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Field measurements of integrated MultiPACK supermarkets

Christian Schlemminger[(a)], Karl Oskar Pires Bjørgen[(a)], Sverre Foslie [(a)] Yosr ALLOUCHE[(b)]
Armin HAFNER[(b)]

[(a)] SINTEF Energy Research, Kolbjørn Hejes vei 1, 7491 Trondheim (Norway)
[(b)] Norwegian University of Science and Technology, Department of Energy and Process Engineering, Kolbjørn Hejes vei 1, 7491 Trondheim (Norway)

1 ABSTRACT

Integrated energy systems for supermarkets are becoming popular for the shop owners due to significant energy and cost savings. Integrated system means: the centralized refrigeration unit delivers the entire freezing, cooling and Air Conditioning demand of the Supermarket. Only the natural working fluid CO_2 is applied within the units.
Within the EU funded project MultiPACK, a series of demonstration supermarkets are developed and monitored across Southern Europe (Portugal and Italy).
The energy performance of the MultiPACK unit in Portugal is compared to comparable shop in the region. The MultiPACK system configuration is explained as well as the baseline configuration, i.e. the reference shop. The first-year operation indicates a 30% reduction in energy demand for the Portuguese shop with the MultiPACK unit when comparing with a shop containing a baseline standard cascade configuration (CO_2 & HFC134a).
Keywords: modern CO_2 refrigeration technology, Ejector, Compressor

2 INTRODUCTION

The preferred system choice for the cooling and freezing equipment in European supermarkets are CO_2 refrigeration systems. According to Shecco. the number of installed transcritical units in Europe has passed 20.000 installations in 2020, most of them are located in the Northern part of Europe and have achieved great performance advantages, i.e. energy savings compared to previous systems. This has led to the spread of the technology to southern countries challenged by high ambient temperature operations.
Various adapted system layouts have been developed during the past decade, to provide the end-users suitable solutions. The adaptation of the system architecture considers mainly the local climate or specific demands for the application with respect to integrate most of the energy related functions. Nekså at al.1998, introduced the idea of integrated solutions including heating by heat recovery in the beginning of CO_2 revival for the refrigeration sector. Nowadays units providing refrigeration, air conditioning and heating are offered to the market, as developed within the EU project MultiPACK. Their success is related to their cost and performance competitiveness, as demonstrated by Karampour and Sawalha, 2018. D'Agaro et al, 2019 made a substantial effort to document field performance of CO_2 systems. They also developed suitable models to predict annual performance.
Minetto et al, 2018 documented and demonstrated during the EU project SuperSmart that non-technological barriers can hinder the diffusion of energy efficient solution in the HVAC&R sector, especially in supermarkets. Therefore, the EU funded project MultiPACK aims to assure demanding end-users that integrated CO_2 refrigeration systems are providing the best feasibility, reliability, energy efficiency of and promoting a fast transition to low environmental impact solutions. The confidence raising campaign is made by installation and monitoring of fully integrated state-of-the art systems in South European Climate regions.

In this work, a system developed and installed in Portugal (Porto de Mos, Lisbon area) as being one of the 6 demonstration sites the project MultiPACK is presented; data from the field demonstrate its performance in summer operation defeating the high ambient temperature conditions. The system also includes AC operation and some heating functionalities.

3 SYSTEM LAYOUT

The characteristics and functions of a MultiPACK unit are refrigeration, space heating and cooling and hot water production, are all implemented in the same appliance. The unit itself is adopting the main state-of-the-art technologies for CO_2 refrigeration units as: ejector supported parallel compression, ejectors for expansion work recovery, minimized superheat for evaporators with suction pressure receiver and liquid ejectors for possible liquid recirculation.

3.1 Schematic of the units

The **Multipack unit** is based on a booster concept with parallel compression and expansion work recovery with ejectors, as shown in Figure 1. The space heating and cooling demand of the supermarket is supplied by means of two roof top ventilation units, where CO_2 directly flows into the heating and cooling coils. The arrangement of the roof top units enables also dehumidification, however, which was not utilized in the test campaigns for 2019.

Three semi-hermetic compressors are installed at Medium Temperature (MT comp) level, three compressors at Low Temperature (LT comp) level, and four units are dedicated for Air Conditioning (AC comp) (2). Smooth capacity modulation is achieved by inverter drives for compressors: two compressors at MT level, one at LT and one at AC are connected via frequency converters respectively. The total installed electrical power for compressors and fans is 177kW, this excludes the fans for the air handling unit.

