Honeywell

PFAS REACH Annex XV Restriction Report

1ST Public Consultation (22 March – 25 September 2023)

<u>Commercial Refrigeration, Air conditioning and Heat pumps sub-uses of fluorinated refrigerants – request for exclusion or time unlimited derogation from the PFAS REACH Restriction Proposal</u>

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Executive Summary

Honeywell International Inc. (hereinafter - **Honeywell**)[1] is a global manufacturer and importer of various fluorinated gases to the European Union (**EU**), including hydrofluorocarbons (**HFC**) and hydrofluoroolefins (**HFO**) refrigerants and their mixtures (**blends**), primarily used in commercial, industrial as well as domestic refrigeration, heating, ventilation and air conditioning (**RHVAC** or **HVAC**, including heat pumps) applications.

On 13 January 2023, the competent authorities of five EEA member states (**Dossier Submitters**) submitted to the European Chemical Agency (**ECHA**) the *PFAS REACH[2] Annex XV Restriction Report* (**Proposal**).[3] Honeywell submits the following information, comments and proposals to the ECHA 1st public consultation on the Proposal.

Contrary to what the Dossier Submitters claim, there are a range of PFAS substances, including various fluorinated gases, that are not very persistent (vP) as such and do not degrade to vP substances in meaningful amounts. For instance, the gases HFC-125, HFC-143a, HFC-245fa, HFO-1234ze(E), HFO-1233zd(E), HFO-1336mzz(E), HFO-1336mzz(Z), HCFO-1233zd(E) degrade in the atmosphere to carbon dioxide (CO_2), Hydrogen fluoride (HF) and insignificant amounts of the only PFAS arrowhead substance - trifluoroacetic acid (**TFA**).[4] Also comprehensive conclusive scientific evidence, including from respective REACH registration dossiers, confirms that many PFAS (comprising, HFC/HFO) are low hazard gaseous substances that do not exhibit risks similar to PBT/vPvB substances under Article XIII REACH. Thus, they should be excluded from the scope of the Proposal.

According to the REACH registration dossier and Chemical Safety Report (CSR) for TFA[5], although the substance fulfils certain criteria for persistency, it has scientifically established DNEL/PNEC thresholds and is not classified as PBT or vPvB substance under Annex XIII REACH. It does not raise equivalent levels of concern under Article 57(f) REACH.[6] In this respect, ECHA already reviewed and evaluated a TFA dossier without concluding on the need for further regulatory actions.[7]

Moreover, according to the most recent 2022 UNEP/WMO report: *"TFA abundance and its environmental impacts have been assessed in many previous Assessments (e.g., Montzka, Reimann et al., 2011; Montzka, Velders et al., 2018; Carpenter, Daniel et al., 2018). Previous Assessments concluded that the environmental effects of TFA due to the breakdown of HCFCs and HFCs are too small to be a risk to the environment over the next few decades based on the projected future use of hydrocarbons, HCFCs, and HFOs."*[8]

The most recent EEAP 2022 Assessment Report also concludes that *"based on projected future use of these precursors of TFA [incl. HFC/HFO], no harm is anticipated"* and that TFA *"is unlikely to cause adverse effects out to 2100"*.[9]

Detailed analysis on HFC/HFO degradation products and relevant hazard, exposure and risks assessments of TFA is provided in the Honeywell submission reference no: 76bb3d12-2101-4390-82cf-3498b47e8015.

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1 See the list of acronyms and abbreviations (aligned with the Proposal) in **Annex I** below.

2 *Regulation (EC) No 1907/2006 of the European Parliament and of the Council of 18 December 2006 concerning the Registration, Evaluation, Authorisation and Restriction of Chemicals (REACH), establishing a European Chemicals Agency, amending Directive 1999/45/EC and repealing Council Regulation (EEC) No 793/93 and Commission Regulation (EC) No 1488/94 as well as Council Directive 76/769/EEC and Commission Directives 91/155/EEC, 93/67/EEC, 93/105/EC and 2000/21/EC* (**REACH** or **REACH Regulation**).

3 On 22 March 2023, ECHA published the *PFAS REACH Annex XV Restriction Report* in the Registry of restriction intentions until outcome and started the 1st *Annex XV report consultation* with a final deadline for comments on 25 September 2023.

4 TFA yields rates (molar), see section 3.8, Fig. 12 and pages 314-319 of the *Environmental Effects of Stratospheric Ozone Depletion, UV Radiation, and Interactions with Climate Change*, EEAP 2022 Assessment Report; Please also see detailed EFCTC position paper Published evidence supports very low yield of TFA from most HFOs and HCFOs.

5 Trifluoroacetic acid, EC number: 200-929-3, CAS number: 76-05-1

6 See e.g. *Mammalian toxicity of trifluoroacetate and assessment of human health risks due to environmental exposure*, Wolfgang Dekant, Raphael Dekant, 17 February 2023

7 E.g., in 2017-2021, ECHA concluded comprehensive dossier evaluation of Trifluoroacetic acid, without indications of the need for further actions.

8 Page 137,*Scientific Assessment of Ozone Depletion: 2022*, GAW Report No. 278, 509 pp.; WMO, 2022.

9 See pages 25 and 259 of the EEAP 2022 Assessment Report.

In addition, many HFC/HFO gases are already comprehensively/adequately regulated in EU and beyond, including via effective Risks Management Measures (RMMs) under the *EU F-Gas Regulation*[10], *MAC Directive*[11] (**F-Gas Regulation**), ELV Directive[12], Industrial Emissions Directive[13] and other legislation. These laws mandate *inter alia* progressive limitations on placing on the market (e.g., HFC (F-Gas) quotas and certain equipment bans), comprehensive containment measures (leaks controls, servicing certification for HFC/HFO in RHVAC), product (eco-)design and safe use standards (e.g., *ISO 5149-1:2014, EN 378,* disposal and end-of-life requirements (e.g., recuperation and re-use of F-gases)). These regulations could be strengthened at any time, if warranted.

Therefore, even those HFC/HFO gases that degrade to TFA in substantial rates, such as HFO-1234yf, HFC-134a or HFC-227ea, should be excluded from the PFAS restriction scope due to the absence of unacceptable or not adequately controlled risks within the meaning of Articles 68 - 69 REACH.

Furthermore, contrary to the requirements of *Part II, Section 3 of Annex XV REACH Regulation*, the Proposal is missing an objective, credible and specific enough assessment of *"information on the risks to human health and the environment related to the manufacture or use of the alternatives"*[14] as well as on consistency of these alternatives with wider-EU decarbonization and sustainability policies (including, European Green Deal, Fit for 55, REPowerEU, etc.). These assessments are particularly important as far as certain key RHVAC uses of HFC/HFO are concerned.

In this respect, the "*careful and impartial"* assessment of all available information, including submitted by stakeholders during two Calls for Evidence (CfE) preceding the Proposal,[15] unequivocally demonstrates the scarcity of safe and sustainable alternatives for many uses of HFC/HFO fluorinated gases including in commercial, industrial, and domestic RHVAC applications. Bans on such uses as suggested in the Proposal will result in very high costs on the society and the environment (climate change) and will be contrary to wider-EU policies as well as principles of the EU law.

In this respect, alternative refrigerants referred in the Proposal (often misleadingly called "natural refrigerants"), including CO2 (R-744), ammonia (R-717) and certain hydrocarbons (e.g., propane (R-290), isobutane (R-600a)) are suggested by the Dossier Submitters without adequate assessments of corresponding safety risks such as flammability, toxicity, very high operating pressures, etc. In the meantime, objective assessments of their intrinsic properties and reported incidents (Annexes II-IV) involving those refrigerants demonstrate (see section 3 below) that respective risks are considerably higher, and often cannot be adequately controlled, than from *"fourth generation"* HFC/HFO refrigerants specifically designed for these respective uses.

Moreover, two comprehensive studies in Appendixes 1 and 2 below, demonstrate that in case of substitutions proposed by Dossier Submitters for RHVAC sector the electricity consumption and respective GHG emissions will result to additional annual 6.9 TWhr/yr of demand and 2.7 MTonne/yr of CO2eq GHG emissions, and will incur additional electricity cost of 1-3.4 Billion €/yr for ~44% of the overall EU air conditioning and heat pumps (AC/HVAC) sector. The proposed substitutions will also add 5.7 TWhr/yr to annual demand on the electricity grid, 2.4 MTonne/yr of CO2eq emissions and additional electricity costs of 0.8-3 Billion €/yr in ~64% of the total commercial refrigeration sector. These costs, combined with potential losses or damages from potential incidents (see above) are too high and disproportionate in comparison with alleged concerns due to persistency of the TFA substance, which is negligible and we have demonstrated in our submission to ECHA with reference. This approach to alternatives is also against wider EU policies on climate change, decarbonization and sustainable energy. It will also add, as we state above 1-3.4 Billion €/yr for ~44% of the overall EU air conditioning and heat pumps (AC/HVAC) sector.

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[10] *Regulation (EU) No 517/2014 of the European Parliament and of the Council of 16 April 2014 on fluorinated greenhouse gases and repealing Regulation (EC) No 842/2006* (as amended and currently under review, available here).

[11] *Directive 2006/40/EC of the European Parliament and of the Council of 17 May 2006 relating to emissions from air conditioning systems in motor vehicles and amending Council Directive 70/156/EEC* (as amended).

[12] *Directive 2000/53/EC of the European Parliament and of the Council of 18 September 2000 on end-of life vehicles (as amended)*

[13] Directive 2010/75/EU of the European Parliament and of the Council of 24 November 2010 on industrial emissions (integrated pollution prevention and control) (Recast)

[14] Appendix E.2 contains only basic general information on alternative substances (e.g., CAS number, harmonised CLP classification and similar).

[15] 2 Stakeholder Consultation on a Restriction for PFAS - August-October 2021.

Considering all available information, Honeywell submits that the following HFC/HFO fluorinated refrigerants: HFC-125, HFC-143a, HFO-1234ze(E), HCFO-1233zd(E), HFO-1336mzz(E), HFO-1336mzz(Z), HFC-245fa, HFC-365mfc, HFO-1234yf, HFC-134a, HFC-227ea, HFC-236fa, should be excluded from the scope of restriction or their uses in commercial RHVAC/HVAC applications should be subject to time unlimited derogations in line with the provisions of Articles 68 and 69 REACH.

In line with previous practices this exclusion or derogation should also cover maintenance or repair, refitting and reselling activities involving second hand RHVAC systems already placed on the market or installed.

1. Introduction

Refrigerants in use today for the refrigeration, air conditioning and heat pumps (RHVAC) applications include hydrofluorocarbons (HFC) substances and blends such as HFC-410a (R410A), HFC-404a (R404A), HFC-407C(R407C) and HFC-134a (R134a). These refrigerants with high Global Warming Potential (GWP) have significant impact on the environment from the global climate/warming perspective.[16] According to Kyoto Protocol, HFC are regulated as strong greenhouse gases (GHG). As per the Kigali Amendment to the Montreal Protocol, developed countries should reduce HFC consumption to 80% of their baseline by 2045. In EU, the F-gas regulation (*EU F-Gas Regulation*) aims to phase down HFC substances on the basis of their high GWP. In 2020, the United States Environmental Protection Agency (EPA), invoked similar legislation to phase down production and consumption of HFCs to 15% of the baseline levels by 2036.

