LIFECYCLE CLIMATE PERFORMANCE OF CO2 CONVENI-PACK

Daikin Europe N.V.

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ABSTRACT

The following report provides a comprehensive overview of a lifecycle climate performance analysis of the R744 (CO_2) and R410A Conveni-Pack with similar capacities in the frame of the NaturalHVACR4LIFE project. The analysis addressed the climate impact of the product in three sectors; namely, 1) direct emissions as a result of refrigerant leakage, 2) indirect emissions due to energy consumption, materials and transport and 3) the embodied emissions accounting for material recycling and refrigerant manufacturing. The impact of the refrigerants, difference in the annual energy consumption as a result of the difference in efficiency and the materials used in the product were recognized as definite factors considering the difference in the climate impact of both units. The effect of a diminishing greenhouse gas emission intensity factor for the production of electricity in the EU as a result of the carbon neutrality target by 2050 on the combined emissions from the unit during its lifetime is also considered. A sensitivity analysis on the leakage rate and the recovery of the refrigerant during the disposal of the unit, at the end of its life, is presented to highlight the impact of leak tightness and refrigerant recovery on the overall emissions.

Keywords: LCCP, Lifecycle, GWP, R-744 (CO_2), R-410A, emissions, refrigerant, energy efficiency

EXECUTIVE SUMMARY

This report presents a lifecycle climate assessment (LCCA) of the DAIKIN CO_2 Conveni-Pack (CO_2 CVP), a newly developed integrated refrigeration and air conditioning unit that uses a non-fluorinated (natural) alternative to fluorinated gases, namely carbon dioxide (CO_2). This new technology has been piloted by Daikin Europe and tested in Belgium and Spain and is currently being demonstrated in supermarkets in Germany, France and Italy as part of the Natural HVACR 4 LIFE Project, whose objective is to develop an air-conditioning and refrigeration system that uses a non-fluorinated (natural) refrigerant.

Because fluorinated gases do not damage the atmospheric ozone layer, they have been used in many applications as substitutes for ozone-depleting substances. Due to the fact that fluorinated gases have relatively high global warming potential, the European Union is proposing a revision of the European F-gas Regulation, further phasing down the emissions of fluorinated refrigerants in existing and new equipment, where alternatives exist. Under the LIFE project, DAIKIN Europe is currently working with CO_2 as a refrigerant in an integrated refrigeration and air-conditioning unit, known as CO_2 Coveni-Pack unit.

In this report the life-cycle performance of the CO_2 (R744) Conveni Pack (CO_2 CVP) is assessed and compared to the one of the R410A Conveni Pack (R410A CVP). The comparison is possible because these are units of equal capacities in terms of refrigeration, cooling, and heating. The comparison is based on the life-cycle climate performance (LCCP) method that evaluates the climate impact of a refrigeration and air conditioning/heating unit during its lifetime: from the raw materials used during production of the unit to its disposal at the end of life – cradle to grave approach. The LCCP bases the assessment on:

1) direct emissions
2) indirect emissions, and
3) embodied emissions.

Direct emissions are derived from the annual refrigerant leakage and the refrigerant which cannot be recovered or is disposed of at the product end of life.

Indirect emissions are linked to energy consumption as well as the materials used in manufacturing and assembling the unit. Indirect emissions include also emissions due to transport of the components required to assemble the unit at the factory and the transport of the packaged and assembled unit to the end user.

Finally, embodied emissions are those emissions linked to the reuse of the recycled materials to manufacture the unit and the emissions linked to producing the refrigerant itself.

The results obtained by the LCCP methodology show that for both the CO_2 CVP unit and the R410A CVP unit, indirect emissions from energy consumption contribute to the largest emissions' share, which is 96% and 65% respectively of the total emissions. While the R410A CVP unit produces higher direct emissions linked to the refrigerant leakage during its lifetime and at disposal of around 33%, the CO_2 CVP unit on the other hand has negligeable direct emissions.

Although the indirect emissions linked to materials as well as the embodied emissions are negligeable for both units, these are higher for the CO_2 CVP unit because of its higher weight and larger size in comparison to the R410A CVP unit. Since the number and overall weight of the components is greater, due to the technical redesign required for the CO_2 unit to achieve the same performance as the R410A unit counterpart (same capacity output), indirect emissions, due to transportation and logistics, are also higher for the CO_2 CVP unit.

To conclude, indirect emissions from the annual energy consumption and those linked to transport of the CO_2 unit are greater compared to the R410A unit. The negligible direct emissions linked to the annual refrigerant leakage makes the CO_2 CVP unit more environmentally sustainable. In fact, it is estimated, through a sensitivity data analysis, that a low annual refrigerant leakage rate, less than 0,8% of the total refrigerant charge in the unit, and a high refrigerant recovery rate over 85% would be necessary for the R410A CVP unit to have a more favourable LCCP than that of the CO_2 CVP unit and thus a lower carbon footprint.

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METHODOLOGY

Lifecycle climate performance (LCCP) is a method to evaluate the climate impact of a refrigeration and AC component over its lifetime, from the “cradle to the grave” - right from the effect of the raw materials to the disposal of the unit at the end of the tenure. The LCCP encompasses the Total Equivalent Warming Impact (TEWI), which is a metric used to evaluate the climate impact of such a product as a result of direct and indirect emissions from the use and disposal of the unit over its lifetime, in addition to the contribution of the embodied emissions in the recycling of the material used and the production of refrigerant [1]. The unit discussed in this report is the Conveni-Pack (CVP), which is an integrated refrigeration, space heating and cooling unit, typically used in supermarkets. The CO_2 CVP with R744 refrigerant (non-fluorinated refrigerant) has been compared to its previous, R410A (fluorinated refrigerant) counterpart. The analysis was done within the time period from 2021 till 2030.

