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Energy efficiency of an integrated refrigeration and air-conditioning system using test and site measurements

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ABSTRACT

From 2020 through 2022, Daikin Europe aims to investigate the reduction of CO2 emissions and the impact of the raw materials used, by monitoring an integrated system installed in supermarkets across Europe, having engaged in an EU funded LIFE project called NaturalHVACR4Life. The integrated system studied throughout the project and this paper is the CO2 Conveni-pack, a Daikin product, which provides simultaneous refrigeration and space heating or cooling with the possibility of heat recovery. The Total Equivalent Warming Impact (TEWI) of the integrated unit was compared to an R410A unit using test measurements, where, the CO2 unit was found to emit significantly lower emissions over a period of 10 years. Furthermore, energy performance of a unit operating in a real shop in the EU has been discussed. The delivered energies by the unit in these shops were calculated using a 'Compressor Curve' method, which estimates the refrigerant mass flow in absence of expensive flow meters. This method has also been presented and discussed. Finally, a comparison in the peak and off-peak operation of the units at the two sites has been presented and discussed.

Keywords: Refrigeration, Carbon Dioxide, Heat recovery, TEWI, SEPR, Energy Efficiency.

1. INTRODUCTION

In an effort to support and imbibe the regulations imposed concerning the emissions of fluorinated gases across the European Union by the IPCC under the United Nations framework, Daikin Euorpe N.V. has participated in an EU funded LIFE project called 'NaturalHVACR4LIFE' (EC, 2014). Through this project, it is the aim to demonstrate a combined refrigeration and space heating and cooling product called the 'CO2 Conveni-pack' in various supermarkets across the EU. The key objectives of this project include the monitoring of these demonstrations accompanied by the analysis of this data, development of a cassette indoor unit compatible with such CO2 installations and a thermal storage prototype for peak shaving and additional reduction in carbon emissions, improvement of energy efficiency standards and regulations, training of service engineers and technicians in such CO2 technologies and dissemination of information through various media. This text is a follow up of previously published literature titled 'Energy performance of combined refrigeration, heating and cooling system in real applications' and 'TEWI and energy assessment of integrated CO2 refrigeration, heating and cooling technology'. Apart from an introduction to the system and its operation, an improvement on the above mentioned texts is presented based on the feedback received for the same in the section related to the Total Equivalent Warming Impact comparison. A detailed discussion on the precision of the mass flow estimation method is presented. Based on observations from real sites, a monthly overview of delivered energies is presented for two independent sites with a comparison of the seasonal energy performance ratio and a brief overview of temperature satisfaction achieved indoors. Furthermore, a comparison of the delivered refrigeration capacities is provided for both sites with respect to the ambient temperature and a difference in the peak and off-peak operation is also discussed. The text is concluded with prevailing challenges regarding the technology and the project and important conclusions derived from the analyses performed.

2. OPERATION, ANALYSES AND OBSERVATIONS

2.1. CO2 Conveni-pack

The Conveni-pack is an integrated refrigeration, air conditioning and heating solution intended typically for convenience stores and supermarkets. Initially, the product was developed with R-410A, but with the onset of progressive regulations, a non-HFC, natural solution with CO2 as the refrigerant was developed. The unit utilises heat recovered from the refrigeration cabinets to provide space heating indoors with an additional possibility of operating as a heat pump. It is equipped with two low stage compressors, one each for refrigeration and air-conditioning respectively and a common high-stage compressor as shown in the schematic in Figure 1. The compressors are patented swing compressors which are similar in concept to rotary compressors but lack the sliding vane assembly leading to a single piece construction eliminating pressure leaks. The switching between the heating and cooling modes is performed using a set of solenoid valves.

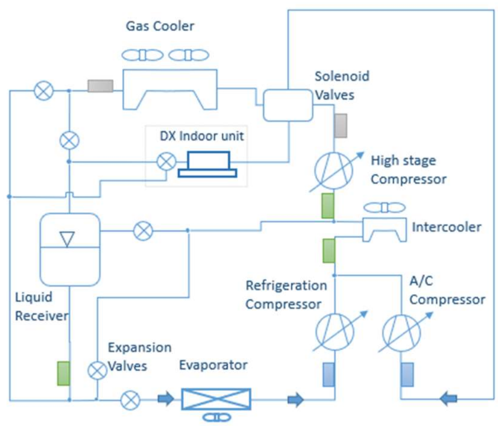

Figure 1: Schematic of the unit

2.2. TEWI comparison

TEWI has been defined as the impact of a refrigeration system on global warming over its lifetime with regard to the use, disposal and recovery (NASRC, 2017). The equation used for this is as shown in Eq. (1).

$$TEWI = (GWP \cdot L_{annual} \cdot n) + GWP \cdot m \cdot \left(1 - \alpha_{recovery}\right) + (E_{annual} \cdot \beta \cdot n) \qquad \text{Eq. (1)}$$

This equation comprises direct and indirect emissions of the technology over the lifetime considered. The first two terms in the equation show the direct emissions caused as a result of the Global Warming Potential of the refrigerant, the annual leakage rate, refrigerant charge and the recovery rate of the system. The last term represents the indirect emissions as a result of the annual energy consumption and emission factor based on the energy mix of the region. The values used for the parameters in the equation are given below in Table 1.