Consequently, the industry opted to evaluate and commercially develop several lower-GWP replacements. This resulted in specifically engineered *"fourth-generation"* of unsaturated organic compounds composed of hydrogen, fluorine and carbon - hydrofluorolefins (HFO). Nowadays, pure HFO and their blends with HFC[17] are the most prominent (ultra-)low-GWP alternatives to high-GWP HFC also owing to zero Ozone Depletion Potential (ODP) and favorable thermophysical properties.[18]

Hydrocarbons such as propane (R290) are also being evaluated as possible substitutes for HFC. However, their applications in RHVAC (particularly in large commercial systems) are limited due to the flammability concerns.[19] Carbon-dioxide (CO_2 or R744) refrigerant liquid is also being intensively evaluated; however, it has significantly lower energy efficiency especially in warm to hot climate conditions and requires much more advanced technology to meet the current HFC/HFO baseline energy efficiency standards.[20] Another potential alternative often labelled as a "natural refrigerant" – is ammonia (NH_3 or R717) – and it is a byproduct of energy-intensive industrial processing of hydrocarbons characterized by very high GHG emissions (fertilizers, etc.). While ammonia may have favorable thermodynamics, it is highly toxic for humans/animals and therefore cannot be used in large loads closer to public places. There is a substantial number of grave/deadly incidents involving these *"natural refrigerants"* worldwide (see **Annexes II and IV** below).

In this respect, the "*fourth-generation"* refrigerants and refrigerant blends containing HFC/HFO such as HFC-125, HFC-143a, HFO-1234ze(E), HCFO-1233zd(E), HFO-1336mzz(E), HFO-1336mzz(Z), HFC-245fa, HFC-365mfc, HFO-1234yf, HFC-134a, HFC-227ea, HFC-236fa and their blends such as R448A, R449A-C, R454A-C, R455A, R450a, R513A, R515A-B, R456A, R471A, R474A, R476A, R479A, R482A, are specifically designed to be safer, more energy efficient and environmentally friendly solutions for the RHVAC industry. Risks of their uses in closed RHVAC systems cannot be considered unacceptable and are already adequately controlled via other risk management measures (RRMs) within the meaning of Articles 68-69 of the REACH Regulation (see section 2 below).

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[16] *Overview of low GWP mixtures for the replacement of HFC refrigerants: R134a, R404A and R410AÉtude des mélanges à faible PRP pour le remplacement des frigorigénes HFC R134a, R404A et R410A*, Y. Heredia-Aricapa a, J.M. Belman-Flores a, A. Mota-Babiloni b, J. Serrano-Arellano c, Juan J. García-Pabón, March 2020.

[17] On existing refrigerants and their blends se the *List of refrigerants*.

[18] *Performance Evaluation Of R471A In Refriger aluation Of R471A In Refrigerated Displa ated Display Cabinet y Cabinet And Walk-In-Coole*r, Kaimi Gao, Nilesh Purohit, Elizabet Vera Becerra, Ronald Vogl , Ankit Sethi, 2022.

[19] *Natural and synthetic refrigerants, global warming: A review*, Naeem Abas, Ali Raza Kalair, Nasrullah Khan, Aun Haider, Zahid Saleem, Muhammad Shoaib Saleem, July 2018.

[20] *Integrated supermarket refrigeration for very high ambient temperature*, Nilesh Purohit, Vishaldeep Sharma, Samer Sawalha, Brian Fricke, Rodrigo Llopis, Mani Sankar Dasgupta, December 2015; *Overview of low GWP mixtures for the replacement of HFC refrigerants: R134a, R404A and R410AÉtude des mélanges à faible PRP pour le remplacement des frigorigénes HFC R134a, R404A et R410A*, Y. Heredia-Aricapa a, J.M. Belman-Flores a, A. Mota-Babiloni b, J. Serrano-Arellano c, Juan J. García-Pabón, March 2020.

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Therefore, REACH restrictions on the above HFC/HFO substances envisaged in the Proposal are not legally justified and will result in disproportionately high costs (economic, safety, energy and environmental) for society. It is particularly evident as far as decarbonization (GHG emissions) and energy consumption or efficiency goals of wider-EU policies are concerned, as demonstrated below.

In this regard, Study 1 in Appendix 1 below holistically compares the scenario of complete replacement of installed *Commercial Refrigeration* stores in European Region to the HFC/HFO based refrigerant solution (R455A or R471A)[21] or to the "natural refrigerants" solution using industrial fluids like CO_2 and R290 (propane). Use of ammonia refrigerants in such public places is very risky due to its high toxicity. Total GHG emissions in terms of equivalent CO_2 emissions (CO_2eq) and overall cost of electricity to operate the *Commercial Refrigeration* systems is compared for the above HFC/HFO vs non PFAS based solutions.

Study 2 in Appendix 2 below presents the calculations of equivalent CO_2 emissions (CO_2eq) and electricity consumption costs for current HFC/HFO refrigerants in comparison to non-PFAS solutions (i.e., hydrocarbons, CO_2 , and ammonia) for *Commercial Air conditioning and heat pump* sub-sector.

2. Absence of unacceptable risk within the meaning of REACH

In section 1.1.6 of the Proposal the Dossier Submitters concluded that *"all PFAS" (i.e., as a group)* should *"be treated as non-threshold substances for the purposes of risk assessment in a similar manner to PBT/vPVB substances"* and that any of their releases *"can be used as a proxy for risk"*. This conclusion is manifestly erroneous as far as many HFC/HFO refrigerants and their atmospheric degradation product trifluoroacetic acid (TFA) are concerned. It is also too simplistic, in our view, to group all PFAS together in this manner.

2.1. Objective assessments of HFC/HFO and their degradation products

2.1.1. Unjustified grouping of *"all PFAS"*

Grouping of HFC/HFO refrigerants used in RHVAC applications with all other PFAS is not scientifically and legally justified. In this regard, the 2021 OECD's PFAS definition used in the Proposal is not conceived for regulatory purposes, which is also acknowledged by the Dossier Submitters. Moreover, according to the respective OECD report, it does not give any information on the hazards of substances, even regarding their very persistent (vP) properties, or uses, exposure and risks.[22] In other words, the OECD itself is clear that its definition of PFAS was not intended to be used for regulatory action because it is too broad to enable an effective, science-based risk assessment, which would result in regulation of these (over 10 000) chemical compounds as an entire group. The UK Health and Safety Executive (HSE)[23] service and US Environmental Protection Agency (EPA)[24] share the same opinion.

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[21] Solstice® L40X - a blend of 75.5% R1234yf (HFO-1234yf), 21.5% R32 (HFC-32), and 3% CO2, with a GWP of as low as 146; or Solstice® N71 - a blend of 78.7% R1234ze(E) (HFO-1234ze(E)), 17% R1336mzz(E) (HFO-1236mzz(E)) and 4.3% of the fire suppressant HFC-227ea, getting a GWP of 148.

[22] See pages 8 and 25, *Reconciling Terminology of the Universe of Per- and Polyfluoroalkyl Substances: Recommendations and Practical Guidance*, ENV/CBC/MONO(2021)25, OECD, 9 July 2021 (available here): *"The term "PFASs" is a broad, general, non-specific term, which does not inform whether a compound is harmful or not, but only communicates that the compounds under this term share the same trait for having a fully fluorinated methyl or methylene carbon moiety."*

[23] See also in section 1.3 of the Analysis of the most appropriate regulatory management options (RMOA), The UK HSE, April 2023, *"A generic PFAS definition may not be particularly useful from a regulatory perspective, and it may be more appropriate to consider regulatory approaches on the basis of particular PFAS groups and/or uses."*

[24] The US EPA also uses a narrower working definition of PFAS as "*Chemicals with at least two adjacent carbon atoms, where one carbon is fully fluorinated and the other is at least partially fluorinated"* in their National PFAS testing strategy (see in section 3) as well as their PFAS strategic roadmap. EPA's use of this working definition provides focus on PFAS of concern based on their persistence and potential for presence in the environment and for human exposure. Regarding degradation products, the EPA Office of Chemical Safety and Pollution Prevention have opined that *"trifluoracetic acid is a well-studied non-PFAS."*

The most recent 2022 United Nations Environmental Program Environmental Effects Assessment Panel (EEAP) Report (EEAP 2022 Assessment Report)[25], unequivocally cited a common agreement among experts that *"all PFAS should not be grouped together, persistence alone is not sufficient for grouping PFAS for the purposes of assessing human health risk, and that the definition of appropriate subgroups can only be defined on a case-by-case manner"* and that "*it is inappropriate to assume equal toxicity/potency across the diverse class of PFAS"*.[26] The Report further concludes that *"Trifluoroacetic acid has biological properties that differ significantly from the longer chain polyfluoroalkyl substances (PFAS) and inclusion of TFA in this larger group of chemicals for regulation would be inconsistent with the risk assessment of TFA"*[27]

Please refer on the inconsistency of grouping methodologies of the Proposal to relevant sections of Honeywell submission reference no: bb6e00b6-571b-467a-ae79-7b046c6c9ab4.

2.1.2. Hazard and risk assessments of HFC/HFO and TFA

Contrary to the assertions made by the Dossier Submitters, there are PFAS substances, including many fluorinated HFC/HFO gases that are low-hazardous, have low-Global Warming Potential (GWP), are not (v-)persistent (not P/vP) and do not degrade to vP substances in meaningful amounts. For instance, the REACH registration dossiers and Chemical Safety Reports (CSR) for the fluorinated gases HFC-125, HFC-143a, HFO-1234ze(E), HCFO-1233zd(E), HFO-1336mzz(E), HFO-1336mzz(Z), HFC-245fa, HFC-365mfc, HFO-1234yf, HFC-134a, HFC-227ea, HFC-236fa, contain conclusive scientific evidence demonstrating that these substances have properly quantified DNEL/PNELs, are not persistent and do not exhibit risks similar to PBT/vPvB substances under Article 57(f) and Annex XIII REACH. Their REACH registration dossiers also do not demonstrate an existence of "*supporting concerns"* or hazards assessed in section 1.1.4. of the Proposal, including bioaccumulation, accumulation in plants, endocrine or (eco)toxicological effects, etc.

Therefore, the conclusions of the Dossier Submitters in section 1.1.6 of the Proposal, that all HFC/HFO must be treated as *"non-threshold substances"* with the overall concern *"very similar to those of the PBT/vPvB substances"* and with any release as *"a proxy for risks"* are not legitimate and not substantiated in the Proposal. [28]

In the meantime, according to the REACH registration dossier and CSR for trifluoroacetic acid (TFA)[29], this substance has also scientifically established DNEL/PNEC thresholds for relevant compartments, does not fulfil criteria for a PBT or vPvB substance under Annex XIII REACH. Neither does it raise equivalent levels of concern under Article 57(f) REACH.[30] In this respect, ECHA already reviewed/evaluated the TFA dossier without concluding that further regulatory actions were needed.[31]

Indeed, there is robust scientific evidence that only a few mainstream fluorinated gases ultimately degrade to TFA in over 30% molar yields rates (e.g., HFO-1234yf, HFC-227ea, HFC-134a).[32] Many other HFC/HFO (HFC-125, HFC-143a, HFO-1234ze(E), HCFO-1233zd(E), HFC-245fa, HFC-365mfc, etc.)[33] have small estimated TFA atmospheric conversion yields and are a *"minor source of TFA"* [34] resulting in *de minimis* increase in TFA concentrations. According to the conclusions of Chapter 6, section 3.8 of the EEAP 2022 Assessment Report, respective *"releases will add to the existing load of*

25 *Environmental Effects of Stratospheric Ozone Depletion, UV Radiation, and Interactions with Climate Change*, 2022 Assessment Report, Environmental Effects Assessment Panel (EEAP), available at - http://ozone.unep.org/science/eeap

26 *Grouping of PFAS for human health risk assessment: Findings from an independent panel of experts*, J.K. Anderson, et al., 2022

27 See pages 278 and 279 of the UNEP EEAP 2022 Assessment Report.

28 See analysis and conclusions of section 1.1.6 (Risk characterisation) of the Proposal.

29 Trifluoroacetic acid, EC no: 200-929-3, CAS no: 76-05-1, Molecular formula: C2HF3O2

30 See e.g., *Mammalian toxicity of trifluoroacetate and assessment of human health risks due to environmental exposure*, Dekant *et al*, 17 February 2023.

31 E.g., in 2017-2021, ECHA concluded comprehensive dossier evaluation of Trifluoroacetic acid, without indications of the need for further actions.