The LCCP of both units were calculated using the following equation:

$$LCCP = Direct\ emissions + Indirect\ emissions + Embodied\ emissions \tag{1}$$

$$Direct\ emissions = C \cdot (L \cdot ALR + EOL) \cdot (GWP + Adp.GWP) \tag{2}$$

$$Indirect\ emissions = \sum_{n=2021}^{2030} AEC \cdot EM_n + \sum m \cdot MM + \sum m_c \cdot d \cdot FCI + M \cdot D \cdot FCI \tag{3}$$

$$Embodied\ emissions = \sum m_r \cdot MR + C \cdot (1 + L \cdot ALR) \cdot RFM + C \cdot (1 - EOL) \cdot RFD \tag{4}$$

where,

C is the refrigerant charge in kg,

ALR is the annual leakage rate in %,

L is the lifetime in years,

EOL is the End of Life disposal of refrigerant charge in %,

GWP is the Global Warming Potential given in kgCO2e/kg,

$Adp.GWP$ is the Adaptive Global Warming Potential given in kgCO2e/kg,

AEC is the Annual Energy Consumption in kWh,

EM_n is the Greenhouse Gas Emission intensity per year n in kgCO2e/kWh,

n is the number of years,

m is the weight of the unit in kg,

MM are the material manufacturing emissions in kgCO$_2$e/kg,

m_c is the weight of component in tonne,

d is the distance to manufacturing plant in km,

FCI is the Freight Carbon Intensity per tonne.km,

M is the weight of the unit in tonne,

D is the distance to the end user form manufacturing facility in km,

m_r is the weight of the recycled material in kg,

MR are the material recycling emissions in kgCO$_2$e/kWh,

RFM are the refrigerant manufacturing emissions in kgCO$_2$e/kg, and

RFD are the refrigerant disposal emissions in kgCO$_2$e/kg.

DIRECT EMISSIONS

Equation 2 can be divided into two components which comprise the direct emissions. As shown below:

- The first component **I** deals with the emissions as a result of the leakage of the refrigerant over its lifetime, while,
- The second **II** indicates the emissions as a result of the refrigerant which cannot be recovered or would be disposed at the end of life.

$$Direct\ emissions = C \cdot (\underbrace{L \cdot ALR} + \underbrace{EOL}) \cdot (GWP + Adp.GWP)$$

I II

An annual leakage rate (ALR) of 5% was chosen for both, the R744 CVP and the R410A CVP based on [2]. However, a separate analysis with an ALR of 2% was also performed as the product specifies enhanced tightness and thus a lower leakage rate, results of which are shown in the appendix. 85% of the total refrigerant charge was assumed to be recovered during the disposal of the unit, thus, leaving only 15% of the charge (EOL) to emit to the environment [3].

An important parameter in the calculation of these emissions and for the comparison between the two refrigerants is the Global Warming Potential (GWP). While the GWP of CO_2 is 1kgCO_2e/kg, meaning that the GWP of every refrigerant is indexed to that of CO_2, this value for R410A is 2088 kgCO_2e/kg [4]. Adp.GWP is the GWP of atmospheric degradation product of the refrigerant and is assumed to be 0 for the two refrigerants considered. The charge (C), was considered to be 20 kg for the R410A CVP and 43 kg for the R744 CVP, which are the average installation charges for the respective units for same capacities.

INDIRECT EMISSIONS

The environmental impact as a result of the indirect emissions from the units were based on three different components as shown in equation 3:

I. Annual energy consumption

II. Material manufacturing

III. Transport emissions

$$Indirect\ emissions = \underbrace{\sum_{n=2021}^{2030} AEC \cdot EM_n}_{I} + \underbrace{\sum m \cdot MM}_{II} + \underbrace{\sum m_c \cdot d \cdot FCI + M \cdot D \cdot FCI}_{III} \tag{3}$$

I. Annual energy consumption

The emissions of the unit occurring indirectly as a result of the unit's annual energy consumption were calculated as described in this section. The annual energy consumption was calculated for the same refrigeration, space heating and cooling loads for both Conveni-Packs based on ambient temperature bins as prescribed in the standards for refrigeration [5] and for space cooling and heating [6] and similar design capacities. Based on the corresponding Coefficient of Performance (COP) for both units, the respective annual energy consumption was calculated. As the loads for both, the CO_2 and R410A Conveni-Packs, are the same, the properties of the refrigerants leading to a difference in performance result in a different annual energy consumption of the units. In order to evaluate the overall CO_2-equivalent emissions from the annual energy consumption, the greenhouse gas emission intensity was used. The greenhouse gas emission intensity factor indicates the amount of equivalent CO_2 emissions produced per unit of electricity generated in $kgCO_2e/kWh$. The chart below is a projection of an EU-27 average greenhouse emission intensity over a period of 30 years, since it is aimed to reach carbon neutrality by 2050, [7]. The lifetime of the unit has been marked in blue and projections beyond this year in red. The extension until 2050 provides a linear projection for the lifetime of the unit and beyond.

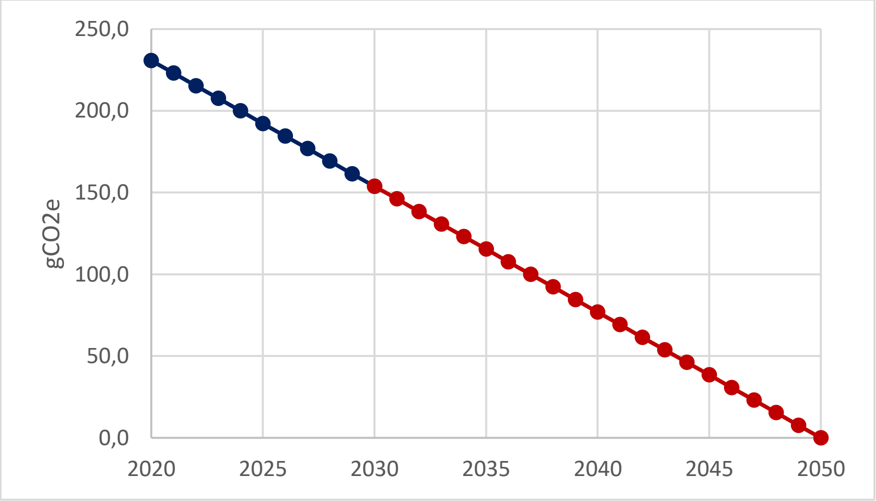

Figure 1: Greenhouse gas emission intensity EU-27, based on [7]