Table 1: Parameters used for TEWI calculation EC (2017) Llopis (2020)

Parameter	R410A	R744	Unit
GWP	2088	1	
L_{annual}	2	2	%
n	10	10	years
m	20	30	kg
$\alpha_{recovery}$	50	50	%
E_{annual}	23062	24119	kWh/year

Based on feedback received from the previous text, as mentioned in the introduction chapter, a leakage rate of 2% was considered as opposed to 1%. Although a leakage rate of 1% has been proclaimed in the product information, a leakage rate of 2% in compliance with existing literature was chosen. A higher difference of about 37%, as compared to 34%, in TEWI was observed between the units. Lifetime emissions of about 72.649 kg-CO2 eq. were calculated for the R410A unit as compared to 45.427 kg-CO2 eq. for the CO2 unit. This shows that parameters affecting the direct emissions as a result of the refrigerant, such as leakage rate and recovery rate have a negligible impact on the TEWI of the CO2 unit, but a significant one on the HFC unit.

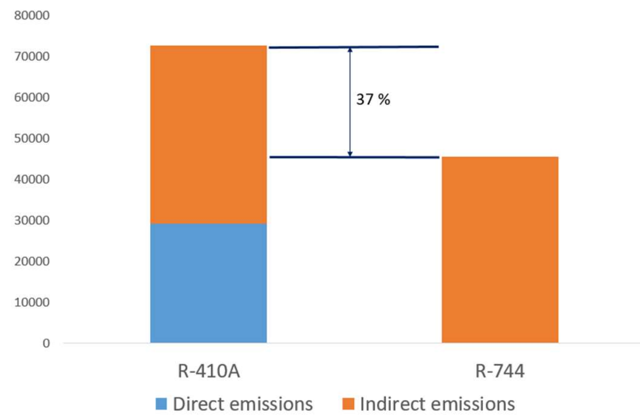

Figure 2: TEWI comparison between R-410A and R-744

2.3. Mass flow estimation and validation

In order to evaluate the performance of the units on site, the delivered energies were calculated using unit operational data. This data included temperature and pressure of the refrigerant at various points in the cycle and compressor speeds and valve opening degrees. This data, however, did not include the mass flow of the refrigerant which is an important parameter in the calculation of the capacities. The mass flow of CO2 in such systems needs to be calculated using a Coriolis CO2 flow meter which are expensive devices, and thus infeasible to install at every monitoring site. In addition to this, they are often intrusive installations. To substitute the use of such a flow meter, a method to estimate the CO2 mass flow in this unit has been developed. This method has been validated with measurements from a prototype store where the CO2 flow meter has been installed.

The following graphs in Figure 3 illustrate the precision of this estimation method, independently for refrigeration, heating and cooling. The X-axes of these graphs describe the deviation of the calculated values using this method from the measured values from the prototype store in %. The Y-axes show the occurrence of this deviation in the considered dataset. Each graph consists of two lines indicating the resolution, i.e. blue indicating an hourly resolution and red, a daily resolution. In the top-left figure representing refrigeration, it can be seen that above 80% of the values on an hourly basis are within 10% of the measured values, while 100% of these values are within 10% on a daily basis. Similarly for cooling in the top-right graph, about 70% of the values are within 5% of the measured values, while this number rises to more than 80% on a daily basis. It can be observed that this method precisely calculates the mass flows and as a result, the capacities, without over-estimating the values. For heating, due to the presence of various operation modes including heat recovery, the method is less precise than the above. Yet, on a daily basis a precision within 10% can be achieved for about 80% of the dataset for heating. This also shows an increase in the precision with a drop in resolution, ensuring highly precise calculations on a monthly and annual basis.