32 See detailed EFCTC position paper on the topic *Published evidence supports very low yield of TFA from most HFOs and HCFOs* ; see also detailed discussion in Chapter 6, section 3.2 of the EEAP 2022 Assessment Report.

33 TFA yields rates (molar), see section 3.8, Fig. 12 and pages 314-319 of the *Environmental Effects of Stratospheric Ozone Depletion, UV Radiation, and Interactions with Climate Change*, EEAP 2022 Assessment Report.

34 E.g., Chapter 6, Fig. 11 of the EEAP 2022 Assessment Report.

TFA in the environment but predicted amounts are well below the threshold for concern with respect to human and environmental health." Therefore, TFA could not be considered as a non-threshold substance with any release as a proxy for risks. The related risks cannot be considered as unacceptable under Article 68 REACH and are incomparable with effects of restrictions (bans) envisaged in the Proposal for all fluorinated gases. The HFC/HFO in question do not degrade to other PFAS either and thus should be excluded from the scope of the Proposal.

For detailed information and objective assessments of TFA, please refer to the previous Honeywell submission no: 76bb3d12-2101-4390-82cf-3498b47e8015.

2.2. Existing adequate RMMs

Full-life cycle emissions of fluorinated gases as refrigerants in RHVAC applications are already effectively and adequately controlled by other RMMs under relevant EU legislation, including the *EU F-Gas Regulation*[35], tight industry standards[36] as well as national and EU waste laws.[37] These measures mandate *inter alia* effective quantitative limitations on placing on the market (e.g., HFC (F-gas) phased down volume quotas and equipment bans), containment measures including leak controls and reporting, servicing certification of HFC/HFO in RHVAC/MAC, product (eco-)design and safety standards (e.g., *ISO 5149-1:2014*, *EN 378*), disposal and end-of-life requirements (e.g., recuperation and re-use). These regulations could be strengthened at any time, if warranted.

In this respect, HFC/HFO fluorinated gases (F-Gases) as refrigerants are fully contained and function in RHVAC closed loop systems. Their emissions are subject to rigorous obligatory containment RRMs (on leaks controls, end-of-life collection, and disposal, etc.), under the EU F-Gas legislation. According to the very first words of Article 1 of the F-Gas Regulation, its key objective is the same as that aimed by the Proposal - reduction of emissions, i.e.: *"The objective of this Regulation is to protect the environment by reducing emissions of fluorinated greenhouse gases"*. According to the European Commission, F-Gas legislation is an example of *"European success story"*.[38] Therefore, uses of HFC/HFO substances are already adequately controlled from the perspective of the main goal of the REACH restriction Proposal. Grouping these substances with other potentially hazardous and less controlled PFAS within one universal REACH restriction process is disproportionate, flawed and legally unjustified.

In addition, TFA related risks due to emissions of fluorinated HFC/HFO gases are adequately controlled also within the meaning of section 6.4 of Annex I of the REACH (as demonstrated in CSR). The current and projected concentrations of TFA are many folds lower than the established DNEL/PNEC and MoEs thresholds for relevant compartments, the adopted daily intake LW_{TW} values or drinking water standards.[39] Thus, human exposure to TFA from HFC/HFOs atmospheric degradation is also negligible, while upstream environmental emissions of these F-Gases are already subject to effective EU emission and risk control measures (see above). Therefore, the conclusions in section 1.1.6 of the Proposal that all PFAS exhibit risks very similar to PBT/vPvB and that any PFAS emissions should be considered as a proxy for unacceptable risks that are not adequately controlled, are erroneous, as far as HFC/HFO refrigerants are concerned.

3. Hazards and safety concerns of proposed alternatives

Erroneously labelled alternative *"natural refrigerants"* such as ammonia (R-717), hydrocarbons (R-290 or propane) and CO_2 (R-744) are industrial manufactured, synthetic chemical substances (by-products of fossil fuels processing) with important hazard and exposure characteristics including toxicity, anesthetic/asphyxiant effects and/or high flammability, which considerably limit their practical applications, e.g., as RHVAC refrigerants in buildings and in public spaces. For many applications so-

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35 *Regulation (EU) No 517/2014 of the European Parliament and of the Council of 16 April 2014 on fluorinated greenhouse gases and repealing Regulation (EC) No 842/2006* (as amended and currently under review, available here).

36 For instance, ISO 5149-1:2014 specifies the requirements for the safety of persons and property, provides guidance for the protection of the environment, and establishes procedures for the operation, maintenance, and repair of refrigerating systems and the recovery of refrigerants.

37 Directive 94/62/EC on packaging and packaging waste; Directive 2008/98/EC on waste (Waste Framework Directive).

38 EU crackdown on climate-wrecking F-gases hits heat pump snag, Politico, 9 November 2022.

39 See in detail *Mammalian toxicity of trifluoroacetate and assessment of human health risks due to environmental exposure*, Dekant *et al.*, 17 February 2023.

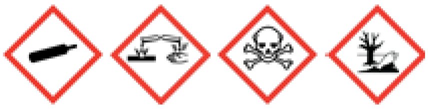
called natural refrigerants could be considered as genuine *"regrettable substitutions"* leading to grave incidents as well as other safety and environmental concerns (see **Annexes II, III and IV**).[40]

In this respect, the number of fatalities reported for HFC/HFO is orders of magnitude lower than for e.g., ammonia systems, even though there are by far more fluorocarbons systems in use.[41]

3.1. Ammonia

Anhydrous ammonia (NH3, EC no.: 231-635-3; CAS no.: 7664-41-7) used as a refrigerant consists of at least 99.5% pure ammonia. The latter is produced in massive quantities due to the fertilizer industry (mainly via Haber-Bosch process, with low efficiency and recycling of unconverted gases).[42] According to the REACH registration dossier for ammonia, it is mildly flammable (ASHRE – 2L), very toxic (Toxic if inhaled (cat. Acute Tox. 3), Severe skin burns and eye damage (cat. Skin Corr. 1B), Very toxic to aquatic life (cat. Acute 1) with long lasting effects (cat. Aquatic Chronic 2)) substance.

Ammonia CLP hazard classification & labelling:



Industrial ammonia production emits more CO_2 than any other chemical-making reaction[43]. Therefore, its production in the EU is covered by carbon emissions reductions policies under the EU ETS and its import will be subject to the EU Carbon Border Adjustment Measures (CBAM). In the atmosphere, ammonia can bind to other gases to form ammonium, which has particularly negative impacts on cardiovascular and respiratory health systems.[44] Ammonia can have a direct toxic effect on vegetation and can lead to changes in species composition (biodiversity) due to nitrogen deposits.[45] It is also a strong aquatic pollutant.[46] End of life handling of ammonia refrigerants is technically complex, costly, and presents risk for health and the environment. Disposing of contaminated ammonia requires incineration or an aqueous treatment due to its dangerous chemical properties. These processes create hazardous waste.[47]

Due to the high toxicity (lethal in certain doses) and flammability (also combustible) of anhydrous ammonia, RHVAC installations using this chemical are governed by strict national regulations. Service personnel on site must have appropriate training/accreditation to handle ammonia to ensure safe operation of the system. Many SMEs currently in RHVAC servicing business would not qualify. Ammonia is also aggressive to other materials such as copper, zinc and many other. Hence, the maintenance costs of such systems are very high due to the price of spare parts and the need for regular (every 3 months) deep cleaning of the systems. In practice, ammonia used close to public areas and in big charges (e.g., commercial indoor chillers, RHVAC systems or heat pumps in public buildings) could lead to high health and safety risks.[48] Regardless of strict safety measures in place, numerous

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[40] See on detailed comparisons of ammonia, CO_2, propane (R290) and HFC/HFO refrigerants in *Safety first when choosing a refrigerant! EFCTC Factsheet on published refrigerant-related accidents.*

[41] *Working Fluid Safety. Annex 20, Report No. HPP-AN20-1, Berghmans, J. (1994)*, IEA Heat Pump Programme, ISBN 90-73741-10-6, IAE Heat Pump Centre, Sittard, The Netherlands.

[42] *The Future of Ammonia: Improvement of Haber-Bosch ... or Electrochemical Synthesis?*, also *Current and future role of Haber–Bosch ammonia in a carbon-free energy landscape,* Collin Smith, Alfred K. Hill and Laura Torrente-Murciano, Department of Chemical Engineering, University of Bath, BA2 7AZ, Bath, UK., 2019.

[43] *Industrial ammonia production emits more CO2 than any other chemical-making reaction. Chemists want to change that.*

[44] *Impact of ammonia emissions from agriculture on biodiversity*.

[45] *Ibid.*, also *Ammonia - is it causing your algae problems?*

[46] *Ecological and toxicological effects of inorganic nitrogen pollution in aquatic ecosystems: a global assessment,* Camargo J, Alonso A (2006), Environment International 32:831-849; Constable M, Charlton M, Jensen F, McDonald K, Craig G, Taylor K (2003) An ecological risk assessment of ammonia in the aquatic environment. Human and Ecological Risk Assessment 9(2):527-548; and many others.

[47] *Environmental Health Criteria 54: Ammonia.* ,IPCS (International Programme on Chemical Safety) (1986), United National Environment Programme, International Labour Organisation, World Health Organization.

[48] See in detail A Review of Safety Issues and Risk Assessment of Industrial Ammonia Refrigeration System, Dheyaa Ashour Khudhur, Tuan Amran Tuan Abdullah, and Norafneeza Norazahar, ACS Chemical Health & Safety 2022 29 (5), 394-404 DOI: 10.1021/acs.chas.2c00041

incidents with ammonia refrigeration systems are reported worldwide and provided selectively in **Annex II**. Some of these incidents have led to fatalities.[49]

In addition, anthropogenic atmospheric emissions of ammonia in the EU are subject to national member states emissions reduction commitments under Directive (EU) 2016/2284[50] which aims to reduce emissions of certain strong atmospheric pollutants, including ammonia.[51]

3.2. Hydrocarbon refrigerants

Hydrocarbon refrigerants (Propane (R-290), Isobutene (R-600a), Propylene/propene, etc.) are by-products from the petrochemical industry and are highly/extremely flammable and explosive gases (cat. Flam. Gas 1A).

Propane CLP Hazard classification & labelling:

Some recent workplace fire incidents concerning flammable refrigerant gases have directly contributed to injuries, deaths and damage to property (buildings fires, explosions - see selected examples in **Annex III** below). Combustion products of some hydrocarbon refrigerants and mixtures are toxic. Gaseous hydrocarbons other than methane are heavier than air and will displace air in lungs resulting in asphyxiation.[52] They are also strong atmospheric photochemical ozone precursors that can cause air quality concerns (volatile organic compounds (VOC) and photochemical ozone creation potential (POCP) concerns).[53] These characteristics make these hydrocarbons unsuitable for larger RHVAC and insulation foams (building) applications as well as for the automotive and transportation sector due to strong safety concerns.

All devices that use hydrocarbons as a refrigerant must be approved by national competent authorities before they are sold, installed or used and only holders of a gas work license can do work on the gas system of hydrocarbons refrigeration appliances.[54] Proper leaks and concentrations control/alarm systems must be in place too. This significantly increases the total cost of ownership of these systems.

3.3. Carbon dioxide (CO_2)

Major CO_2 (R744) refrigerant shortcomings are:

- *Pressure* - Very high operational pressures (10 times that of current refrigerants) that require complete redesign and retooling of all major RHVAC components. Leaks quickly result in the air emission of the whole refrigerant charge, leading to non-functionality of the overall system and respective products losses (food, medicines, blood, etc.).
- *Acute Toxicity Exposure Level (ATEL)* – Even smallest CO_2 leaks can result in large leak volume due to high pressure causing safety concerns due to its low ATEL 30,000 ppm (54 g/m3)[55].

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[49] Can be a precursor for explosive materials and is listed in the potential risks for terrorist attacks.

[50] *Directive (EU) 2016/2284 of the European Parliament and of the Council of 14 December 2016 on the reduction of national emissions of certain atmospheric pollutants, amending Directive 2003/35/EC and repealing Directive 2001/81/EC*.