II. Material manufacturing

The impact as a result of the materials used in manufacturing the unit was evaluated based on the weight of all the components used in each sub-assembly of the unit. The weight of each component was calculated as a product of the volume of the component, based on its dimensions, and the density of the material of the component. The list of the components and the dimensions were derived from the Bill of Materials (BOM) of the concerned product. The materials composing the entire structure and their corresponding densities were considered as follows: the CO_2 equivalent emissions per unit weight of the material used were calculated using the MEErP values, indicating the climate impact of each material used, as shown in Table 1 [8]

Table 1: Density and manufacturing emissions of materials

MATERIAL	DENSITY [kg/m^3]	EMISSIONS [kgCO_2e/kg]
Steel (sheet/tube)	7800	2,8/1,4
Copper (Cu) [Wire/Tube]	8900	6,2/2,7
Aluminum (Al)	2700	10
Iron (Fe)	7800	4,2
Plastic [ABS/PVC]	1052	3,3/2,7
Wood	500	3,3
Sealing	1500	2,7
Vinyl	385	2,2
Cardboard	155	0,7

For the CO_2 Conveni-Pack (CVP), a total weight of 765 kg. was used and for the R410A Conveni-Pack, 393 kg. was considered. The sub-assemblies into which the total weight of the units was divided included the various components of the unit along with the packaging.

III. Transport emissions

This section deals with the emissions as a result of transporting the components required to assemble the unit at the factory and the emissions concerning the transport of the packaged unit to the end user. To evaluate the impact of the transportation of components and materials to the manufacturing site, information concerning the location of the source producer of each component was obtained. Based on the accessibility to the manufacturing site in Ostend, Belgium from the source, the resultant tonne-kilometers (tonne-km) for each component were calculated. The product of the tonne-km and the emission factor depending on the mode of transport resulted in the total CO_2 emissions from the transportation of each component. The carbon intensity per tonne-km for each mode of transport was assumed as follows:

Table 2: Freight emission intensity [3]

MODE OF TRANSPORT	CO_2 EMISSIONS [gCO_2/tonne-km]
Airplane	602
Ship	8
Train	22
Truck	62

For the transportation of the unit to the end user, the location assumed for the end user was Germany and the mode of transport considered was road freight by truck. Based on the total packed weight of the unit and a distance of 500 kms., the total emissions were calculated using the product of the tonne-km and the carbon intensity of truck transport as shown in Table 2.

EMBODIED EMISSIONS

These emissions are not considered to impact the climate directly, but are inherent in the process of product production and disposal. The two components comprising these emissions are as shown in equation 4. The component in equation 4 representing the refrigerant disposal emissions has been omitted due to a lack of explanation and description of the factors involved in calculating it in the referred literature. Additionally, the impact of disposal methods such as incineration was reviewed and considered to be negligible.

$$Embodied\ emissions = \underbrace{\sum m_r \cdot MR}_{\text{I}} + \underbrace{C \cdot (1 + L \cdot ALR) \cdot RFM}_{\text{II}} \qquad (4)$$

I. Material recycling

II. Refrigerant manufacturing

I. Material recycling

The emissions concerned with the production of the recycled material used to manufacture the unit were calculated using the weight of each material in the unit and the specific material recycling emissions as shown in the table below. Emissions corresponding to recycling metals and plastics were considered.

Table 3: Material recycling emissions

Material	CO_2 EMISSIONS [$kgCO_2e/kg$]
Metals	0,07
Plastics	0,01

NOTE: The data is based on [2]

II. Refrigerant manufacturing

This section deals with the emissions as a result of producing the two refrigerants used in the units, i.e. R744 and R410A. These emissions depend upon the charge of the refrigerant, the annual leakage rate, lifetime and the specific refrigerant manufacturing emissions. The factor given below also includes the energy consumed in recovering the refrigerant. The manufacturing emissions used were as follows:

Table 4: Refrigerant manufacturing emissions

Refrigerant	CO_2 EMISSIONS [$kgCO_2e/kg$]
R744	0,97
R410A	10,7

NOTE: The data is based on [2] and [9]

RESULTS

Based on the above mentioned description of the methodology, the following results were obtained for both the R744 and R410A CVP's.

The below chart provides an overview of the contribution of the various components comprising the LCCP analysis. For both the units, it can be observed that the indirect emissions due to energy consumption comprise the largest portion of the distribution. For the CO_2 CVP, they comprise 96% of the total emissions while for the R410A equivalent unit the share is about 66%. For the unit with fluorinated refrigerant, the direct emissions contribute significantly as a result of refrigerant leakage during its lifetime and at disposal. This is negligible for the CO_2 unit. The remaining share of emissions are accounted for by the materials used in the unit and negligible embodied emissions. To further elaborate on the impact of the choice of the refrigerant on the climate performance, the absolute emissions from the analysis are shown in Figure 4 based on the category. It's interesting to note that although the unit with fluorinated refrigerant is more efficient than the CO_2 refrigerant unit due to the lower annual energy consumption and having lower indirect material emissions, the total emissions from the R410A unit are significantly higher. This can be attributed to the significantly higher direct emissions as a result of the large difference in the GWP values between the two refrigerants.