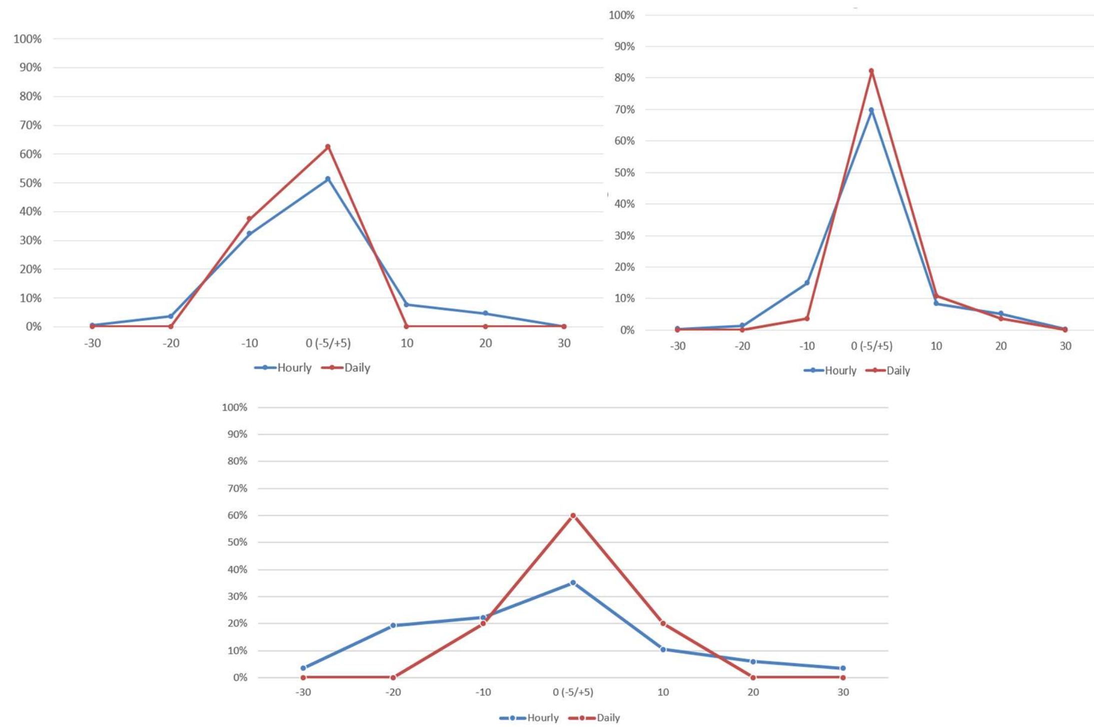

Figure 3: Precision of mass flow method

2.4. Observations from monitoring of actual sites

The following topics discuss important observations and comparisons between two real demonstration sites. The topics address a monthly overview of delivered energies throughout the year focussing on refrigeration, AC cooling and heating energy delivered through a heat pump operation or as heat recovered from the refrigeration cabinets. The SEPR difference between the two sites is discussed with a brief correlation to test results obtained from a local demonstration shop. A description of temperature satisfaction achieved in the shop as a result of space heating/cooling is given. Finally, a graphical description of the delivered refrigeration capacities at both sites with respect to the ambient temperatures is shown, also highlighting a weekday/weekend pattern observed in the operation of the unit at both sites.

2.4.1. Monthly overview

The following equations explain how the delivered capacities were calculated. These capacities were further multiplied by the time period to obtain the delivered energies. The equations given below refer to the delivered refrigeration capacity in Eq. (2), delivered heating capacity in Eq. (3) and AC cooling capacity in Eq. (4).

$$Ref_{cap} = m_{ref} \cdot (h_{ref,out} - h_{ref,in}) \qquad \text{Eq. (2)}$$

where m_{ref} is the mass flow of the refrigerant in kg/s and $h_{ref,out}$ is the enthalpy of the refrigerant at the outlet of the refrigeration cabinets in kJ/kg. This is calculated using the suction temperature and pressure at the low stage compressor. $h_{ref,in}$ is the enthalpy of the refrigerant at the inlet of the cabinets, calculated using the liquid temperature and pressure in the liquid receiver.

$$Heat_{cap} = m_{heat} \cdot (h_{heat,in} - h_{heat,out}) \qquad \text{Eq. (3)}$$

where $h_{heat,in}$ is the enthalpy of the refrigerant at the inlet of the indoor units, which is calculated using the gas temperature of the refrigerant and the high pressure measured at the discharge of the high stage compressor. $h_{heat,out}$ is the enthalpy at the outlet of the indoor units calculated using the liquid temperature and the high pressure.

$$AC_{cap} = m_{AC} \cdot \left(h_{AC,out} - h_{AC,in}\right) \qquad \text{Eq. (4)}$$

where $h_{AC,out}$ is the enthalpy of the refrigerant at the outlet of the indoor units, calculated using the suction temperature and pressure at the low stage compressor on the AC side. $h_{AC,in}$ is the inlet enthalpy of the refrigerant at the indoor units.

The graphs below display monthly delivered energies at two different sites under the project scheme. On the primary axis of the graph is the energy delivered in kWh and on the secondary axis is the temperature in ℃. Along with the delivered energies, the maximum ambient temperature occurring during the month is also shown. It was observed that site 2 showed a lower heating demand than site 1. Majority of the heating demand at site 1 can be seen to have been provided using heat recovery as can be seen from Figure 4. Any additional heating was provided through the heat pump operation of the unit. During the summer too, a demand for heating was observed, even requiring heat pump operation to satisfy this demand. This can be attributed to the small shop area of about 100 m^2 and the use of open refrigeration cabinets. In shops like these, the ambient temperature can be speculated to have a negligible effect on the operation, as even with a maximum ambient temperature of about 39℃, a heating demand arose due to the cold generated by the open cabinets. In site 2, however, a high cooling demand was observed due to low indoor setpoints of 16℃ and 17℃. The maximum ambient temperature observed during the cooling season at this site was around 36℃. A large proportion of heat recovery was also observed at this site during the heating season accompanied by minor heat pump operation.