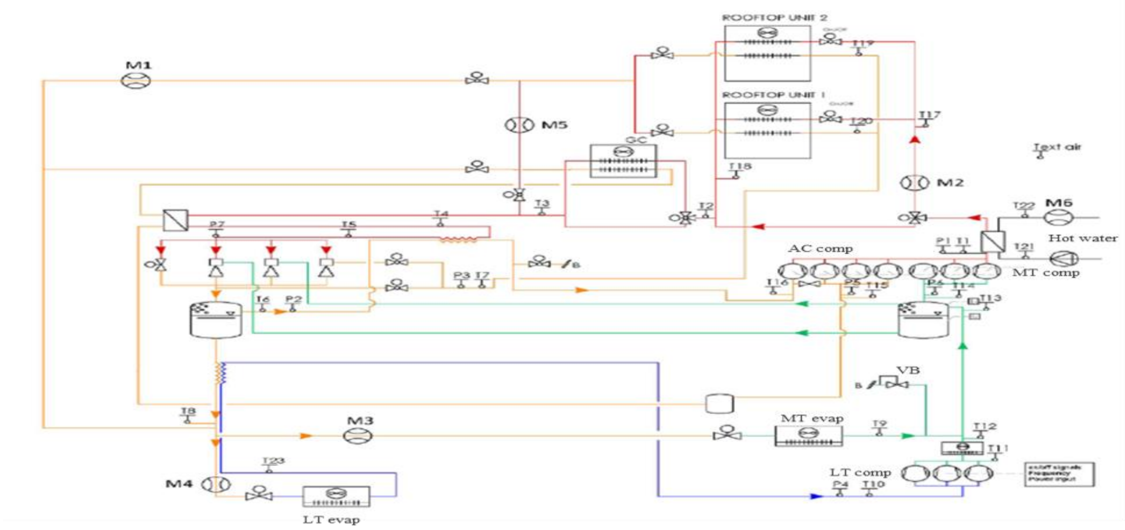

Figure 1 Multipack system layout

The operation of the MultiPACK unit can be described as follows: high pressure CO_2 can be applied for heating hot water up to 60°C before the remaining heat can be utilized in the roof top air handling unit (AHU). During the summertime excess heat of the CO_2 is rejected by the gas cooler (GC) to the ambient air. In winter operation the GC is partial or complete bypassed. The expansion to intermediate pressure level in the range of 35 to 45 bar is done by means of different ejector types or utilization of an electronically activated high side pressure control valve. The liquid receiver downstream the ejectors separates flash gas and liquid phase and accumulates the liquid to manage charge variations in the circuit and to provide sufficient liquid head. The liquid CO_2 is subcooled and distributed to the LT, MT and AC evaporator respectively. The LT load of the supermarket comprises of cabinets, freezing rooms and an ice machine. The liquid CO_2 mass flow supplied to the LT load is measured by a Coriolis mass flow meter (M4). The expansion to LT evaporation pressure is realized with electronic expansion valves separately controlled for each load. The low-pressure gas from the LT evaporators is heated due to subcooling of the liquid CO_2 before it is compressed by the LT compressors to MT receiver pressure level. The MT loads comprised of open and closed cabinets and cold rooms, which are equipped with separate controlled electronic expansion / metering valves. The supplied liquid CO_2 mass flow to the MT loads is measured by Coriolis mass flow meter (M3). A separator in the suction line prevent MT evaporator liquid to return to the MT compressors. In case of liquid occurrence in the separator a liquid ejector is activated to return it to the receiver. A second ejector compresses parts of the gases CO_2 back to the liquid receiver and is thereby unloading the MT compressors. The AC can be provided either utilizing direct expansion (DX) downstream the GC. In this case, a Coriolis mass flow meter (M5) is utilized to determine the CO_2 mass flow rate. Beside the DX AC mode an ejector supported AC operation can be applied using a low pressure lift high entrainment ratio ejector. In this case the entire vapour of the AC evaporators enters the ejector and is lifted to the receiver pressure level. Coriolis mass flow meter (M1) measures the CO_2 mass flow rate. The direct evaporation in the AHU heat exchanger can be operated with ultra-low superheat. The increased flash gas amount during AC operation is handled by dedicated AC compressors. The AC compressors can also be utilized for additional heat rejection mode (heat pump mode). This mode is triggered if the excess heat available from standard cooling mode is not covering the heat demand requested by the AHU. The heat pump mode utilizes ambient air as heat source by applying a separate set of coils in the gas cooler to evaporate liquid supplied by the liquid receiver. A solenoid valve is installed allowing an independent heat pump functionality for some AC compressors, while others still can remove flash gas. In heat recovery mode, the high pressure to set to be 85 bar.