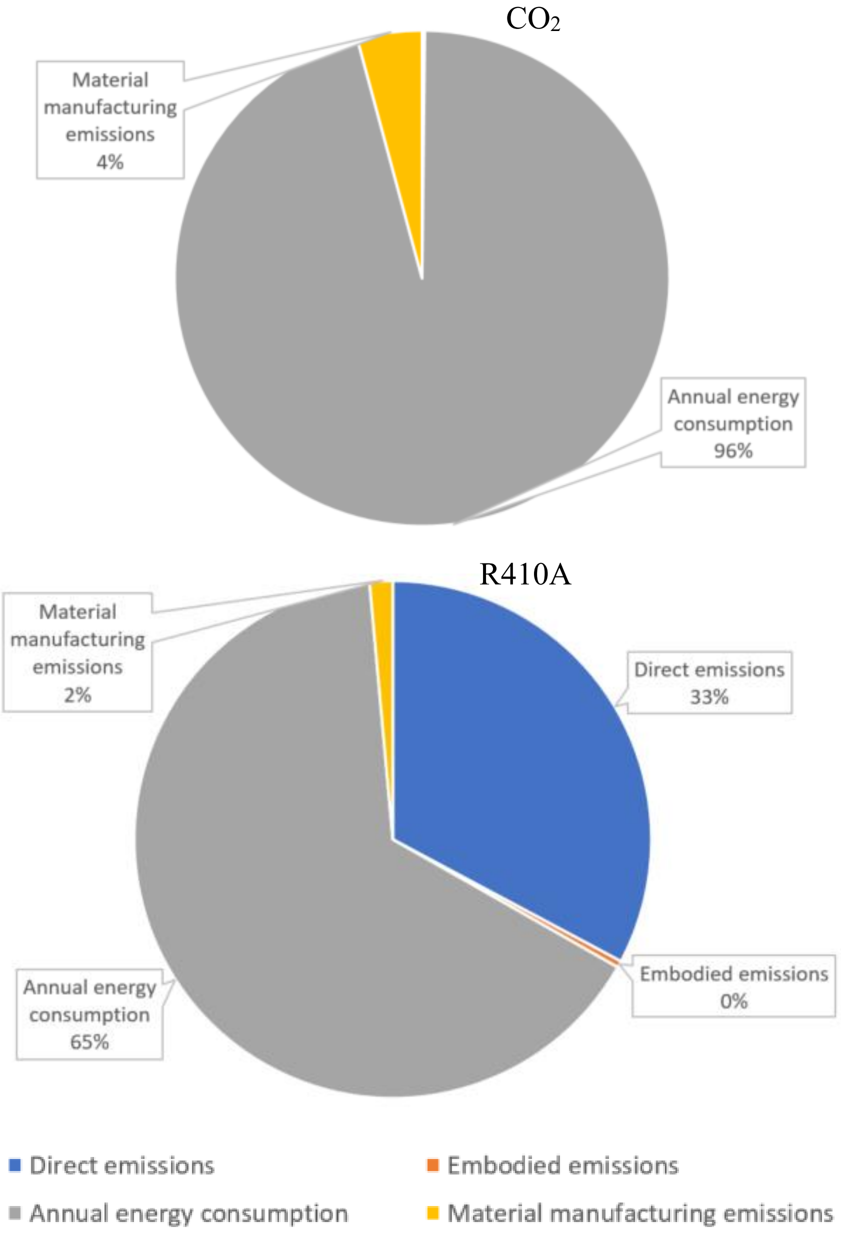

Figure 2: Lifecycle emission distribution for CO_2 CVP [Above] and R410A CVP [Below]