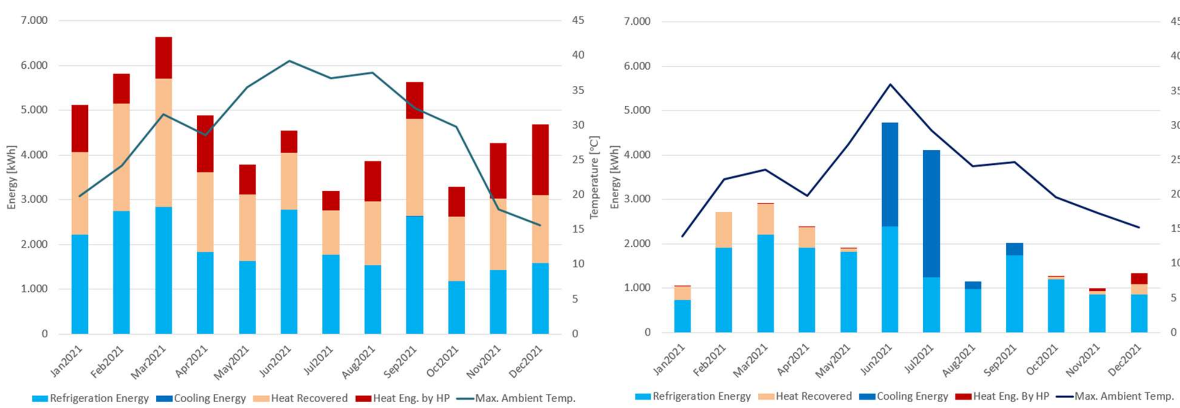

Figure 4: Monthly overview of site 1 (left) and site 2 (right)

2.4.2. SEPR comparison

Based on the monthly energy delivered by the units and the energy consumed, the seasonal energy performance ratio of the units was calculated and compared. It was observed that site 1 showed a 6% lower SEPR than the unit at site 2. Although the unit at site 1 showed consistent operation in heat recovery, the performance was offset by a larger operation of heat pump than the unit at site 2. The demand for heating during the summer months too can be further attributed to, for a lower performance. To analyse the performance of the unit under various operation modes, tests were performed at a prototype store to calculate the energy delivered and consumed. The results from these tests showed that the heat pump operation is 51% less efficient than the heat recovery operation. This inefficiency arises due to the high pressure control which needs to be maintained in order to provide heating at a required set temperature. Any drop in pressure can result in dissatisfaction indoors which is not favourable. These results show that an increase in the efficiency of the heat pump operation with an optimised control can boost the overall performance of the unit.

2.4.3. Delivered capacities

Based on above formulae, the capacity delivered by the unit to the medium temperature refrigeration cabinets is calculated and compared for both sites. The refrigeration capacity, shown in kW, is plotted with respect to the ambient temperature at the location in Figure 5. The ambient temperature was observed to range from a low of -14℃ and a high of about 38℃ for site 1 and from about -9℃ to 35℃ for site 2. The maximum delivered capacity for site 1 was about 10 kW, while for site 2 a slightly lower capacity of about 8 kW was observed. The dependence of refrigeration capacity on the ambient temperature is evident from these graphs as a slight increase in the refrigeration capacity is seen with respect to the temperature. As can be seen from the figure representing site 1 on the left, two high occurring patches are observed between the 2 to 4 kW and 5 to 7 kW range. These patterns were found to be attributed to the weekday and weekend/closing hours operation of the unit in site 1. Such obvious patterns were not observed in site 2. This will be discussed in further detail in the succeeding section.

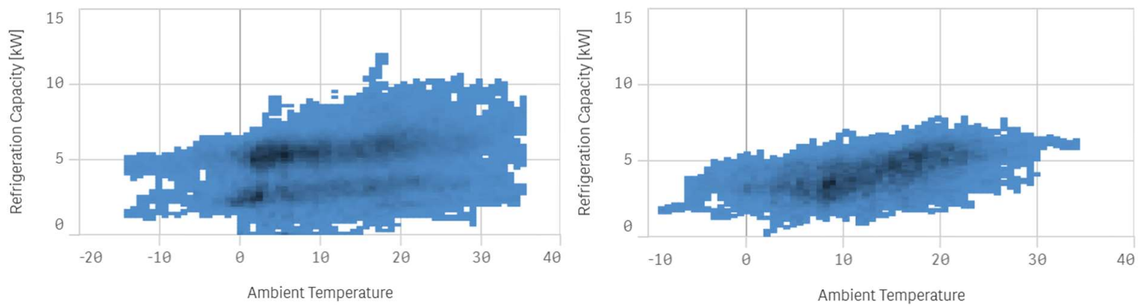

Figure 5: Delivered refrigeration capacity at site 1 (left) and site 2 (right) with respect to ambient temperature

2.4.4. Weekly patterns observed

As shown in the previous section for the delivered refrigeration capacities, two distinct patches of capacities were observed for site 1 at similar ambient temperature ranges. The same was not observed for site 2. The graphs below show the average refrigeration capacity per day of the week for both sites. Although the days of closure for both sites were different, a discerning pattern can be observed, especially for site 1. Site 1 remained closed during both, Saturdays and Sundays, while site 2 remained closed only during Sunday. In the figure describing the operation for site 1, a difference of about 36% in the delivered refrigeration capacity can be observed between weekdays and weekends. While the average delivered capacity during the weekdays was about 5,2 kW, during the weekends, it was observed to drop to around 3,4 kW. This difference was largely due to the activities performed in the shop, in addition to the demand reduction during the weekends. Activities such as the operation of an oven in the presence of open refrigeration cabinets adds to the load during the weekdays.