A simplified schematic of the **reference supermarket** system layout is shown in Figure 2, here a R744/R134a cascade system is used to provide LT and MT cooling. Two separate R410A chillers are directly connected to two AHUs. The total installed electrical power for compressors (LT, MT, AC) and condenser fans is 232kW, this excludes the fans for the air handling unit.

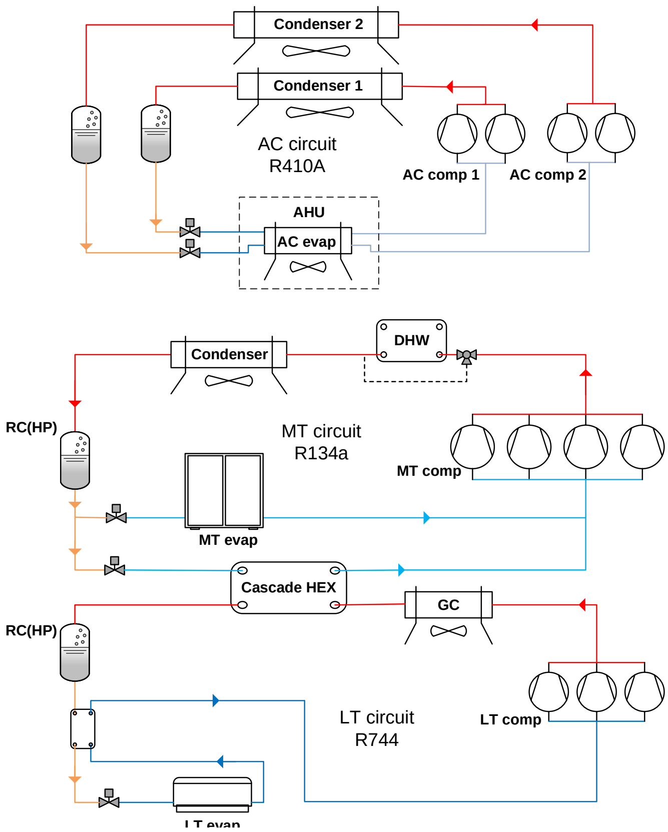

Figure 2 Simplified system layout for referance supermarket in cooling mode
(heat pump mode of AC circuit is not drawn here)

The subcritical LT part is a classical subcritical R744 circuit. Is comprised of three compressors where one is connected to an external frequency converter. The high-pressure gas is cooled first by a gas cooler before it is condensed at e.g. -3°C against the evaporating R134a. A high-pressure liquid receiver, downstream the condenser, accumulates the liquid to manage charge variations in the circuit providing sufficient liquid head. The liquid R744 is further subcooled by the returning superheated LT gas before it is distributed to the LT evaporators, which are equipped the separate expansion devices. The LT load comprises of cabinets and freezing rooms at evaporation temperature of about -33°C. Sufficient superheat needs to be maintained to prevent liquid return to the compressor.

The MT cooling is provided by a R134a rack comprising of five compressors where one is connected to an external frequency converter. Heat from the high-pressure gas can be utilized for hot water production before it is condensed against ambient air with two parallel condensers. A high-pressure liquid receiver, downstream the condenser, accumulates the liquid to manage charge variations. The liquid refrigerant is directly not subcooled but directly distributed to the MT evaporators. The MT load comprises in the shop of open and closed cabinets and cold rooms and the LT circuit condenser. Sufficient superheat needs to be maintained to prevent liquid return to the compressor.

The R410A heat pump/chillers used for air conditioning of the reference supermarket are built as symmetric circuits connected to a common evaporator, as show in Figure 2. The heat pump functionality is not shown here. Each circuit comprises of two parallel compressors connected to an air-cooled condenser. The condensed refrigerant is accumulated in a high-pressure liquid receiver to secure liquid head during load variation. The low-pressure working fluid evaporates in a common evaporator coil mounted in the AHU. Heating can be realized by the heat pump function i.e. reverse operation utilizing a switching valve of the R4101A chillers (for simplicity not shown in Figure 2). Also, at the reference shop no heating was required in the investigated period.