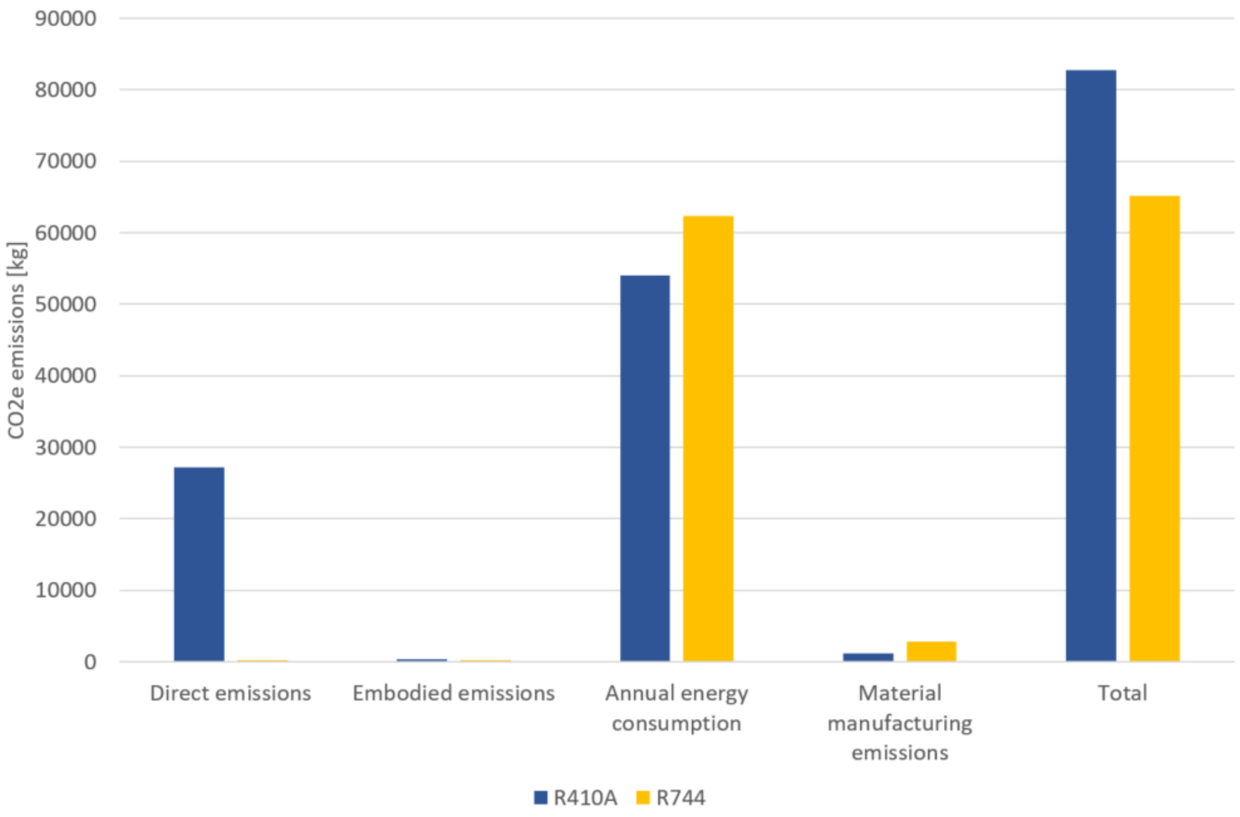

Figure 3: Total lifecycle CO_2e emissions

DIRECT EMISSIONS

This section describes the distribution of the direct emissions between annual leakage and end of life leakage. As seen above, the annual leakage emissions were considered to occur every year based on an assumed annual leakage rate and one-time-only end of life emission, during the disposal of the unit. The following graph shows the weight of each component for both refrigerants. As visible, the recurring emissions due to the annual leakage of the refrigerant greatly outweigh the one-time emissions occurring at the end of the tenure of the units. Although the absolute emissions between the two refrigerants are vastly different as shown in Figure 4 as a result of the difference in GWP values, they share a similar distribution between the components. Thus, this proportion can be regarded independent of the type of refrigerant used, and a function of the lifetime, the annual leakage rate and the end of life emissions.

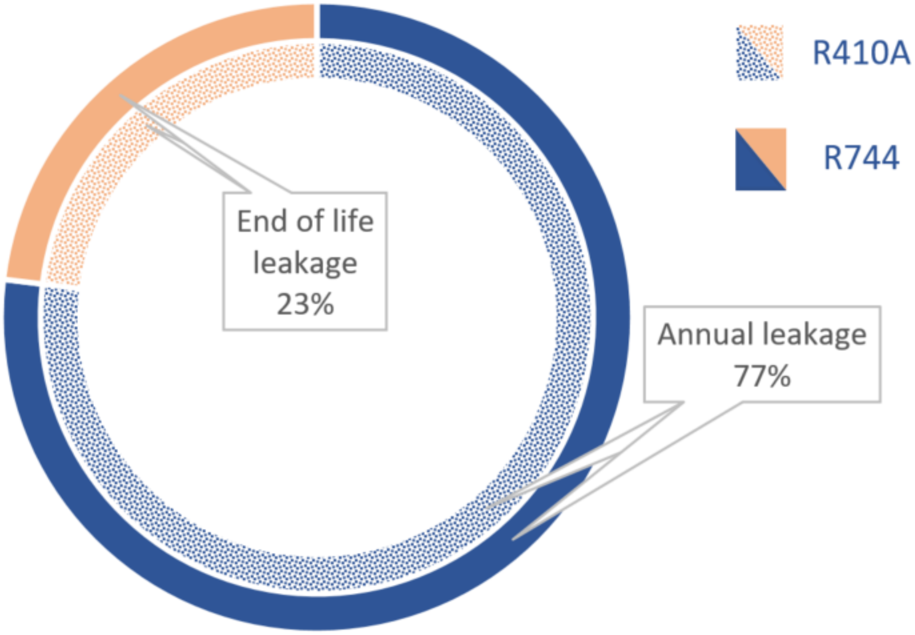

Figure 4: Direct emissions distribution

INDIRECT EMISSIONS

Energy consumption emissions

As seen in the overview of the lifecycle emissions, the indirect emissions were responsible for the highest contribution to the lifecycle emissions for both units. These emissions, as mentioned previously, are primarily due to the annual energy consumption of the units. The annual energy consumption of the R410A unit was found to be 13% lower as compared to the R744 unit. As explained in the section above, the emissions as a result of the energy consumption are a function of the greenhouse gas emission intensity. With the EU target of reaching carbon neutrality by 2050, it was assumed that the carbon intensity for electricity generation would be 0 gCO_2e/kWh in the Member states of EC. With the help of the projection discussed in the previous section, the lifecycle emissions for both units were calculated based on an installation in 2022 and one in 2030. It can be seen that although the difference between the two is similar even in 2030, the impact of the indirect energy emissions would have reduced significantly due to the decarbonization effect. The direct emissions however are not affected and will remain the same even with completely decarbonized power generation. It can also be implied from the graph that with reduced indirect emissions and assuming no technological developments, the R410A CVP would take nearly 8 years to reach the current emission levels of the CO_2 CVP unit. Eventually, by 2050, only the effect of the refrigerant and the materials can be expected to contribute to these emissions. Thus, from this analysis it can be observed that even though the current situation presents the indirect emissions to be the dominant contributor to the lifecycle emissions, with diminishing greenhouse gas emissions, the effect of the refrigerant due to charging, leakage and disposal will remain as the sole and vital influencer on the lifecycle climate performance of units using refrigerants.

