermarket was defined as energy efficient when its total energy consumption was below 400 kWh $m^{-2}year^{-1}$ compared to supermarkets from Denmark, Sweden and The Netherlands, with respect to the total supermarket area, electrical bills of the entire supermarket sites need to be collected.

CONCLUSIONS

After more than one year operations, the Italian MultiPACK commercial refrigeration HVAC&R systems results are disclosed. While reliability and serviceability are confirmed, the next step requires comparison of MultiPACK systems KPIs, both traditional, like specific energy consumption, and non-in-kind, like second law analysis (Minetto et al, 2019) with data collected from traditional systems. This is the next step for the MultiPACK project.

ACKNOWLEDGEMENTS

The MultiPACK Project has received funding from the European Union's Horizon 2020 research and innovation programme, under grant agreement No 723137.

NOMENCLATURE

e	specific energy (kWh m^{-2} day^{-1})	av	average
E	Energy (KWh)	DHW	Domestic Hot Water
p	Pressure (bar)	ex	external
P_{el}	Electrical Power (kW)	ev	Evaporation
Q	Thermal Power (kW)	GC	Gas cooler
T	Temperature (°C)	H	Heating
Suffixes and acronyms		LT	Low temperature application
AC	Air Conditioning	m	month
AHU	Air Handling Unit	max	maximum
AUX	Auxiliary	MT	Medium temperature application

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http://dx.doi.org/10.18462/iir.gl.2020.1162