3.2 Measuring devices

3.2.1 MultiPACK

The instrumentation of the Multipack comprises of pressure, temperature, refrigerant and water mass flow, compressor input power and total power measurements. Figure 1 indicates the position of the sensors at the refrigerant site. Temperatures probes are commercial type NTC 10 kΩ sensors represented with T, having a declared precision is ±0.5°C at 25°C and ±1.0 K in the range -40°C to +90°C. Pressure transducers are commercial type piezoresistive pressure transmitters and are labeled with P, having an accuracy ranging from ± 1%FS for sensors up to 60 bar and ± 4 %FS for 150 bar sensors. Three-phase electric power meters measure Total power input to the pack (P_{TOT}), power input to Low Temperature (P_{LT}), Medium Temperature (P_{MT}), and Auxiliary (P_{AUX}) compressors. Their accuracy is ± 0.5 % FS. The status of every single compressor and the inverter frequency are also acquired. The liquid level in the liquid receiver is monitored in order to detect the

status of the liquid ejectors since the activations of it depends on the liquid level in the receiver.
Refrigerant mass flows is measured by 5 Coriolis mass flow meters with an accuracy ± 1 % reading. M_1 measures the mass flow in cooling mode with expansion work recovery and M_5 with DX operation, respectively. M_2 determines the hot CO_2 gas mass flow to the Roof top units in heating mode. M_3 measure CO_2 mass flow to MT loads and M_4 to the LT loads. The heat utilized for hot water production is measured by the magnetic mass flow meter M_5, located on hot water side and two NTC temperature sensors at water inlet and outlet of the plate heat exchanger, respectively.

3.2.2 Reference supermarket

The reference shop is equipped with temperature measurements having an accuracy of ±1.0 K in the range -40 °C to +90 °C. As for the MultiPACK the compressor frequency and the operation status were logged during operation. The installed three-phase electric power meters are not solely connected to the refrigeration plant and can therefore not be used for analysis. The electric power demand is calculated using compressor manufacturer data. The ambient temperature is measured utilizing the air inlet temperature probe of the AHU, having the same accuracy as the other probes.

3.3 Shopping area heating and cooling demand

The MultiPACK demonstration site in Portugal is located in Porto de Mos and has about 2400m^2 in air-conditioned area, whereas a similar supermarket is about 60km away having 2100m^2 in air-conditioned area. The dimensioning cooling capacities are listed in Table 1 for comparison.

Table 1 Dimensioning temperatures, capacities of the MultiPACK and reference supermarket

	Porto de Mos		Reference	
Service	**Temp.**	**Capacity**	**Temp.**	**Capacity**
LT total	-30°C	24kW	-33°C	20kW*
MT total	-4°C	100kW	-11°C	112kW
AC total (cooling)	10°C	180kW	10°C	164kW
AC total (heating)	30°C	160kW	30°C	150kW

*Condensing at -2°C

As shown in Table 1 the installed capacities at the Porto de Mos site and the reference shop are very similar. The deviation of the installed capacities is 17%, 12%, 13% and 6% for LT, MT AC cooling and AC heating, respectively. However, the main difference is as for the other systems developed in the MultiPACK project (Minetto et al., 2018; Minetto et al., 2019, Hafner et al, 2020), the pack is integrated and provides LT MT, AC cooling and hot water production simultaneously (summer operation). If heating is requested from the AHU (no AC cooling required) the heat recovery from the pack to the AHU is triggered. In this operation the gas cooler is partly or completely bypassed, and heat delivered to the AHU directly. The heating mode of the pack is activated in case of higher heat request from the AHU than the heat recovery from the LT and MT operation can provide (winter operation). In this case the ambient air is utilized as additional heat source using a separate coil in the GC as evaporator. Further, a high site pressure of e.g. 85 bar is set. Despite the MultiPACK the reference shop has only simultaneous LT, MT and hot water production. The AC cooling and the AC heating is provided by the separate chiller / heat pump units not utilizing the advantage of heat recovery from the refrigeration.