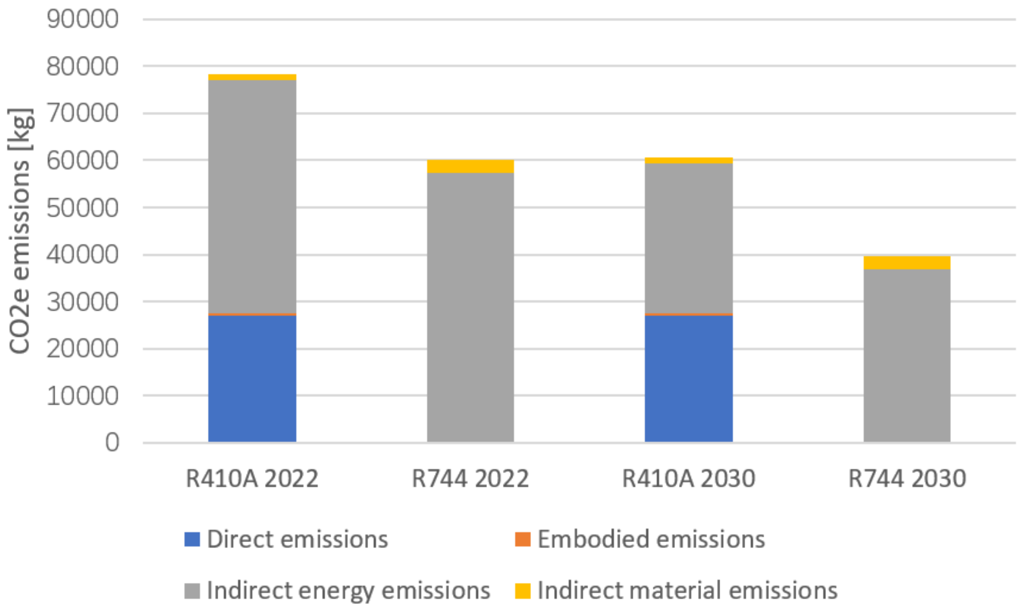

Figure 5: Total LCCP for CVP units installed in 2022 vs. 2030

Material and transport emissions

The contribution of the raw materials to the climate impact, as mentioned in the description, has been divided into three categories; components and materials, refrigerant and logistics. The chart below shows the emissions for each category. It was considered important to present the results regarding this section per category since this helps in understanding the major contributors to the emissions in the raw materials. Although it is clear that the total emissions are significantly greater for the fluorinated refrigerant unit, the emissions on a component and material level for this unit are actually lower compared to the CO_2 unit, Figure 6. This was expected as the overall weight and size of the R410A CVP is lower than that of the CO_2 CVP counterpart. Since the number and overall weight of components is greater, the overall emissions due to the transportation and logistics are also higher for the CO_2 unit. On a material level, it can be observed from Table 5, that metals such as steel, copper and aluminum contribute largely to the indirect material emissions for both units. Considering the larger size and weight of the CO2 unit, considerably higher amounts of metals are used.

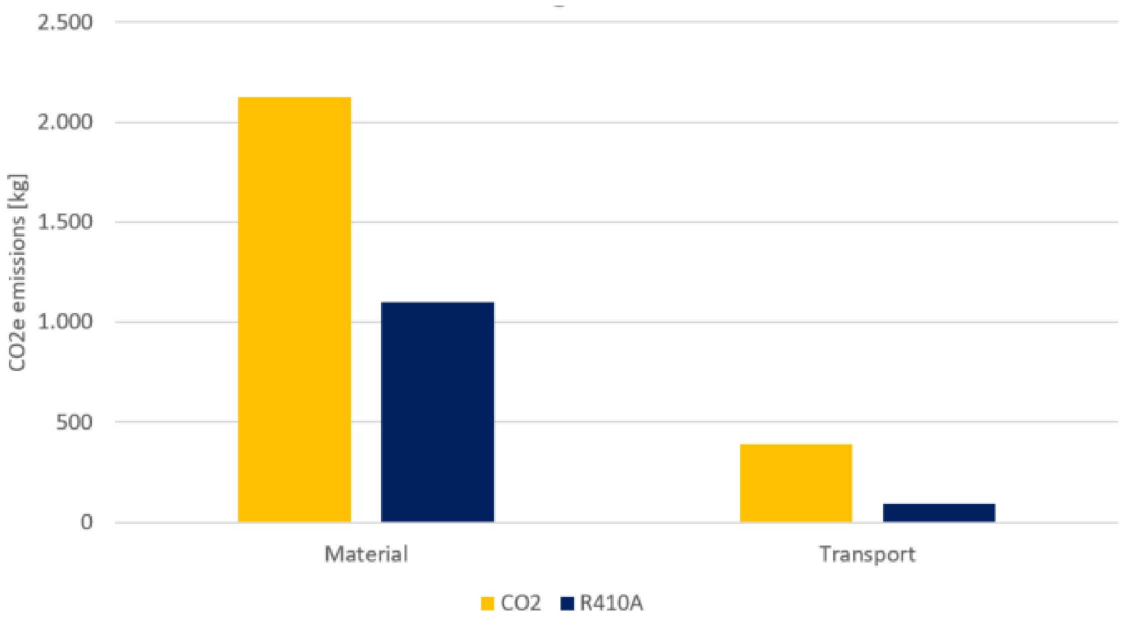

Figure 6: Indirect emissions from materials and logistics

Table 5: Indirect material emissions

Material	Weight [kg]		Emissions [kgCO_2e]	
	R744	R410A	R744	R410A
Oil	14,1	5,9	42,4	17,7
Steel	473	209,8	1070	456,3
Iron (Fe)	17,8	10,4	19,5	43,3
Copper (Cu)	148	52,3	400,3	141,6
Aluminum (Al)	44,1	25,7	441,2	257
Plastic	8,1	4,6	26,7	75
Wood	26,9	15,5	88,8	51,2
Sealing	0,1	1,1	0,4	2,2
Vinyl	13	13,7	26,1	30
Cardboard	26	11	9,3	5,3

EMBODIED EMISSIONS

As seen in the overview of the lifecycle emissions, the embodied emissions play a negligible role in the total climate impact of both systems. As described previously, for the recycling emissions, the weight of the materials were aggregated into either plastics or metals and the corresponding emission factor was applied, Table 6. The emissions for the production of refrigerants were calculated based on the refrigerant charge and the respective emission factor, Table 7.