[51] Also subject to control under *The 1999 Gothenburg Protocol to Abate Acidification, Eutrophication and Ground-level Ozone (Gothenburg Protocol)*

[52] https://chem.libretexts.org/Courses/University_of_Arkansas_Cossatot/UAC%3A_Chem_1014/Chapters/8%3A_Organic_Chemistry_of_Hydrocarbons/8.13%3A_Physical_Properties_of_Hydrocarbons

[53] Subject to control under *The 1991 Geneva Protocol concerning the Control of Emissions of Volatile Organic Compounds or their Transboundary Fluxes* and *The 1999 Gothenburg Protocol to Abate Acidification, Eutrophication and Ground-level Ozone (Gothenburg Protocol)* , see also EFCTC summary page VOCs And POCPs.

[54] See e.g. Q&A What do service engineers need to know about flammable refrigerant rules?, *IEC 60335-2-89 flammable refrigerant limit change*.

[55] See in *Gas detection in refrigeration systems.*

- *Ecotoxicity* - CO2 leakage in water harmful for marine life.[56]
- *Safety* - The servicing of CO_2 refrigeration equipment with these high pressures increases the likelihood of accidents (systems blowouts), particularly for transport refrigeration/AC in road incidents (shrapnel and fragmentation of components, freeze burns (due to low boiling point), etc.). High coefficient of liquid expansion can cause pipe ruptures (HFO liquid expansion rate of 15% vs 42% for CO2). In addition, CO_2 is harmful when exposed to it for several hours at low concentrations (1-3%). At concentrations above 10% it may cause fatalities due to the lack of oxygen uptake potentially leading to suffocation and asphyxia.[57] Also refer to Annex IV listing certain selected incidents due to CO_2 refrigerants.
- *Reliability* - Retaining CO_2 in the refrigerant system is a challenge given the small molecule size and higher pressures needed. More frequent refrigerant servicing is likely required and can reduce overall efficiency when low charge conditions exist (particularly important for small commercial chillers, etc.).
- *Performance in hot weather* - CO_2 as a refrigerant in RHVAC systems loses efficiency in hot weather conditions. This considerably increases energy/electricity consumption, estimated to be two and half times higher in hot climates as opposed to more temperate conditions.[58] Given increasing climate temperatures due to global warming, this will become even more problematic for RHVAC applications in all sectors (industrial, commercial (especially in small/mid-size chillers/refrigerators and SMEs), public, private uses) in the near future.
- *Energy efficiency and GHG emissions* – The SAE International study demonstrated that due to higher energy needs, CO_2 HVAC systems resulted in a 10-15% increase in total CO_2 equivalent GHG (indirect) emissions when evaluated across population biased weather patterns for Europe and North America.[59] See also in detail in section 4 and Appendices 1-2 below.
- *Vibration and noise* - Elevated vibration and noise characteristics of CO_2 high pressures coupled with reduced dampening of normal rubber based refrigerant hoses may have a significant effect on customer satisfaction.
- *Costs* - Higher costs for both manufacturers and consumers will have a societal impact, based on both economies of scale and premium materials or structural requirements to maintain the higher pressures.

CO_2 refrigerants are by products of other industrial processing of fossil fuels (e.g., natural gas and coke) resulting in other environmentally harmful by-products such as Nox, NH3, HCN, HCl, methane leaks, and slags, etc. which are very difficult and expensive for safe disposal.

Some other aspects to consider while evaluating options available for different applications is the initial capital expenditure and the maintenance costs. For supermarkets, the Proposal refers to CO_2 as an alternative, which is thermodynamically less efficient than HFC/HFO based solutions. To improve the efficiency of CO_2 systems cycle enhancements such as flash gas bypass, parallel compression, adiabatic condensers and ejectors are often used for CO_2 systems. These enhancements increase the complexity of the system resulting in higher initial cost as well as the maintenance cost of CO_2 systems compared to HFC/HFO based solutions. Further, since CO_2 refrigeration systems operate at extremely high pressures technicians need to be trained specifically for handling CO_2. The design of CO_2 systems also needs to consider effects of unplanned events such as power failures which can lead to rise in system pressure beyond the system design pressure rating which could potentially lead to loss of entire CO_2 refrigerant charge leading to refrigerated product loss. Due to these additional system complexities and the requirement to employ specially trained technicians the maintenance cost of CO_2 systems is higher than HFC/HFO based systems. Therefore, continued use of HFC/HFO's should be allowed to ensure end users have the flexibility of using the appropriate system architecture and refrigerant based on their needs and are not adversely impacted by the higher capital expenditure and higher maintenance cost of CO_2 systems. The costs of these systems, in terms of increased energy cost and hiring extra staff are passed on to the consumer. The increased CO2 emissions also mean it is hard to meet the goals of the EU's green deal.

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[56] See on Ocean acidification, and *Lethal effects on different marine organisms, associated with sediment–seawater acidification deriving from CO2 leakage*

[57] *Safety first when choosing a refrigerant! EFCTC Factsheet on published refrigerant-related accidents.*

[58] https://docs.lib.purdue.edu/cgi/viewcontent.cgi?article=2881&context=iracc-Figure 8

[59] SAE International CRP1234, Industry Evaluation of low global warming potential refrigerant HFO1234yf, 12/9/2008 - https://www.sae.org/standardsdev/tsb/cooperative/crp1234summary.pdf

In addition, uses of CO2 refrigerants in RHAC applications are not more environmentally friendly when compared with HFC/HFO in terms of all GHG emissions due to higher electricity needs (i.e., "*indirect emissions*"). As generalized in a table below[60] and scrutinized in detail in section 4 and Studies 1-2 below, HFO-1234ze(E) systems emit 30% less CO_2 then R774 systems during their lifetime.

Fluid	Annual electricity consumption by the system	CO_2eq – indirect due to electricity generation to drive the system	CO_2e – direct due to the leaks	CO_2e -total
[-]	[kWh]	[tons of CO_2]	[tons of CO_2]	[ton of CO_2]
R-1234 ze	21 662	9.31	0.016	**9.32**
CO_2	28 477	12.25	0.002	**12.25**

The above problems make CO_2 technically concerning and economically undesirable to implement in many RHVAC systems at the required scale and level of safety. The overall effect of using CO_2 as a substitute for HFC/HFO would be negative for consumers, the economy, GHG emission reduction targets and aims of the European Green Deal, Fit for 55 and REPowerEU plans (see section 4 below). It is noteworthy that it is technically and/or economically impossible to transform many existing RHVAC systems for use of alternative refrigerants. Existing systems and those that are already designed will require stable supply of HFC/HFO refrigerants until the end of their lifecycle which is 10-15 years for small/medium, and over 30 years for large installations such data centres, district heating, etc.

4. Studies on HFC/HFO alternatives in *Commercial Refrigeration* and *AC and heat pumps* sub-uses

Table 1 below provides an overview of systems that are installed in EU grouped by application. The two applications (sub-uses) considered for the corresponding studies are: Study 1 - *Commercial Refrigeration* and Study 2 - *Commercial Air-conditioning (AC) and heat pumps*.

Detailed explanations and calculations are provided in the respective robust study summaries in Appendixes 1 and 2 below.

The Proposal outlines several NIK (not-in-kind) replacement options for current HFO/HFC products in the above applications (sub-uses).[61] These alternative substances (so-called - "*natural refrigerants*"), include CO_2 (R-744), ammonia (R-717) and certain hydrocarbons (e.g., propane (R-290)). The HFC/HFO solutions (pure R1234ze(E) (HFO-1234ze(E)), and blends R455A, R471A)[62] and NIK solutions addressed in the studies are also listed in Table 1.

Table 1 – Overview of systems installed in EU

Application	End use	Technology	Capacity range	HFC/HFO solutions	NIK
Commercial Refrigeration	Convenience Store	DX system	5 – 20 kW	R455A	R290
		Distributed water-cooled			
		DX system	20 – 80 kW	R455A	R290

60 Assumptions used: Medium temperature refrigeration system; Evaporating temperature -10°C, condensing temperature variable through the year, assumed climate conditions like Hamburg (Germany); Cooling capacity 10 kW, charge of the system 15 kg, annual leak rate 15%; COP is for the typical piston reciprocating compressor used in refrigeration sector, energy efficiency class of the heat exchangers with fans "C"; Carbon intensity for energy production is 430g CO2 / kWh.

61 See Table 2 and Table 8 (pages 92-94), Annex E (sections E.2.8.2.2 and pages 248-249) and Annex A (section A.3.9.1.1).

62 R455A (Solstice® L40X) a blend of 75.5% R1234yf (HFO-1234yf), 21.5% R32 (HFC-32), and 3% CO2, with a GWP of as low as 146; and R471A (Solstice® N71) a blend of 78.7% R1234ze(E) (HFO-1234ze(E)), 17% R1336mzz(E) (HFO-1236mzz(E)) and 4.3% of the fire suppressant HFC-227ea, getting a GWP of 148.

	Small Supermarket	Distributed water-cooled			
	Supermarket	Transcritical booster	80 – 300 kW	R471A	R744
		DX Cascade		R455A	
	Hypermarket	Transcritical booster	300 – 600 kW	R471A	R744
		DX Cascade		R455A	
	Remote CDUs (not included in this evaluation)				
Commercial Air conditioning and Heat Pump	Light Commercial	Rooftop	20 – 50 kW	R1234ze(E)	R290
		VRF			
		Split systems		R455A	
		Monoblock			
	Chillers	Small	20 – 100 kW	R1234ze(E)	R290
		Medium	100 – 500 kW	R1234ze(E)	R290
		Large	> 500 kW	R1234ze(E)	R717
	District cooling/heating (not included in this evaluation)				
	Residential (not included in this evaluation)				

Accordingly, Study 1 proves that converting all supermarkets in the EU to propane (R290) and other so-called natural refrigerants fluids (i.e., CO_2, R744) would annually add 5.7 TWhr/yr demand on the electricity grid, which would result in adding an additional 2.4 MTonne/yr of CO_2eq of GHG emissions and additional electricity cost per year of 0.8-3B€/yr (billions of euro).

Widespread use of ammonia (R717) in the Commercial Refrigeration sector is not possible due to safety concerns as a result of its higher toxicity.[63]

The Study 2 demonstrates that converting to natural refrigerants (i.e., propane (R290) and ammonia (R717)) would annually add 6.9 TWhr/yr demand on the electricity grid, which would result in additional 2.7 MTonne/yr of CO_2eq of GHG emsiosns and additional electricity cost of 1-3.4 B€/yr.

Use of CO_2 systems in those applications is very technically challenging due to its low critical temperature, it suffers efficiency losses when applied to typical rating conditions for ACs[64]

In this regard, the continued use of HFC/HFOs in supermarkets, light commercial and chillers applications would avoid approximately 12.5 TWhr/year of additional energy demand per year. These applications still only represent ~55% of *Air-conditioning and heat pumps* and *Commercial Refrigeration* sub-uses. Hence the actual energy avoidance by the continues use of HFC/HFOs in RHVAC applications would be much larger providing substantial contribute to the EU green energy transition plans.

63 https://ozone.unep.org/system/files/documents/RTOC-assessment%20-report-2022.pdf page 108
64 https://ozone.unep.org/system/files/documents/RTOC-assessment%20-report-2022.pdf page 148

It is evident that the above consequences of the Proposal to restrict PFAS and subsequently banning HFC/HFO for the RHVAC sector would drastically impact the EU's decarbonization goals which aim to cut GHG emissions by at least 55% by 2030 and REPowerEU plans. Respective cost on the society and environment will be too high and disproportionate in comparison with the alleged concerns due to persistency of TFA.