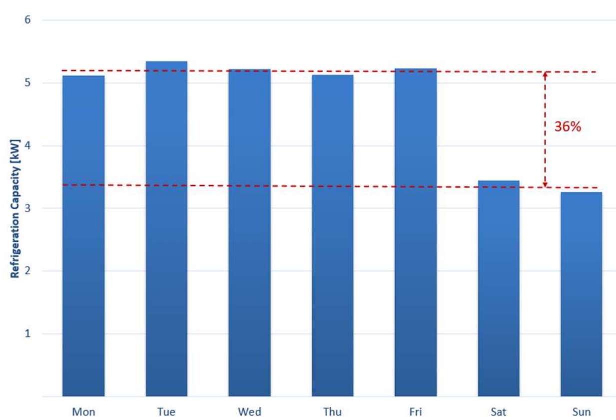

Figure 6: Peak/Off-Peak operation at site 1

For site 2, a much lower difference of about 19% between the open and closed hours is observed. An overall lower delivered capacity of about 4,2 kW was observed at this site during operational hours. This can be attributed to the larger number of closed refrigeration cabinets and a larger floor area of the shop.

Figure 7: Peak/Off-Peak operation at site 2

2.5. Challenges

Currently, no methodology exists in calculating SEPR of such a combined refrigeration and air-conditioning system with the appropriate consideration of heat recovery. A proposed methodology to enable the inclusion of heat/energy recovery in a fair and suitable manner for the evaluation of such systems is currently being validated by a third party research institute. It is the aim to propose this methodology for inclusion in future standards concerning similar technologies. Monitoring and recording real operational data is invaluable and equally challenging from the point of view of logistics, economics and maintenance. The CC method, as discussed in the previous sections, has been proposed as one solution to tackle this challenge, by eliminating the need for installation of expensive and often intrusive CO2 Coreolis flow meters. Although it has been observed to have a high precision for lower resolutions, detailed study and research can help in implementing a more robust estimation method. Data management and handling is equally important and crucial in such projects. To overcome the challenges of CO2 as a refrigerant, the development of a thermal storage concept is currently being studied with the help of a prototype. It will be studied if a concept like this can be used to make CO2 technologies more favourable in the warm climate regions. Finally, with the growth in CO2 technologies in the market, there is a constant need for a knowledge transfer between engineers, technicians, installers and researchers. It is the aim of this project to share as much information as possible to improve the state of the art and help in further development.

3. CONCLUSIONS

Based on the analyses performed using test measurements, a significantly lower TEWI was calculated for the CO2 unit as compared to the R410A unit over a lifetime of 10 years. This was achieved due to the negligible direct emissions of the CO2 unit. To substitute installation of expensive flow meters at real sites, a mass flow estimation method was validated using measured data. The validation showed high precision for the results obtained from the method for refrigeration, cooling and heating. This precision was improved as the resolution of investigated data was lowered, thus, for the purpose of calculating SEPR of such systems, it can be concluded to be a cost-effective solution. Based on the data investigated from real sites, a monthly overview comparison showed a higher heating demand for site 1 than site 2, with site 1 requiring heating during the summer too. The higher amount of heat pump operation at site 1 translated into a lower seasonal energy performance ratio as compared to the unit at site 2. It can be concluded that the type of refrigeration cabinets and the size of the shop play a crucial role in the annual energy performance of the unit. Finally, a prominent off-peak and peak pattern observed at site 1 presents an opportunity for further improvement of annual performance of units through suitable and optimised control strategies.

ACKNOWLEDGEMENTS

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NOMENCLATURE

TEWI	Total Equivalent Warming Impact	*GWP*	Global Warming Potential
L_{annual}	Annual leakage rate (%)	*n*	Lifetime (years)
m	Refrigerant charge (kg)	$\alpha_{recovery}$	Refrigerant recovery rate (%)
E_{annual}	Annual energy consumption (kWh/year)	β	Emission factor (kg/kWh)
Ref_{cap}	Delivered refrigeration capacity (kW)	m_{ref}	Refrigerant mass flow (kg/s)
$h_{ref,out}$	Outlet enthalpy of refrigerant at cabinets (kJ/kg)	$h_{ref,in}$	Inlet enthalpy of refrigerant at cabinets (kJ/kg)
$Heat_{cap}$	Delivered heating capacity (kW)	m_{heat}	Refrigerant mass flow at indoor units during heating (kg/s)
$h_{heat,in}$	Enthalpy of refrigerant at inlet of indoor units while heating (kJ/kg)	$h_{heat,out}$	Enthalpy of refrigerant at outlet of indoor units while heating (kJ/kg)
AC_{cap}	Delivered AC cooling capacity (kW)	m_{AC}	Refrigerant mass flow at indoor units during AC cooling (kg/s)
$h_{AC,in}$	Enthalpy of refrigerant at inlet of indoor units while AC cooling (kJ/kg)	$h_{AC,out}$	Enthalpy of refrigerant at outlet of indoor units while AC cooling (kJ/kg)
SEPR	Seasonal Energy Performance Ratio		

REFERENCES

European Commission, “Refulation (EU) No 517/2014 of the European Parilament and of the Council of 16 April 2014 on fluorinated greenhouse gases and repealing Regulation (EC) No 842/2006,” Official Journal of the European Union, 2014.