Table 6: Material recycling emissions

Material	Emissions [kgCO_2e]	
	R410A	R744
Metals	22,9	52,5
Plastics	0,2	0,09

Table 7: Refrigerant producing emissions

Refrigerant	Emissions [kgCO_2e]
R410A	321
R744	44

SENSITIVITY ANALYSIS

Effect of leakage rate

As seen in the previous sections, the effect of the refrigerant has the most significant impact on the overall emissions of the unit. As discussed, these calculations have been performed with assumed values for certain parameters related to the refrigerants, which can be expected to have effect on the result. In this section, the impact of the annual leakage rate will be investigated on the lifecycle climate performance. For the previous calculations, a leakage rate of 5 % was chosen. For the purposes of the current chapter analysis, the leakage rate was varied by ±2%. In the chart below, the difference observed from varying the leakage rate is expressed in percentages from the base case of 5 % leakage rate for the R410A unit. The effect of the annual leakage rate was found to be negligible in the LCCP outcome for the CO_2 CVP. Therefore, only the results concerning the R410A unit are discussed. While the difference in percentage can be observed on the X-axis, the Y axis represents the three cases for the leakage rates; i.e. base of 5%, +2% and -2%.

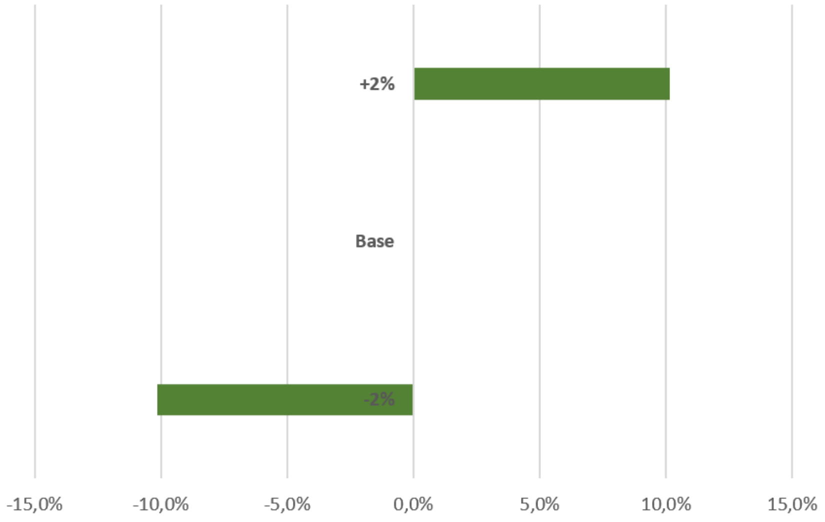

Figure 7: Sensitivity analysis of leakage rate for R410A CVP

Increasing the leakage rate, as expected, resulted in overall higher lifecycle emissions by 10% compared to the base case due to the increased direct emissions and refrigerant manufacturing emissions. Lowering the leakage rate, on the other hand, resulted in 10% overall lower lifecycle emissions compared to the base case.

Also an interesting conclusion from varying the annual leakage rate was that, for the same end of life leakage rate as for the base case, an annual leakage rate below 0,8% (the break-even point) would lead to lower lifecycle emissions for the R410A unit compared to the CO_2 CVP.

Effect of end of life leakage

The end of life leakage rate was considered to be 15% for the base case scenario. The impact of varying this rate by ±10% was investigated on the overall climate performance. Similar to the above analysis concerning the leakage rate, a negligible difference was observed in the overall emissions of the CO_2 CVP. As can be seen from Figure 8, decreasing the leakage during disposal or increasing the end of life recovery rate by 10 % causes a decrease in the lifecycle emissions by about 5% or increase by 5% respectively. It was seen that even recovering 100% of the fluorinated refrigerant at the end of life (0% leakage during disposal) would still result in higher lifecycle emissions compared to the non-fluorinated refrigerant solution.