5. Future technologies for HFC/HFO and alternative refrigerants

The studies in Appendixes 1 and 2 below considered the current technologies used with HFC/HFO refrigerants, which haven't been studied for as long as the not-in-kind (NIK) solutions, such as R290, CO_2 and R717. These estimates are still conservative as the potential improvements from new technologies over the next 20 years have not been considered. Although R290 has inherently better thermophysical properties than some of the HFC/HFO refrigerants it does not benefit significantly from most cycle improvements. Most of the focus on R290 systems must be on charge reduction due to its higher flammability, thus performance is not prioritized. CO_2, on the other hand, has been thoroughly investigated in the past decades and even considering its state-of-the-art systems the performance still can't overcome the drawbacks in this refrigerant for some applications. Although as R717 has been known as one of the best refrigerants in terms of its thermophysical properties, it's highly toxic and it doesn't benefit from most of the technological advancements in cycle architecture or RHVAC component design.

For a more realistic projection of next-generation system performance a few essential technologies must be considered to envision the future efficiency of the sector:

- *Compressors:* centrifugal oil-free compressors have initially been developed for very large capacities and are being downsized down to 15 kW unitary cooling capacity, including both cooling heating and refrigeration designs (high- and low-pressure lifts). When this technology can be applied to smaller Chillers, Roof tops, VRF, Heat pumps and refrigeration systems a breakthrough in efficiency will happen as is the case today in large capacities. Typical Seasonal efficiency increases can be as high as 25% when comparing this technology to traditional oil-lubricated positive displacement compressors.

  It is fundamental to understand that new centrifugal oil-free compression (e.g., Turbocor) can only fit to HFC/HFO low level of pressures to be reliable and efficient, so there is no possibility to use it for R290, CO_2 or R717. Moreover, the oil-free design will benefit from a constant Coefficient of Performance (COP) along the years when it has been demonstrated a continuous ageing degradation of COP in oil-lubricated chiller technologies, up to 20% after 20 years.[65]

- *Ejectors, Sub-Coolers:* these technologies, already applied since more than 10 years in CO_2 refrigeration, have demonstrated a significant boost in efficiency by enhancing the refrigeration cycle. HFC/HFO will benefit as well from these new options. Expected efficiency increase is above 10% for each technology.

  As CO_2 is already using them there will be no additional change to the baseline CO_2 systems efficiency of 2023.

  As far as R290 is concerned, the drastic refrigerant charge limitation linked to its explosivity will not permit its use as either ejector or sub-cooler easily, as both solutions will increase the refrigerant charge enough to be above the safety standards allowances.

  For R717, the trend of 'low charge Ammonia' Chillers and HP (due to its Toxicity) will also restrict the access to refrigeration cycle enhancement technologies.[66]

6. Conclusions

Total exclusion or time unlimited derogations for HFC/HFOs uses in refrigeration, heating, ventilation, air-conditioning (RHVAC) sectors from potential REACH restrictions should be granted. Uses of

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65 Energy Star Building Manual, 2008. Chapter 9 - Heating and Cooling; ASHRAE Research Project Report RP-751: Experimental Determination of the Effect of Oil on Heat Transfer in Flooded Evaporators with R-123, R-134A, ASHRAE, 1999; Final Report: Compressor Degradation Assessment and Wear Mitigation Strategy, Zheng, Y., Bellstedt, M., 2014, Meat & Livestock Australia Limited, North Sydney NSW, Australia. pp 19.

66 Ibid. and Emerging Oil Free Technologies, Good, R., 2018.

respective HFC/HFO as well as their decomposition product TFA do not entail unacceptable risks that are not adequately controlled within the meaning of Articles 68-69 REACH.

Moreover, potential substitutes do not provide the required safety, technical specifications or performance of final products or installations for critical use application. Even in the mid-to long term, technically feasible chemical, and functional alternatives acceptable from standpoints of safety, health, environment, and costs would not be available. In case of the proposed REACH restrictions, substitution costs for all actors within supply chains of many critical industries (food, medicines, automotive, electronics, data centers, heat pumps, etc.) as well as for consumers and society would be incomparable with alleged persistency risks of HFC/HFO's decomposition product TFA.

Inevitable effects on electricity consumption, respective GHG emissions and annual costs in case of substitutions discussed in the Proposal will amount to additional annual over 6.9 TWhr/yr demand of electricity, the 2.7 MTonne/yr of CO2eq GHG emissions, and additional electricity cost of 1-3.4 Billion €/yr for ~44% of the overall *Air conditioning and heat pumps* (AC/HVAC) and will annually add 5.7 TWhr/yr demand on the electricity grid, additional 2.4 MTonne/yr of CO2eq emissions and additional electricity cost of 0.8-3 Billion €/yr for ~64% of the total *Commercial Refrigeration* sub-uses. These costs are unacceptably high for society and disproportionate in comparison with alleged concerns due to the persistency of TFA. This approach is also against wider EU policies on climate change, decarbonization and sustainable energy.

Therefore, Honeywell submits that the following HFC/HFO fluorinated refrigerants should be excluded from the scope of the Proposal: HFC-125, HFC-143a, HFO-1234ze(E), HCFO-1233zd(E), HFO-1336mzz(E), HFO-1336mzz(Z), HFC-245fa, HFC-365mfc, HFO-1234yf, HFC-134a, HFC-227ea, HFC-236fa, or their uses in RHVAC/HVAC applications should be subject to time-unlimited derogations in line with the provisions of Articles 68 and 69 REACH.

In line with previous practices, this exclusion or derogation should also cover maintenance and repair, refitting and reselling activities involving used/secondhand RHVAC systems already placed on the market.[67]

[67] See Example 5, Examples of conditional derogations, pages 58-62, *Guidance for the preparation of an Annex XV dossier for Restrictions; see also para. 7 of entry 72, para. 8 of entry 50 or paras. 3 and 10 entry 68 of Annex XVII REACH.*

Appendix 1

Study 1 - Commercial Refrigeration

1. Investigated Systems

Four typical refrigeration store formats are considered in this investigation (Table 6.1). The chosen store formats cover all the typical system architectures used in commercial refrigeration applications. The number of stores, refrigerant charge for each store format and the system capacity based on average store floor area are adopted from a published report (Planet Retail, 2018). The refrigerants considered for this investigation are listed in Table 2. R471A is a non-flammable refrigerant which has a GWP of less than 150 and possesses capability to be used conventionally and efficiently in new designs of medium temperature refrigeration systems (Gao et al., 2022; Tangri et al., 2022). While R455A is a mildly flammable (A2L) refrigerant with GWP of less than 150 which is a low GWP replacement for R404A in both medium and low temperature applications. R471A is considered as HFO based solution for the medium temperature loads while R455A as a HFO based solution for the low temperature side. Only for supermarkets and hypermarkets, a cascade configuration with R471A on high side while R455A in low side is considered within the HFO based solutions. For non HFO based solutions, R290 is considered as the refrigerant for the convenience stores and the small supermarkets while CO_2 for the supermarkets and the hypermarkets. R290 based systems are self-contained water-cooled units and the heat rejected by these systems is dissipated to ambient with a high efficiency chiller. CO_2 systems considered in this investigation are equipped with latest technology upgrades like parallel compressor and multi-jet ejectors.

Table 6.1 - Commercial Refrigeration System Details for European Region

STORE FORMAT	store size	Charge	# of stores	MT cap	LT cap
	(sqm)	(kg)	(-)	(kW)	(kW)
Convenience Store	200	30	126,425	10	2
Small Supermarket	500	60	46382	24	5
Supermarket	1000	300	37111	130	25
Hypermarket	6500	1200	7975	420	80

Table 6.2 - Refrigerant options for Commercial Refrigeration

Store Type	Store Architecture		Refrigerant Options			
			HFC/HFO based Solution		HFC/HFO based Solution	
	HFO based Solution	Non-HFO based Solution	LT	MT	MT	LT
Supermarket	Cascade	Booster DX	R455A	R471A	CO_2	
Hypermarket	Cascade	Booster DX	R455A	R471A	CO_2	
Small Supermarket	DX	Distributed Water Cooled	R455A		R290	
Convenience Store	DX		R455A		R290	

2. Modelling Methodology

Performance models are developed for all the considered system architectures based on compressor coefficients (chosen from OEMs representing the best-case scenario for each refrigerant case) and a certain set of engineering assumptions. Factor of 1.1 is used across all refrigerants to correct the offset of compressor suction temperature (coefficients vs actual suction). Compressor technology considered is piston reciprocating and the compressor coefficients for each refrigerant is listed in Table 6.3. Performance in compared in terms of energy consumption and carbon emissions considering the bin data of Frankfurt, Germany, shown in Figure 6.1, which is assumed to be the representative climate for European region (BinMaker Pro, 2018). Evaporating temperature fixed -8 °C for MT and a fixed -32 °C for LT. Table 6.4 and Table 6.5 lists the condensing temperatures and the leak rates considered for this analysis. Temperature difference of 5K is considered for cascade (R455A/R471A) and secondary heat exchanger (R290). The GWP values adopted from AR4. R290 plug-in cabinets heat dissipation into the store (compressor) not included which in real store must be compensated by air conditioning. Defrost energy is not considered for this comparative investigation. For CO_2 systems, leak rate of 20% considered in this investigation is very conservative, more realistic values in warm ambient are close to 40%. For R290 system, COP of 6 is considered for chiller to dissipate heat from secondary loop. It is assumed to have requirement of chiller annual operation of 60% while remaining 40% is free cooling. Average equipment lifetime of 10 yrs, CO_2 emission factor of 0.43 $kgCO_2$/kWh and electricity cost of (0.15 €/kWh to 0.49 €/kWh) are considered for evaluating the total emissions and cost savings of HFO based solutions vs the non HFO based solutions.

Table 6.3 - Compressor Coefficients

C-store, small supermarket										
R-290 MT, LT										
	C0	C1	C2	C3	C4	C5	C6	C7	C8	C9
Q (W)	3830.431	135.7552	-11.5907	1.608565	-0.67242	-0.6217	0.007699	-0.00596	-0.00378	0.004312
P (W)	450.831	-4.4169	1.159554	-0.179	-0.03595	0.193776	0.002794	0.004547	0.006708	-0.00125
m (kg/h)	33.03167	1.063232	0.170961	0.01102	0.002233	-0.00682	5.59E-05	2.57E-05	-3.7E-05	3.91E-05
R-455A MT										
	C0	C1	C2	C3	C4	C5	C6	C7	C8	C9
Q (W)	46494.4	1666.283	-463.402	21.40508	-13.111	-0.60432	0.10361	-0.10012	0.001673	0.010188
P (W)	1708.66	-136.749	193.9651	-3.97984	6.007311	-1.00466	-0.02825	0.042991	-0.0159	-0.00064
m (kg/h)	777.5583	26.17091	-2.39618	0.322762	-0.03932	-0.02346	0.00166	2.42E-05	-0.00015	8.77E-05
R-455A LT										
	C0	C1	C2	C3	C4	C5	C6	C7	C8	C9
Q (W)	46118.8	1653.827	-462.842	21.25007	-13.1147	-0.59807	0.102769	-0.10043	0.001568	0.010136
P (W)	1713.917	-136.435	193.7564	-3.976	6.005689	-1.00476	-0.02824	0.043008	-0.01592	-0.00065
m (kg/h)	776.4534	26.13952	-2.39591	0.322397	-0.03935	-0.02349	0.001658	2.37E-05	-0.00015	8.77E-05
Supermarket, hypermarket										
R-744 MT										

	C0	C1	C2	C3	C4	C5	C6	C7	C8	C9
Q (W)	41041.31	1391.413	-839.155	19.17435	-11.468	20.90983	-0.04154	-0.39029	-0.37074	-0.55557
P (W)	1524.987	-112.27	123.7113	-1.69211	-0.15058	1.521209	0.003621	-0.03429	0.061404	-0.01464
m (kg/h)	585.6053	21.0829	-3.04977	0.337399	-0.08417	-0.00156	0.003276	-0.00116	-0.00012	-8.2E-05