4 METHODOLOGY

A set of Key Performance Indicators (KPI) was developed in order to compare the MultiPACK and the reference supermarket.
The annual Total Specific Electric Energy Demand (TSED), expressed in kWh per m^2, will be evaluated for a given period and is defined as:

$$TSED_{periode} = \frac{\int_0^{\tau_{period}} P_{tot}(\tau)d\tau}{A_{eff}} = \frac{E_{el,tot,period}}{A_{eff}}$$

Eq. (1)

The overall electric energy consumption $E_{el,tot,periode}$ comprises as a sum of the electric energy consumption of LT, MT and AC compressors gas cooler/condenser.
The profile of Peak Power Duration (PPD), expressed in hours, will be evaluated as:

$$PPD_{period} = \frac{\int_0^{\tau_{period}} P_{tot}(\tau)d\tau}{P_{tot,installed}} = \frac{E_{el,tot,period}}{P_{tot,installed}} \quad \text{Eq. (2)}$$

The PPD is a measure how good the dimensioning of the pack fits to the real electric energy consumption during operation. A number closer to the total number of hours in the selected period, e.g 168h for a week interval, indicates the system running at higher capacity.

The profile of Average Electric Power Demand (AEPD), expressed in kW, will be evaluated as:

$$AEPD_{period} = \frac{\int_0^{\tau_{period}} P_{tot}(\tau)d\tau}{\tau_{period}} = \frac{E_{el,tot,period}}{\tau_{period}} \quad \text{Eq. (3)}$$

The Total Primary Energy Demand (TPED), expressed in kWh per m^2, will be evaluated as:

$$TPED_{periode} = \frac{\int_0^{\tau_a} \dot{E}_{TPED}(\tau)d\tau}{A_{eff}} = \frac{E_{TPED,periode}}{A_{eff}} \quad \text{Eq. (4)}$$

The TPED allows a comparison of different type of primary energy sources, e.g. if heating is provided by natural gas instead of electricity. The conversion from electric energy demand $E_{el,tot,period}$ to primary energy demand E_{TPED} is 2.5kWh$_{primar}$/kWh$_{el}$ for Portugal (Diário 234).

The Energy Efficiency Ratio is calculated in accordance to:

$$EER = \frac{\sum_{t=ti}^{t=tf} Qi}{\sum_{t=ti}^{t=tf} P_{in}i} \quad \text{Eq. (5)}$$

5 RESULTS

The outdoor temperature and the electric power demand of the MultiPACK installation and the reference supermarket from May to June 2019 are shown in Figure 3.

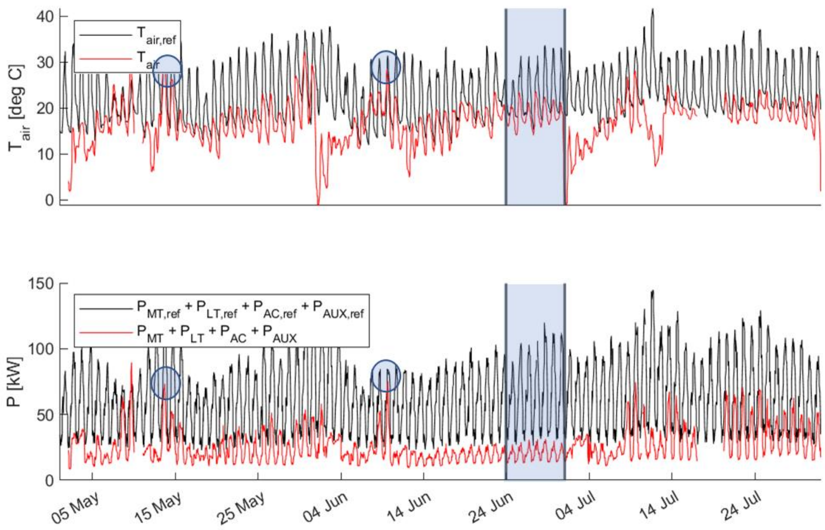

Figure 3 Comparison of total electric power demand of reference and MultiPACK supermarket. The analyzed period is visualized within the vertical lines. Additional data i.e. 13.05.2019 and 09.06.2019 was selected to compare operation at high ambient temperatures.

The outdoor temperature for the reference case is measured onsite, while meteorological temperature data from Monte Real airport represents the outdoor temperature for Porto de Mos. The onsite measurement of the Porto de Mos site was not valid due to effect of solar radiation. Also, the sensor of the reference shop is placed on the south side of the building in the AHU air inlet. The corresponding electrical power demand for Porto de Mos and the reference shop are shown below, including the power consumed by MT, LT, AC and AUX. Over the period shown, the total power demand is considerably lower for Porto de Mos compared to the reference case.