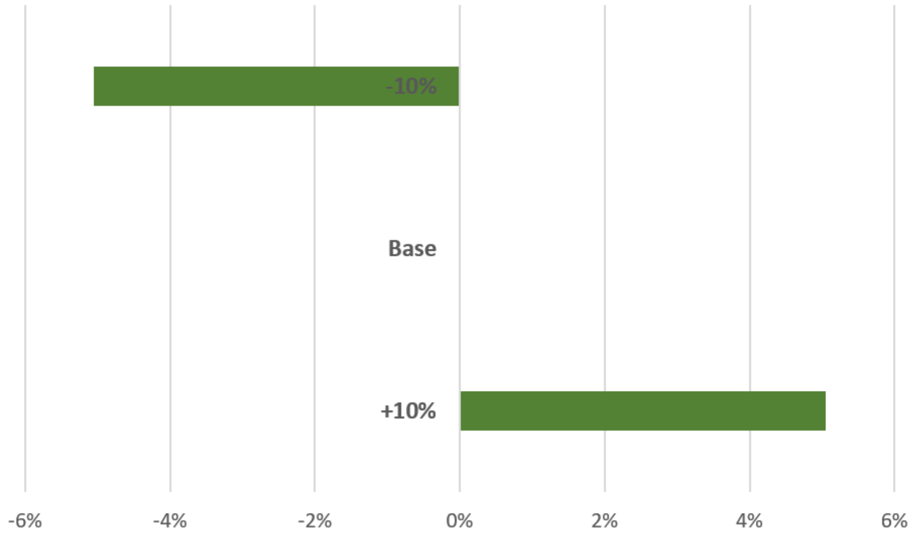

Figure 8: Sensitivity analysis of recovery rate for R410A CVP

CONCLUSIONS

Through a theoretical study and comparison of the lifecycle climate performance of the CO_2 and R410A Conveni-Pack units, it was observed that the CO_2 unit had a 21% better lifecycle performance compared to the fluorinated refrigerant unit over a period of 10 years, in other words, the CO2 CVP had 21% lower lifecycle emissions. Although the HFC unit is smaller in size and lighter than its CO2 counterpart and was observed to have a better annual performance, the effect of the refrigerant as a result of its GWP was found to greatly outweigh these benefits. While 96% of the emissions from the CO2 unit were due to indirect emissions as a result of energy consumption, the proportion of this for the R410A unit was about 65% due to a large contribution of the direct emissions. The direct emissions were found to be largely due to the annual leakage of the refrigerant than the leakage during disposal of the unit. For both units, materials such as steel, copper and aluminium were found to be the major contributors to the indirect emissions as a result of materials. Although the indirect emissions from the annual energy consumption of the CO2 unit under the current situation were found to be greater, the diminishing greenhouse gas emission intensity and negligible emissions through leakage can be expected to make the CO2 CVP more favourable in the future. Through a sensitivity analysis on the annual refrigerant leakage rate and disposal leakage rate, it was observed that a combination of a low annual leakage rate, less than about 0,8% and a high recovery rate are necessary for the HFC unit to have a more favourable LCCP than the CO2 unit.

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APPENDIX A

Results with an annual leakage rate of 2%

Overview

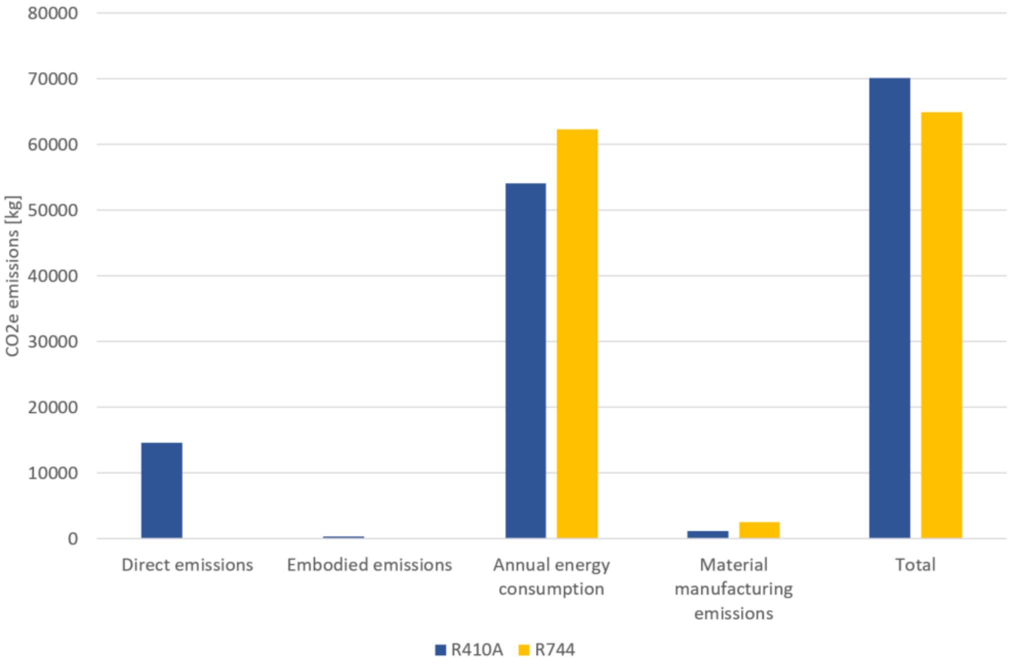
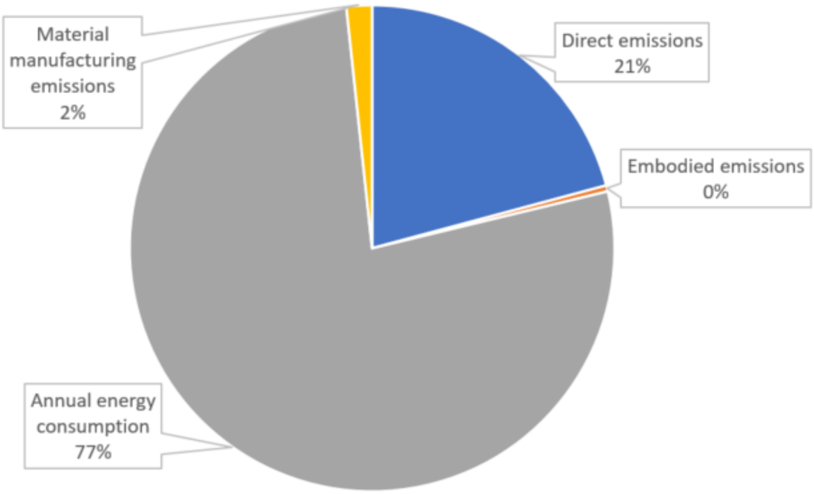


Figure A.1: Overview with 2% ALR

Distribution



FigureA.2: Distribution of LCCP of R410A CVP with 2% ALR

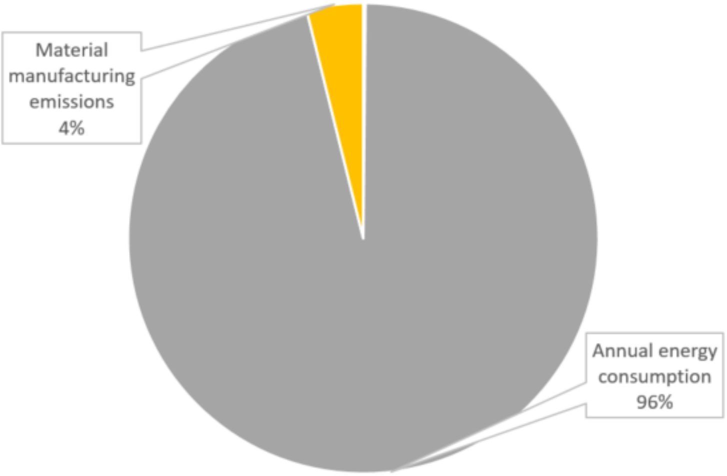


Figure A.3: Distribution of LCCP of R744 CVP with 2% ALR