R-744 LT

	C0	C1	C2	C3	C4	C5	C6	C7	C8	C9
Q (W)	7707.002	250.846	-110.606	2.474551	-2.34275	-0.40303	0.004338	-0.00705	-0.01794	0.008425
P (W)	182.0296	-41.9046	41.51396	-0.94743	1.182989	-0.1921	-0.00552	0.0098	-0.00442	0.000586
m (kg/h)	111.4106	3.641336	-0.52384	0.036707	-7.3E-05	-0.00886	7.24E-05	0.000191	-0.00031	0.000141

R-471A MT (proxy by R-1234ze compressor)

	C0	C1	C2	C3	C4	C5	C6	C7	C8	C9
Q (W)	179484.6	6800.371	-1963.63	105.8457	-45.2238	19.73852	0.663551	-0.62708	-0.03464	-0.21983
P (W)	2630.159	81.5654	1103.599	12.61078	2.778549	-17.0484	-0.09029	-0.2241	0.020984	0.176253
m (kg/h)	3095.229	90.64566	2.232313	0.930813	1.024726	0.095434	0.006572	0.013108	-0.01089	-0.00349

R-455A LT

	C0	C1	C2	C3	C4	C5	C6	C7	C8	C9
Q (W)	46118.8	1653.827	-462.842	21.25007	-13.1147	-0.59807	0.102769	-0.10043	0.001568	0.010136
P (W)	1713.917	-136.435	193.7564	-3.976	6.005689	-1.00476	-0.02824	0.043008	-0.01592	-0.00065
m (kg/h)	776.4534	26.13952	-2.39591	0.322397	-0.03935	-0.02349	0.001658	2.37E-05	-0.00015	8.77E-05

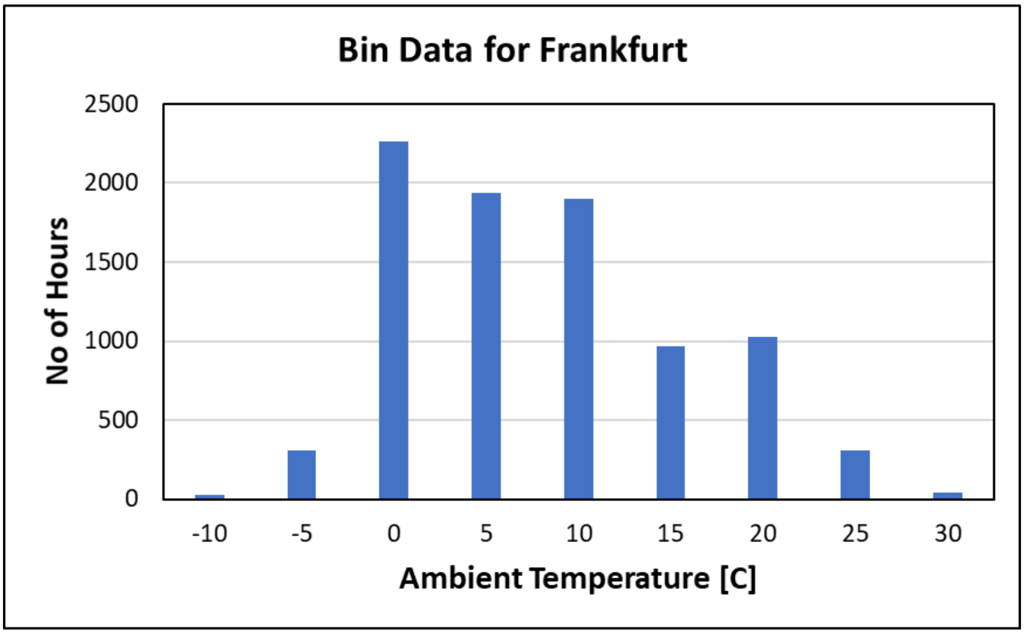

Figure 6.1 - Bin Data for Frankfurt

Table 6.4 - Condensing Temperatures

System	MT range	LT range
CO_2	Ambient +5 K but not lower than 10 ºC, for transcritical operation gas cooler exit temperature is 3K above ambient	Fixed -8 ºC
R290	Fixed 28ºC since plug in cabinets are located inside a store with ~constant temperature	Fixed 28ºC since plug in cabinets are located inside a store with ~constant temperature
R455A and R471A	Ambient +5 K but not lower than 15 ºC	Ambient +5 K but not lower than 15 ºC

Table 6.5 - Leak rates

Refrigerant	Leak rate
CO_2	20% since it is a high-pressure fluid
R290	2% since it works in hermetic system in plug in cabinets
R455A	10% average leak rate in EU for R-404A like fluids in centralized/semi centralized systems
R471A	5% since it is a low-pressure fluid

3. Results

Table 6.6 presents the net savings from electricity and carbon emissions for HFC/HFO based solution vs the non HFC/HFO based solutions over a 10-year period.

Table 6.6 - Total Cost and Emissions Savings for HFOs vs non HFOs based solutions over a 10-year period

PARAMETERS	HFC/HFO Solutions	Non-HFC/HFO Solutions
Annualized Energy Consumption (million kWh)	21145 (78.9%)	26800 (100%)
Total Electricity Cost Lifetime (Billion Euro) Electricity Cost (0.15 €/kWh)	31.8	40.2
Total Electricity Cost Lifetime (Billion Euro) Electricity Cost (0.49 €/kWh)	103.7	131.2

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Lifetime CO_2 Emission (million tons)	91.1	115.2
Total Cost Saving (Billion Euro) Electricity Cost (0.15 €/kWh)	8.4	
Total Cost Saving (Billion Euro) Electricity Cost (0.49 €/kWh)	27.5	
Total CO_2 emission saving (million tons)	24.1	

4. Conclusions

This analysis of energy consumption and CO_2 emissions for HFC/HFO and Non-HFC/HFO solutions show that keeping HFC/HFO refrigerants for the commercial refrigeration sector can save from 8.4 to 27.5 billion euros in energy costs and prevent 24.1 million tons of equivalent CO_2 emissions. By prohibiting the use of HFO refrigerants the European Union will hinder the achievement of its emission goals.

Future technological advancement can further improve the performance of HFO refrigerant-based systems (see section 5 in the main document above).

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Appendix 2

Study 2 - Air-conditioning (AC) and heat pumps study

1. Introduction

Increasing demand for air conditioning and heat pump in Europe requires careful consideration on the phase out of F-gases as refrigerants. Although some of these substances have higher global warming potential than the not-in-kind (NIK) solutions, the increased efficiency due to better thermophysical properties or more efficient systems can lead to lower overall emissions throughout the lifecycle of the systems.

This report below presents the calculations of equivalent CO_2 (CO_{2eq}) emissions and electricity consumption costs for current HFC/HFO refrigerants in comparison to NIK solutions for *Commercial Air-conditioning (AC) and heat pump* sub-uses. The calculations were performed based on estimated system efficiencies for the applications along with the HFC/HFO refrigerant and NIK alternatives shown in Table 1.1.

Table 1.1 - Commercial air conditioning and heat pump applications with HFC/HFO and NIK refrigerants

Application	HFC/HFO		NIK		Average capacity
	Refrigerant	GWP (AR4)	Refrigerant	GWP (AR4)	kW
Light commercial A/C (rooftop) [20 kW<Q<50 kW]	R-1234ze(E)	7	R290	4	30
Light commercial H/P (rooftop) [20 kW<Q<50 kW]	R-455A	146	R290	4	30
Small commercial chiller for A/C [20 kW<Q<100 kW]	R-1234ze(E)	7	R290	4	60
Small commercial chiller for H/P [20 kW<Q<100 kW]	R-1234ze(E)	7	R290	4	60
Medium commercial chiller for A/C [100 kW<Q<500 kW]	R-1234ze(E)	7	R290	4	300
Medium commercial chiller for H/P [100 kW<Q<500 kW]	R-1234ze(E)	7	R290	4	300
Large commercial chiller for A/C [500 kW<Q]	R-1234ze(E)	7	R717	<1	750
Large commercial chiller for H/P [500 kW<Q]	R-1234ze(E)	7	R717	<1	750

The system performance was calculated using both references from performance values in manufacturers' data, when available, and thermodynamic cycle estimations using assumptions that emulate the efficiency of real systems using both HFC/HFO refrigerants and NIK alternatives.

The calculations presented in this section are estimated based on 2023-2043 installation projections for each commercial sector, average CO_2 emission factors and electricity cost in Europe.

2. Investigated Systems

The systems evaluated in this investigation are defined by each application listed in section 1. And will have some effect on the performance calculation for both HFC/HFO and NIK refrigerants. The choice of system type and architecture was done based on what's most used based on market research done by Honeywell. In the commercial sector for lower capacities rooftop systems are used with either an air-to-air configuration or an air-to-water configuration. While for greater capacities chillers are used, with air-water configurations used for small and medium chillers, and water-to-water configurations used for both medium and large chillers.

For light commercial applications rooftop systems are considered for both HFC/HFO and NIK refrigerants. But the HFC/HFO refrigerants use an air-to-air configuration with both indoor and outdoor fin and tube heat exchangers. On the other hand, because the NIK solution (R290) is an A3 refrigerant with limited indoor charges due to flammability, an air-to-water system is used with the entire system packaged on the rooftop and a secondary loop with water or brine pumped indoors.

The R290 systems are all air-water, using a simple compressor, condenser, expansion valve, evaporator cycle architecture. On the other hand, the R1234ze(E) and R455A use a suction line heat exchanger (SLHX) or internal heat exchanger (IHX) which exchanges heat between the outlet of the evaporator and the outlet of the condenser. This component can improve performance for R1234ze(E) and zeotropic blends can use it to increase the average evaporation temperatures (Mota-Babiloni et al., 2015; Domanski and Didion, 1994; Kuratli et al., 1997).

For large commercial chillers both cycles use the same cycle architecture as R290.

To estimate equivalent CO_2 emissions and electricity consumption the yearly installation numbers for light commercial systems and chillers were obtained from several sources. Table 1.2 shows the projected yearly installations in Europe. The compound annual growth rate (CAGR) for each sector is shown at the bottom of the table. The CAGR for light commercial H/P installation was set at 10.0% instead of the predicted to provide reasonable estimates of installation in 2045. All other CAGR values were estimated directly from the data. The BSRIA data for H/P chillers was incomplete, with only Czech Republic, France, Germany, Italy, Netherland, and UK listed, thus the total numbers were extrapolated based on the A/C chiller data from BSRIA. The H/P chiller market analysis by BSRIA also only had sales numbers for 50-100 kW, 1The Large chiller H/P sector was estimated to be 1.2% of the total H/P chiller market, while small H/P chiller are 58.4% and medium are 40.4%.

The values on Table 1.2 for year 2021 and in some cases 2022 are taken from the sources also shown in the table. The projections are extrapolated using a constant growth rate that was adjusted based on the previous years' data for all sectors, expect for the Light Commercial H/P which based on the analysis had inflated numbers due to the natural gas crisis in EU, thus its growth rate of 5.0% was selected to provide a reasonable market size increase.