North American Sustainable Refrigeration Council, “What exactly is TEWI, anyway?,” 23 January 2017. [Online]. Available: https://nasrc.org/articles1/2017/1/23/what-exactly-is-tewi-anyway. [Accessed 15 December 2020]

European Commission, EN 378:2017; AR4: Fourth Assessment Report of the IPCC, 2017

Llopis R., Calleja-Anta D., Maiorino A., Nebot-Andres L., Sanchez D., Cabello R. TEWI analysis of a stand-alone refrigeration system using low-GWP fluids with leakage ratio consideration. International Journal of Refrigeration. June, 2020.

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NaturalHVACR4LIFE

CONVENI-PACK

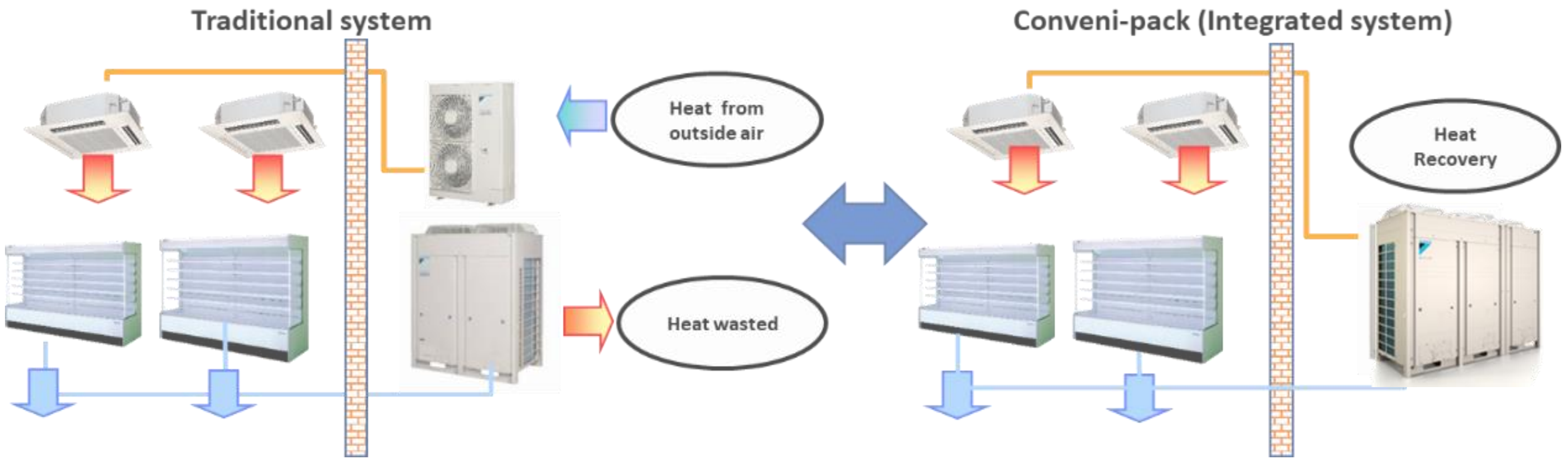
CO2 cassette & thermal storage

Training

Standards & regulations

Dissemination

CO2 Conveni-pack



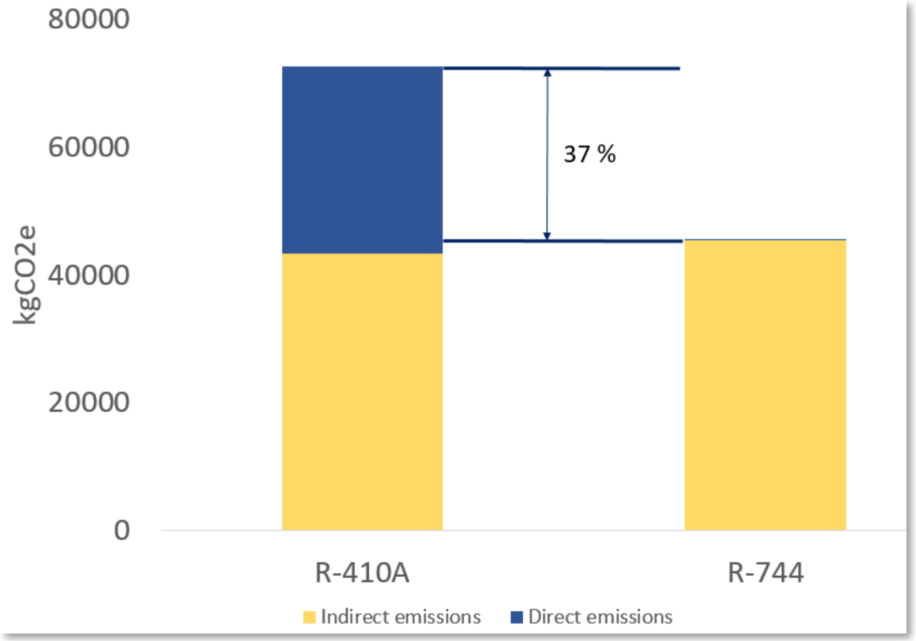
- Uses a 'natural' refrigerant, CO2
- Heat recovery functionality
- Integrated refrigeration, space heating and cooling unit
- CO2 cassette indoor unit