The period analyzed in this study is indicated in Figure 3, i.e. 24th June to 1st of July 2019.

The period is chosen due to relative stable operation for both cases. Figure 4 shows the electric power demand and outdoor temperature for Porto de Mos and the reference shop in more detail during the chosen period. Here the outdoor average temperature is higher for the reference shop with 23.0°C and 18.4°C for Porto de Mos. This will affect the AC power demand, which makes it hard to compare the power demand of these cases. However, the reference shop operates with a constant condensing pressure equivalent to 33°C condensing temperature, allowing the direct comparison of LT and MT demand.

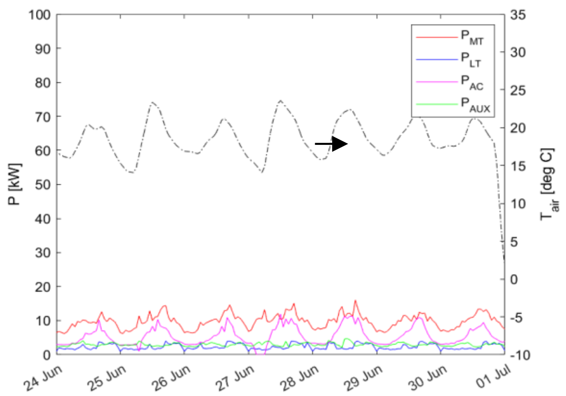

Figure 4 a) Electric power demand of AC, MT and LT ant outdoor temperature of Porto de Mos (arrow indicates the corresponding y-axis).

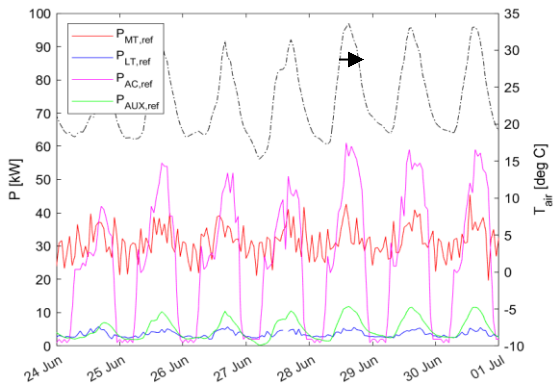

Figure 4 b) Electric power demand of AC, MT and LT of reference site (arrow indicates the corresponding y-axis).

The LT power demand is comparable in amount and volatility for both sites having an average value of 2.3kW and 3.5kW for Porto de Mos and the reference site, respectively. Compering MT power demand reveals a difference from average 9.8kW for Porto de Mos and 32.2kW for the reference shop. This unexpected large deviation can partly be explained by fact of having constant condensing pressure setpoint on the reference shop site and about 10K lower evaporation temperature level. An outdoor temperature adaptive condensing pressure would reduce the electric energy consumption by about 15%, whereas an additional increase of evaporation temperature from -15 °C to -5 °C would result in a total of about 37% reduction. Taking in to account the different outdoor temperatures sill indicates an about 30% lower MT electric energy consumption for the MultiPACK unit at Port de Mos. The above assumptions are based on a Carnot efficiency of 50%. A closer look to the auxiliary electric power demand, dominated by the gas cooler/condenser fan, indicate the same order of magnitude, however the reference shop having a larger one with 5 kW compared to 3 kW for Porto de Mos. The comparison of AC electric power demand indicates a large difference between Porto de Mos reference shop for the investigated week. Here the differences are caused by the higher outdoor temperature of the outdoor air at the reference site, making a direct comparison difficult. In order to indicate the electric power demand at higher outdoor temperatures datasets from 13.05.2019 and 09.06.2019, as shown in Figure 3 were used. Figure 5, Figure 6 and Figure 7 depict the electric power demand of MT, LT and AC, respectively, plotted over the outdoor temperature.