Table 1.2 - Commercial systems projected yearly installations

Year	Yearly installations							
	Light commercial A/C	Light commercial H/P	Small chiller A/C	Small chiller H/P	Medium chiller A/C	Medium chiller H/P	Large chiller A/C	Large chiller H/P
2021*	**275533**	**260734**	**10179**	**12232**	**29084**	**9504**	**37273**	**264**
2022*	**270379**	**273771**	**10423**	**13081**	**29779**	**10164**	**38164**	**282**
2023	280668	316925	10627	14507	30364	11272	38914	313
2024	288414	332771	10984	15822	31384	12293	40221	341
2025	295913	349410	11353	17024	32438	13227	41572	367
2026	303698	366881	11735	18644	33528	14486	42969	402
2027	312169	385225	12129	20285	34654	15761	44412	438
2028	320850	404486	12536	22071	35818	17149	45904	476
2029	327544	424710	12957	24014	37021	18658	47446	518
2030	332480	445946	13393	26128	38265	20301	49040	564
2031	340078	468243	13843	28428	39550	22088	50687	614
2032	348121	491655	14308	30931	40879	24033	52390	668
2033	357292	516238	14788	33654	42252	26149	54150	726
2034	365906	542050	15285	36617	43672	28451	55969	790

2035	374566	569153	15799	39841	45139	30955	57849	860
2036	383029	597611	16329	43348	46655	33681	59792	936
2037	391081	627492	16878	47164	48222	36646	61801	1018
2038	398828	658867	17445	51317	49842	39872	63877	1108
2039	406346	691810	18031	55834	51516	43382	66022	1205
2040	413641	726401	18636	60750	53247	47201	68240	1311
2041	420370	762721	19262	66098	55036	51357	70533	1427
2042	427068	800857	19910	71917	56884	55878	72902	1552
TOTAL (2023-2042)	**7088062**	**10479452**	**296228**	**724394**	**846366**	**562840**	**1084690**	**15634**
Avg. CAGR	**2.1%**	**5.0%**	**3.3%**	**8.8%**	**3.3%**	**8.8%**	**3.3%**	**8.8%**
Source	**EPEE**	**BSRIA and EHPA**	**BSRIA**	**BSRIA**	**BSRIA**	**BSRIA**	**BSRIA**	**BSRIA**

The chiller market segmentation by capacity, compressor technology and outdoor heat exchanger configuration is given by BSRIA 2018 on A/C chillers shown in Table 1.3 with some approximations eliminating niche markets (<1.0%). The same segmentation numbers will be used for the H/P chillers due to lack of data on this market.

Table 1.3 – Chiller market segmentation

Compressor and outdoor heat exchanger configuration	Capacity ranges		
	Q < 100 kW	100 kW < Q < 500 kW	500 kW < Q
Scroll (air source)	67.0%	26.8%	0.0%
Scroll (water source)	33.0%	12.2%	0.0%
Screw (air source)	0.0%	25.7%	71.3%
Screw (water source)	0.0%	4.5%	12.5%
Centrifugal (air source)	0.0%	0.0%	0.0%
Centrifugal (water source)	0.0%	30.8%	16.2%

The different system refrigerant charges for the indirect emission calculations are shown in Table 1.4. These charges were estimated using catalog data from Daikin, and an investigation on Low-GWP refrigerants for a residential air-source heat pump (Li et al., 2022)

Table 1.4 – Estimated nominal charges for each system

Application	R1234ze(E)	R455A	R290	R1234ze(E)	R717
Light commercial A/C (rooftop) [20 kW<Q<50 kW]	6.8		3.0		
Light commercial H/P (rooftop) [20 kW<Q<50 kW]		7.7	3.0		

Small commercial chiller for A/C [20 kW<Q<100 kW]	11.2		6.0		
Small commercial chiller for H/P [20 kW<Q<100 kW]	11.2		6.0		
Medium commercial chiller for A/C [100 kW<Q<500 kW]	41.4		30.0		
Medium commercial chiller for H/P [100 kW<Q<500 kW]	41.4		30.0		
Large commercial chiller for A/C [500 kW<Q]				117.0	50.0
Large commercial chiller for H/P [500 kW<Q]				117.0	50.0

3. CO_2 emission factors and electricity cost

The emission factor was kept constant because COVID-19 disrupted the trend in emission and with Germany shutting down their nuclear power plants and relying on coal the downward trend in emission factors is uncertain. Two electricity costs were used, one for a low-cost scenario and another for a high-cost scenario. The values for CO_2 emission factor and electricity cost are shown in Table 1.5.

Table 1.5 – Average EU CO_2 emission factor and electricity cost

CO_2 emission factor	Electricity cost
kg CO_2/kWh	€/kWh
0.43	0.15nd 0.49

4. Modelling methodology

The CO_2 emissions are comprised of two parts: direct emissions and indirect emissions. The annual direct emissions are calculated by multiplying the annual refrigerant leak rates (Table 1.6) by the system's nominal charges (Table 1.4) and the refrigerant's Global Warming Potential (GWP) (Table 1.1). The refrigerant leak rates are based on the IPCC report (2019). This calculation is shown in equation 1.

Table 1.6 – System leak rates (IPCC, 2019)

Systems	Light commercial A/C (rooftop)	Light commercial H/P (rooftop)	Small commercial chiller for A/C	Small commercial chiller for H/P	Medium commercial chiller for A/C	Medium commercial chiller for H/P	Large commercial chiller for A/C	Large commercial chiller for H/P
Leak rates (%)	4.0	4.0	6.0	6.0	6.0	6.0	6.0	6.0

$$(Direct\ CO_2\ emision) = (Annual\ leak\ rate) * (Nominal\ charge) * (GWP) \qquad (1)$$

The calculation of indirect CO_2 emissions and electricity cost involves determining the total power consumption of each type of system throughout a year. This is achieved by using performance numbers for each system with its respective refrigerant and generating a linear function of its capacity and COP vs. the outdoor air temperature.

These performance curves are then applied to the bin data for a specific location and can be used to calculate the total system power consumption in kWh. With these values it's possible to estimate the indirect CO_2 emissions using equation 2.

$$(Indirect\ CO_2\ emision) = (Annual\ energy\ consumption) * (CO_2\ emission\ factor) \quad (2)$$

The bin data used for this investigation was of Frankfurt and can be found in BinMaker®Pro. This software has a database of the temperature profiles (in number of hours) throughout the year for several locations. Frankfurt was selected to represent an average EU condition. The bin data for Frankfurt is shown in Table 1.7.

Table 1.7 – Temperature bin data for Frankfurt (BinMaker®Pro v4.0)

Temperature (°C)	32.2	29.4	26.7	23.9	21.1	18.3	15.6	12.8	10.0	7.2	4.4	1.7	-1.1	-3.9	-6.7	-9.4
Hours	2	40	90	220	360	664	964	1043	854	850	1083	1315	946	222	83	24

To determine the performance parameters the systems were modelled using Genetron, a Honeywell software for thermodynamic analysis of vapor-compression cycles. This software can calculate the performance of different cycle architectures with assumptions of average evaporator and condenser saturation temperatures, pressure drops and heat losses across components and connecting lines, isentropic/volumetric compressor efficiencies and effectiveness of internal heat exchangers and economizers.

The building zero load outdoor temperatures were defined based on the 3-story large retail values from Lu et al. (2008) which used the Typical Meteorological Year version 2 (TMY2) from the SAMSOM database by NREL. The rating full load temperature for air conditioning is defined by AHRI 210/240 as the rate capacity at 35°C, while for heat pump a balance point of -3°C is used based on the study by Petrak and Petrak (2018). The cooling and heating zero load and full rating load temperatures are shown in Table 1.8.

Table 1.8 – Zero load, full load and balance point temperatures

Operation	Zero load temperature (°C)	Full load or balance point temperature (°C)
Cooling	12.8	35.0
Heating	18.3	-3.3

These values don't apply to water-water heat pump systems which have an extended operation range, as they are not affected by the outdoor air temperature below 0°C.

For each system type, refrigerant and sector 3-4 data points were calculated using reasonable assumptions of saturation temperatures, pressure drops, isentropic efficiencies, volumetric efficiencies, heat losses, condenser subcooling and evaporator superheat. These points were used to define an EER and capacity curves as a function of the outdoor air temperature which can be used with bin data to provide energy consumption curves for each case. For the heat pump cases auxiliary heat is assumed to be provided by electric heaters when needed at lower outdoor temperatures if the capacity cannot match the load demand.

Table 1.9 to Table 1.20 show the assumptions used for each system type, refrigerant and sector.

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Table 1.9 shows the performance for light commercial air conditioning using an air-air system with IHX for R1234ze(E) and air-water system for R290. The average capacity was taken as 30 kW for this sector and used as a baseline for both system calculations at the rating condition. R290 evaporation temperature are adjusted to consider the secondary fluid heat transfer, while condensing temperatures are the same for both systems. System power considers the calculated compressor power and an extra power to fans, control boards and pumps. For light commercial A/C systems the extra power was assumed to be 0.5 kW. The EER can then be calculated using the total estimated system power and the capacity.

$$W_{system} = W_{compressor} + W_{extra} \quad (3)$$

$$EER = \frac{Q_{capacity}}{W_{compressor} + W_{extra}} \quad (4)$$

Table 1.9 – Light commercial A/C cycle parameters

Refrigerant System type	Compressor types	Operating mode	Outdoor air temperature	Evaporation temperature	Compressor suction superheat	Evaporator pressure drop	Compressor displacement	Compressor isentropic efficiency	Compressor volumetric efficiency	Condensing temperature	Condenser subcooling	Condenser pressure drop	IHX effectiveness	IHX pressure drops	EER	Capacity	System power
			°C	°C	°C	kPa	m3/s	-	-	°C	°C	kPa	-	kPa	-	kW	kW
R1234ze(E) Air-air	Scroll	A/C	30	11.7	12.6	22.0	0.0136	0.75	0.95	40	5.0	24	0.5	LL: 5 SL: 10	5.65	30.87	5.47
R1234ze(E) Air-air	Scroll	A/C	35	12.1	14.8	21.5	0.0136	0.73	0.95	45	5.0	21	0.5	LL: 4 SL: 8	4.78	30.24	6.32
R1234ze(E) Air-air	Scroll	A/C	40	12.5	17.1	21.0	0.0136	0.71	0.95	50	5.0	18	0.5	LL: 3 SL: 6	4.10	29.57	7.23
R1234ze(E) Air-air	Scroll	A/C	45	12.9	19.3	20.5	0.0136	0.69	0.95	55	5.0	15	0.5	LL: 2 SL: 4	3.53	28.87	8.19
R290 Air-water	Scroll	A/C	30	5.8	5.5	16.0	0.00941	0.75	0.95	40	5.0	16	-	-	4.80	31.26	6.60
R290	Scroll	A/C	35	6.3	5.5	15.5	0.00941	0.73	0.95	45	5.0	14	-	-	4.01	30.25	7.54

Air-water																	
R290 Air-water	Scroll	A/C	40	6.8	5.5	15.0	0.00941	0.71	0.95	50	5.0	12	-	-	3.42	29.18	8.53
R290 Air-water	Scroll	A/C	45	7.3	5.5	14.5	0.00941	0.69	0.95	55	5.0	10	-	-	2.93	28.03	9.57

Table 1.10 shows the performance for light commercial heat pump systems. R455A is used for the heat pump operation due to its higher capacities compared with R1234ze(E) which benefit performance at low ambient temperatures. The R455A system has its compressor suction superheat controller while using an IHX as shown in the patent by Kuratli et al. (1997). But R290 shows greater capacities at lower ambient temperatures which reduces auxiliary heat needs. Extra system power for light commercial heat pumps is also assumed to be 0.5 kW.