TEWI comparison

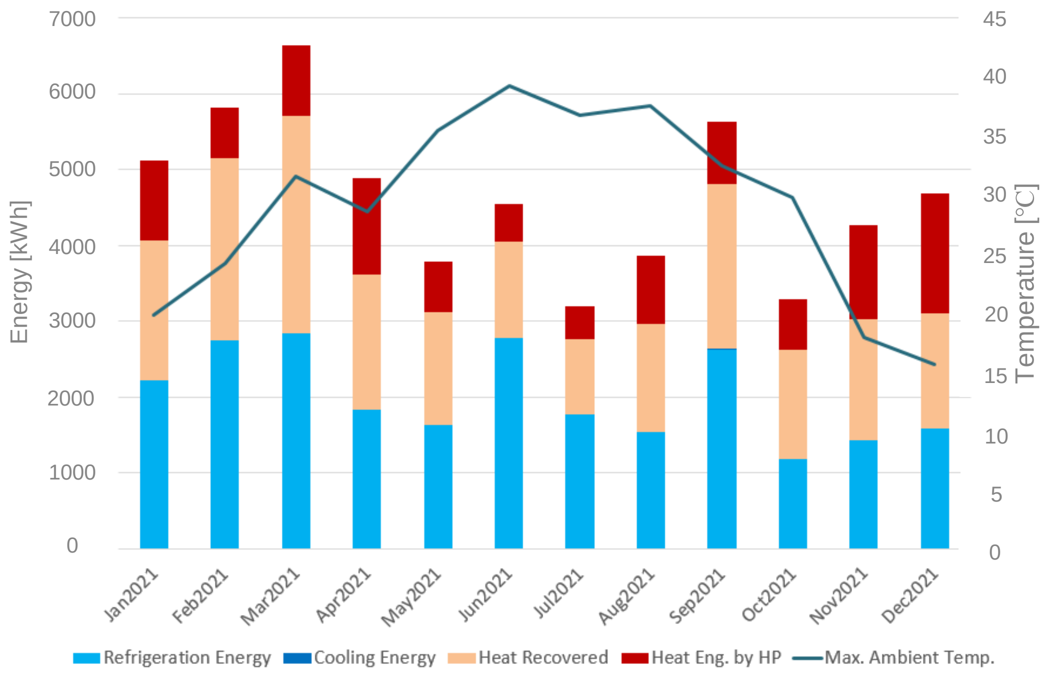
$$TEWI = \overbrace{(GWP \cdot L_{annual} \cdot m \cdot n) + GWP \cdot m \cdot (1 - \alpha_{recovery})}^{\text{Direct}} + \underbrace{(E_{annual} \cdot \beta \cdot n)}_{\text{Indirect}}$$

Parameter	R410A	R744	Unit
GWP	2088	1	
L_{annual}	2		%/year
n	10		years
m	20	30	kg
$\alpha_{recovery}$	50		%
E_{annual}	23062	24119	kWh

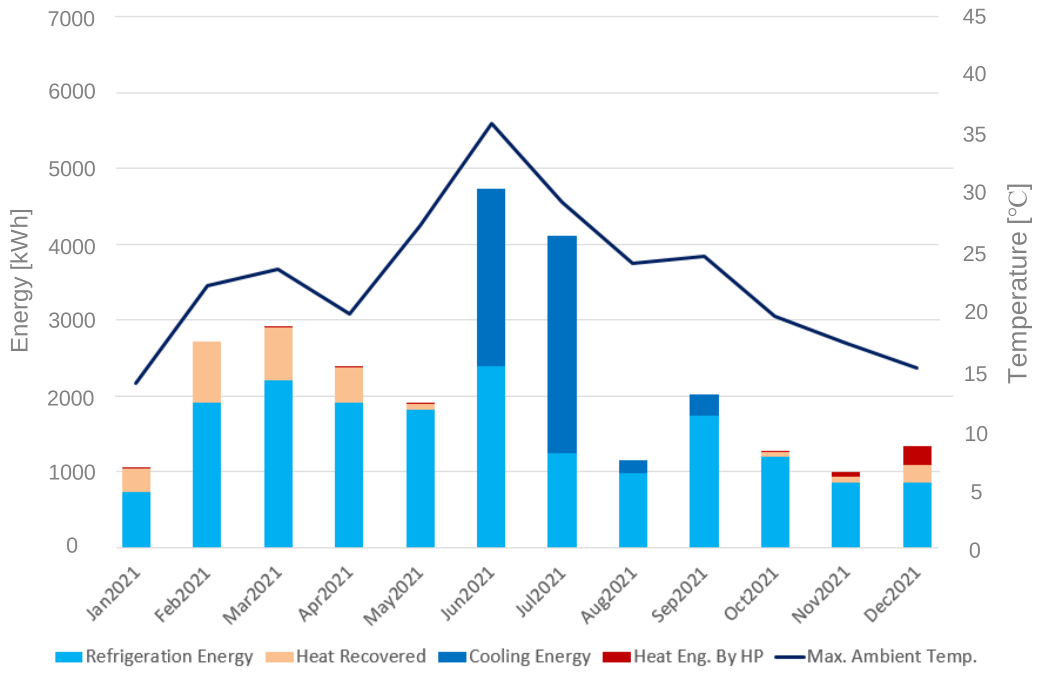
- Total Equivalent Warming Impact compared between similar units with different refrigerants, R410A & R744
- Direct emissions major differentiator on the total impact
- Overall emissions 37% higher for HFC unit despite lower annual energy consumption