For all plots, there is a dependency between power demand and outdoor temperature, where the strongest dependency is found for AC. It can be noticed that the power demand is more uniform of the Porto de Mos caused partially by a higher sampling rate of data points but also from a smoother operation for MT and AC. The three MT compressors of Port de Mos cycle 0.2 compared to 4.63 cycles per hour for the four MT compressors at the reference site. Further a smooth change between the frequency-controlled compressor and the non-frequency controlled can be seen. Since no sudden increase in electric energy demand for the MT is measured. For MT, the power demand of the reference shop is higher for all outdoor temperatures compared to Porto de Mos caused by the constant set point of the condensing pressure and the higher temperature lift. The difference increases at higher outdoor temperatures due to the increased effect of the ejectors.

For LT, the power demands of both shops are similar, here the cycling of the LT compressors at Porto de Mos can clearly be seen and results in 2.43 cycles per hour compared to 3.27 for the reference shop. Porto de Mos seems operate with one or two compressors in operation at similar outdoor temperatures. The few measurement point at elevated outdoor temperatures indicate an outdoor temperature independent LT power demand.
The AC power demand for the reference shop indicates partly non-AC operation up to about 22 °C. However, above the electric energy demand increases in a broad band of about 20 kW up to 61 kW at 34 °C ambient temperature. The measurements of Porto det Mos indicate the frequency-controlled compressor in operation until 24 °C, removing the flash gas efficiently form the liquid receiver. For Temperatures above 24 °C the AC compressors power demand seems to increase with similar slope as from the reference cite, however at about 15 kW level. The highest power demand was recorded at with 38kW at an ambient temperature of 33 °C. During the period investigated the direct expansion mode for the AC cooling was utilized in Porto de Mos.

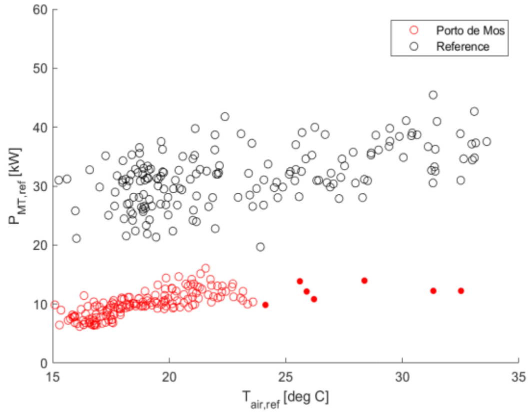

Figure 5 Electric power demand of MT compressors plotted over outdoor temperature. The filled red markers indicate the hot periods outside the week 24.06. to 01.07.2019

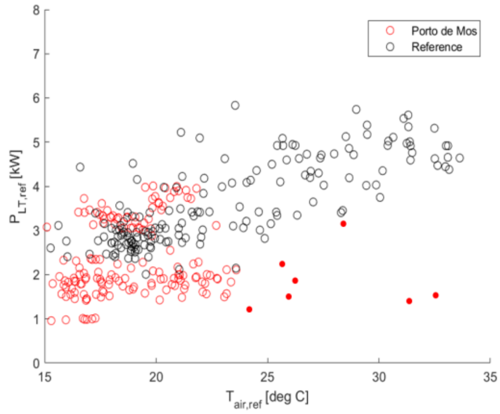

Figure 6 Electric power demand of LT compressors plotted over outdoor temperature. The filled red markers indicate the hot periods outside the week 24.06. to 01.07.2019

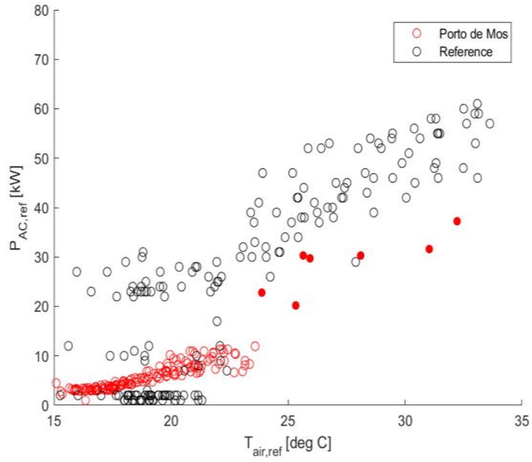

Figure 7 Electric power demand of AC compressors plotted over outdoor temp. The filled red markers indicate periods outside the week 24.6. to 1.7.2019.

Table 2 Comparison Key Performance Indicators of the MultiPACK and reference supermarket for week 24.06.2019 to 01.07.2019 (7 days = 168h)

KPI	Porto de Mos	Refer-ence	unit
Total Specific Energy Demand TSED	1.44	5.52	kWh/m^2
Total Primary Energy Demand TPED	3.60	13.8	$kWh_{primary\ energy}/m^2$
Peak Power Duration PPD	0.12	0.28	$kWh/kW_{installed}$
Average Electric Power Demand AEPD	20.5	68.9	kW
LT load @ LT evaporation temperature	9.0 @ -31°C	@-33°C	kW
MT load @ evaporation temperature	47.4 @ -5.1°C	@-15°C	kW
AC load @ evaporation temperature	7.2 @ +1°C*	n.a.	kW
Energy efficiency ratio EER	3.1	n.a	

*Target evaporation temperature about +10 °C, currently implemented

Table 2 shows key performance indicators calculated for both cases. The values are given as an average over the chosen period of 168h. The total specific energy demand is 3.8 times higher for the reference shop compared to Porto de Mos. The peak power duration is more than double for the reference case compared to the Porto de Mos.

The total electric energy consumption in the week 24.06.2019 to 01.07.2019 was 3452kWh and 11588kWh for Porto de Mos and the reference site, respectively. This results in an average electricity consumption of 20.5kW for Porto det Mos and 68.9kW for the reference site. During the test period there was no heat recovery triggered by the AHU at Porto det Mos, neither at the reference site.
The working conditions of the Multipack were: a high sight pressure of 65.7bar, receiver pressure of 35.6bar, providing on average LT cooling of 9.06kW at -31°C (13.8bar), MT cooling of 47.4 kW at -5.1°C (30.4 bar) and AC of 7.23kW at +1°C (35.6bar). The analysis of the cooling loads and power supply gives a. energy efficiency ratio of the Multipack unit of 3.1.

6 SUMMARY

The research presented in this work is underlining the overall goal of MultiPACK project, filling the knowledge gap of field measurements. The presented activity gives fact based and independent results, showing that CO_2 integrated systems, providing all thermal services for a supermarket, with state-of-the-art technologies, such as: parallel compression, ejectors and evaporator overfeeding, are feasible and reliable and are an available alternative to traditional, non-integrated, solutions.
The flexibility of meeting various supply needs and characteristics can be realized by the modularity of the

MultiPACK. The focus of the paper was tuned towards comparison of two very identical supermarkets in Portugal been characterized as green field (standalone) supermarkets with similar size, airconditioned area, occupant behavior and installed refrigeration capacity at LT, MT, and AC temperature level.
The analysis indicated the saving potential by utilizing the fully integrated CO_2 MultiPACK compared to a CO_2/R134a cascade system with separate air HCAV heat pump/chillers. The analysis was covering a selected week in end June 2019 where both systems were operating in cooling mode and no space heating was required. The investigation indicated a lower total specific energy demand at Porto de Mos compared to the reference site. The reasons for the high energy consumption at the reference site during the analyzed week in June 2019 are detailed discussed above and can be summarized by: a) a higher outdoor temperature, b) outdoor independent condensation pressure set point, c) a considerable lower MT evaporation temperature level. The higher outdoor temperature, results in a higher AC cooling demand.
Further work will be dedicated to adjusting the pressure level control of the liquid receiver in order to further optimize the energy consumption including the application of the AC ejector. The evaluation of other operating conditions covering heat recovery, hot water production and heating mode, as well as to comparing the MultiPACK and the reference site on annular basis.

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NOMENCLATURE

A	Area (m^2)	DHW	Hot Water
AEPD	Average Electric Power Demand (kW)	El	electric
E	Electric energy consumption (kWh)	EEV	Electronic Expansion Valve
P	Electrical Power demand (kW)	Eff	Effective
PPD	Peak Power Duration ($kWh/kW_{installed}$)	GC	Gas cooler
Q	Thermal Power (kW)	H	Heating
T	Temperature (°C)	HP	Heat Pump
TPED	Total Primary Energy Demand (kWh/m^2)	Installed	Installed at dimensioning conditions
TSED	Total Specific Energy Demand (kWh/m^2)	LT	Low temperature application
τ	Time (s)	MT	Medium temperature application
Suffixes and acronyms		RC	Receiver
a	Annual	ref	Reference site
AC	Air Conditioning	Tot	total
AHU	Air Handling Unit	Comp	Compressor
Air	Air/outdoor	Evap	Evaporator
Aux	Auxiliary		

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