Energy overview – site observations



Site 1

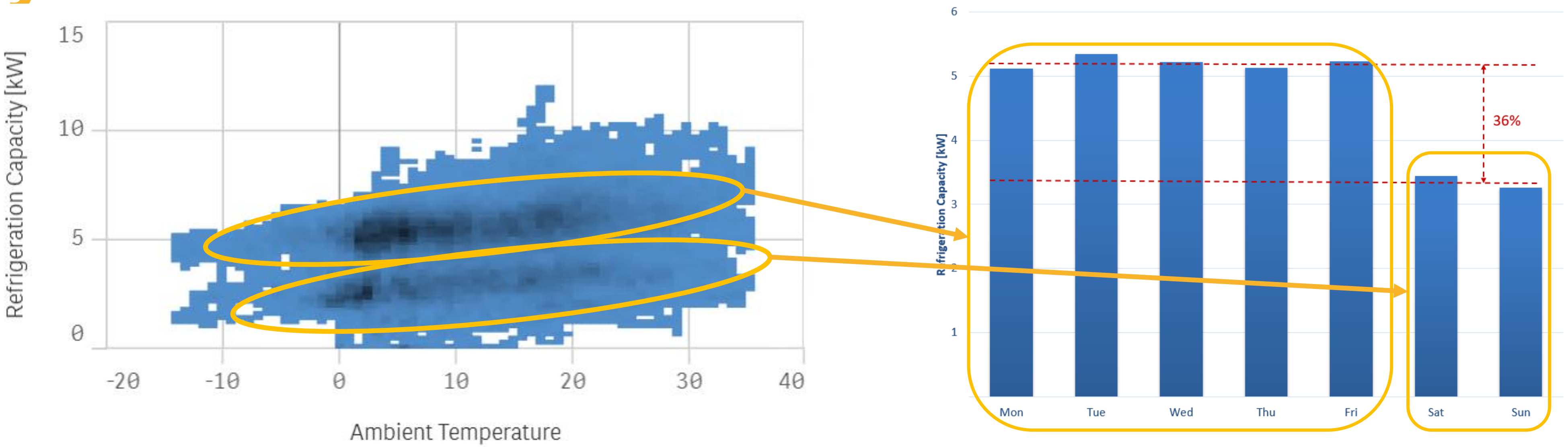


Site 2

- Heating during summer for site 1; 67% heat recovery operation
- Higher cooling demands for site 2 due to low indoor setpoints
- Importance of shop size and type of refrigeration cabinets visible

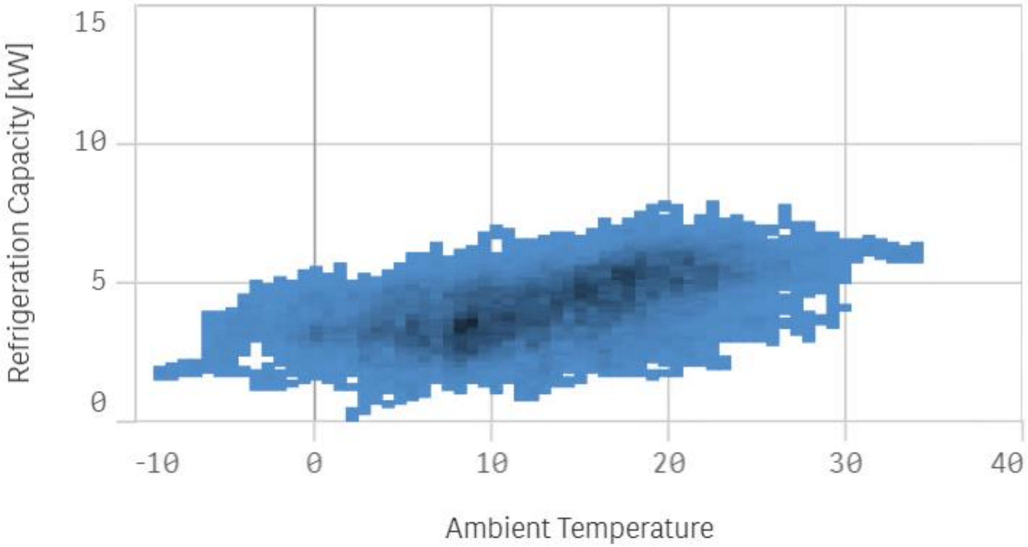
Energy overview – site observations

Site 1



- Weekly pattern shows the impact of activities on the operation of the unit
- Site 1 shows clear distinction between peak and off-peak operation

Site 2



Ongoing work

- Reduce CO_2 emissions by integrating a thermal storage and adiabatic cooling system with the CO_2 CVP
- Water tank with PCM plates having a melting point of 22℃ connected in series with the gas cooler
- To be evaluated at a test site in Valencia and Ostend

Conclusions

- TEWI of R744 CVP < TEWI of R410A CVP

- A large portion of the heating demand can be covered by heat recovery

- Shop sizes, type of refrigeration cabinets and activities in the supermarket should be important design and dimensioning parameters for such applications

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Thank you

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