Table 1.10 – Light commercial H/P cycle parameters

Refrigerant	Compressor types	Operating mode	Outdoor air temperature	Evaporation temperature	Compressor suction superheat	Evaporator pressure drop	Compressor displacement	Compressor isentropic efficiency	Compressor volumetric efficiency	Discharge line temperature drop	Condensing temperature	Condenser subcooling	Condenser pressure drop	IHX effectiveness	IHX pressure drops	EER	Capacity	System power
			°C	°C	°C	kPa	m3/s	-	-	°C	°C	°C	kPa	-	kPa	-	kW	kW
R455A Air-air	Scroll	H/P	8.3	1.72	5.0	18.0	0.00714	0.75	0.95	5.0	35.0	5.0	16	0.5	LL: 5 SL: 10	5.16	29.99	5.81
R455A Air-air	Scroll	H/P	1.7	-5.62	5.0	18.0	0.00714	0.70	0.95	5.0	34.0	5.0	14	0.5	LL: 4 SL: 8	4.10	24.49	5.98
R455A Air-air	Scroll	H/P	-8.3	-14.36	5.0	14.0	0.00714	0.65	0.95	5.0	33.0	5.0	12	0.5	LL: 3 SL: 6	3.24	19.11	5.90
R455A Air-air	Scroll	H/P	-15	-20.86	5.0	11.0	0.00714	0.60	0.95	5.0	32.0	5.0	10	0.5	LL: 2 SL: 4	2.75	15.98	5.81

R290 Air-water	Scroll	H/P	8.3	2.33	5.0	15.0	0.00854	0.75	0.95	5.0	40.0	5.0	16	-	-	4.93	30.01	6.09
R290 Air-water	Scroll	H/P	1.7	-4.33	5.0	13.0	0.00854	0.70	0.95	5.0	39.0	5.0	14	-	-	4.04	25.50	6.31
R290 Air-water	Scroll	H/P	-8.3	-14.33	5.0	10.0	0.00854	0.65	0.95	5.0	38.0	5.0	12	-	-	3.15	19.67	6.25
R290 Air-water	Scroll	H/P	-15	-21	5.0	8.0	0.00854	0.60	0.95	5.0	37.0	5.0	10	-	-	2.68	16.63	6.19

Table 1.11 shows the small chiller A/C systems with similar performance for R1234ze(E) and R290. The small chiller cycles don't use internal heat exchangers and a 1.0 kW of extra system power is assumed. These systems only use scroll compressors but are divided into air-source and water-source, with lower condenser saturation temperatures for the water-source small chillers. Because all chillers considered in this analysis use azeotropic refrigerants the evaporator and condenser pressure drops are defined as saturation temperature changes hereafter.

Table 1.11 – Small chiller A/C cycle parameters

Refrigerant	Compressor types	Operating mode	Outdoor air temperature	Evaporation temperature	Compressor suction superheat	Evaporator saturation temp. drop	Compressor displacement	Compressor isentropic efficiency	Compressor volumetric efficiency	Discharge line temperature drop	Condensing temperature	Condenser subcooling	Condenser saturation temp. drop	EER	Capacity	System power
			°C	°C	°C	°C	m3/s	-	-	°C	°C	°C	°C	-	kW	kW
R1234ze(E) Air-water	Scroll	A/C	30	4.0	5.0	0.5	0.03579	0.75	0.95	5.0	40.0	5.0	1.0	4.57	63.88	13.99
R1234ze(E)	Scroll	A/C	35	4.0	5.0	0.5	0.03579	0.73	0.95	5.0	45.0	5.0	1.0	3.82	60.72	15.90

Air-water																
R1234ze(E) Air-water	Scroll	A/C	40	4.0	5.0	0.5	0.03579	0.71	0.95	5.0	50.0	5.0	1.0	3.22	57.51	17.85
R1234ze(E) Air-water	Scroll	A/C	45	4.0	5.0	0.5	0.03579	0.69	0.95	5.0	55.0	5.0	1.0	2.73	54.26	19.85
R290 Air-water	Scroll	A/C	30	4.0	5.0	0.5	0.0201	0.75	0.95	5.0	40.0	5.0	1.0	4.49	63.67	14.19
R290 Air-water	Scroll	A/C	35	4.0	5.0	0.5	0.0201	0.73	0.95	5.0	45.0	5.0	1.0	3.75	60.62	16.16
R290 Air-water	Scroll	A/C	40	4.0	5.0	0.5	0.0201	0.71	0.95	5.0	50.0	5.0	1.0	3.16	57.50	18.18
R290 Air-water	Scroll	A/C	45	4.0	5.0	0.5	0.0201	0.69	0.95	5.0	55.0	5.0	1.0	2.68	54.30	20.26
R1234ze(E) Water-water	Scroll	A/C	30	4.0	5.0	0.5	0.03402	0.76	0.95	5.0	35.0	5.0	0.5	5.46	63.54	11.64
R1234ze(E) Water-water	Scroll	A/C	35	4.0	5.0	0.5	0.03402	0.74	0.95	5.0	40.0	5.0	0.5	4.51	60.57	13.44
R1234ze(E) Water-water	Scroll	A/C	40	4.0	5.0	0.5	0.03402	0.72	0.95	5.0	45.0	5.0	0.5	3.77	57.56	15.28
R1234ze(E)	Scroll	A/C	45	4.0	5.0	0.5	0.03402	0.70	0.95	5.0	50.0	5.0	0.5	3.17	54.51	17.17

Water-water																
R290 Water-water	Scroll	A/C	30	4.0	5.0	0.5	0.01914	0.76	0.95	5.0	35.0	5.0	0.5	5.37	63.34	11.80
R290 Water-water	Scroll	A/C	35	4.0	5.0	0.5	0.01914	0.74	0.95	5.0	40.0	5.0	0.5	4.43	60.48	13.65
R290 Water-water	Scroll	A/C	40	4.0	5.0	0.5	0.01914	0.72	0.95	5.0	45.0	5.0	0.5	3.70	57.57	15.56
R290 Water-water	Scroll	A/C	45	4.0	5.0	0.5	0.01914	0.70	0.95	5.0	50.0	5.0	0.5	3.12	54.60	17.51

Table 1.12 shows the cycle parameters for the small H/P chillers. The condensing temperature is kept constant assuming indoor water inlet/outlet temperatures of 30°C /35°C, and for the water-water chillers the evaporation temperature is kept at 4.0°C assuming evaporator water inlet/outlet temperatures of 12°C /7°C. Extra system power is 1.0 kW.

Table 1.12 – Small chiller H/P cycle parameters

Refrigerant	Compressor types	Operating mode	Outdoor air temperature	Evaporation temperature	Compressor suction superheat	Evaporator saturation temp. drop	Compressor displacement	Compressor isentropic efficiency	Compressor volumetric efficiency	Discharge line temperature drop	Condensing temperature	Condenser subcooling	Condenser saturation temp. drop	EER	Capacity	System power
			°C	°C	°C	°C	m3/s	-	-	°C	°C	°C	°C	-	kW	kW
R1234ze(E) Air-water	Scroll	H/P	8.3	2.3	5.0	1.0	0.02985	0.75	0.95	5.0	40.0	5.0	0.5	5.13	60.00	11.69
R1234ze(E) Air-water	Scroll	H/P	1.7	-4.3	5.0	1.0	0.02985	0.70	0.95	5.0	40.0	5.0	0.5	4.09	48.51	11.87
R1234ze(E) Air-water	Scroll	H/P	-8.3	-14.3	5.0	1.0	0.02985	0.60	0.95	5.0	40.0	5.0	0.5	3.10	34.60	11.17
R1234ze(E) Air-water	Scroll	H/P	-15	-21	5.0	1.0	0.02985	0.55	0.95	5.0	40.0	5.0	0.5	2.59	27.61	10.67
R290 Air-water	Scroll	H/P	8.3	2.3	5.0	1.0	0.01656	0.75	0.95	5.0	40.0	5.0	0.5	5.07	60.00	11.84
R290 Air-water	Scroll	H/P	1.7	-4.3	5.0	1.0	0.01656	0.70	0.95	5.0	40.0	5.0	0.5	4.06	50.79	12.49
R290 Air-water	Scroll	H/P	-8.3	-14.3	5.0	1.0	0.01656	0.60	0.95	5.0	40.0	5.0	0.5	3.12	39.05	12.52
R290 Air-water	Scroll	H/P	-15	-21	5.0	1.0	0.01656	0.55	0.95	5.0	40.0	5.0	0.5	2.63	32.92	12.53

R1234ze(E) Water-water	Scroll	H/P	-15 to 8.3	4.0	5.0	0.5	0.02808	0.76	0.95	5.0	40.0	5.0	0.5	5.45	59.99	11.00
R290 Water-water	Scroll	H/P	-15 to 8.3	4.0	5.0	0.5	0.01577	0.76	0.95	5.0	40.0	5.0	0.5	5.38	59.98	11.15

Table 1.13 shows the cycle parameters for the medium A/C chillers with scroll and screw compressors. The isentropic efficiency of scroll and screw compressor was assumed to be the same, while centrifugal compressor have higher efficiency, and thus the cycle parameters are shown in Table 1.14. R290 centrifugal chiller catalog data was not found in the literature and Kontomaris et al. (2018) estimated low COP for R290 centrifugal chillers due to its higher operating pressures, thus only R1234ze(E) is considered for the centrifugal chiller section of medium chillers as this refrigerant was found to be suitable for centrifugal compressor (Miyamoto et al., 2019). The extra power consumption for medium chillers is assumed to be 2.5 kW for the EER calculation.

Table 1.13 – Medium chiller A/C cycle parameters (Scroll/Screw compressors)

Refrigerant	Compressor types	Operating mode	Outdoor air temperature	Evaporation temperature	Compressor suction superheat	Evaporator saturation temp. drop	Compressor displacement	Compressor isentropic efficiency	Compressor volumetric efficiency	Discharge line temperature drop	Condensing temperature	Condenser subcooling	Condenser saturation temp. drop	EER	Capacity	System power
			°C	°C	°C	°C	m3/s	-	-	°C	°C	°C	°C	-	kW	kW
R1234ze(E) Air-water	Scroll Screw	A/C	30	4.0	5.0	0.5	0.17684	0.75	0.95	5.0	40.0	5.0	1.0	4.73	315.6	66.69
R1234ze(E) Air-water	Scroll Screw	A/C	35	4.0	5.0	0.5	0.17684	0.73	0.95	5.0	45.0	5.0	1.0	3.94	300.0	76.11
R1234ze(E) Air-water	Scroll Screw	A/C	40	4.0	5.0	0.5	0.17684	0.71	0.95	5.0	50.0	5.0	1.0	3.31	284.2	85.74

R1234ze(E) Air-water	Scroll Screw	A/C	45	4.0	5.0	0.5	0.17684	0.69	0.95	5.0	55.0	5.0	1.0	2.80	268.1	95.62
R290 Air-water	Scroll Screw	A/C	30	4.0	5.0	0.5	0.09948	0.75	0.95	5.0	40.0	5.0	1.0	4.65	315.1	67.77
R290 Air-water	Scroll Screw	A/C	35	4.0	5.0	0.5	0.09948	0.73	0.95	5.0	45.0	5.0	1.0	3.87	300.0	77.51
R290 Air-water	Scroll Screw	A/C	40	4.0	5.0	0.5	0.09948	0.71	0.95	5.0	50.0	5.0	1.0	3.25	284.6	87.51
R290 Air-water	Scroll Screw	A/C	45	4.0	5.0	0.5	0.09948	0.69	0.95	5.0	55.0	5.0	1.0	2.75	268.8	97.81
R1234ze(E) Water-water	Scroll Screw	A/C	30	4.0	5.0	0.5	0.1685	0.76	0.95	5.0	35.0	5.0	0.5	5.70	314.7	55.20
R1234ze(E) Water-water	Scroll Screw	A/C	35	4.0	5.0	0.5	0.1685	0.74	0.95	5.0	40.0	5.0	0.5	4.68	300.0	64.12
R1234ze(E) Water-water	Scroll Screw	A/C	40	4.0	5.0	0.5	0.1685	0.72	0.95	5.0	45.0	5.0	0.5	3.89	285.1	73.25
R1234ze(E) Water-water	Scroll Screw	A/C	45	4.0	5.0	0.5	0.1685	0.70	0.95	5.0	50.0	5.0	0.5	3.27	270.0	82.59
R290 Water-water	Scroll Screw	A/C	30	4.0	5.0	0.5	0.09493	0.76	0.95	5.0	35.0	5.0	0.5	5.60	314.1	56.05

R290 Water-water	Scroll Screw	A/C	35	4.0	5.0	0.5	0.09493	0.74	0.95	5.0	40.0	5.0	0.5	4.60	300.0	65.25
R290 Water-water	Scroll Screw	A/C	40	4.0	5.0	0.5	0.09493	0.72	0.95	5.0	45.0	5.0	0.5	3.82	285.6	74.69
R290 Water-water	Scroll Screw	A/C	45	4.0	5.0	0.5	0.09493	0.70	0.95	5.0	50.0	5.0	0.5	3.21	270.8	84.40

Table 1.14 – Medium chiller A/C cycle parameters (Centrifugal compressors)

Refrigerant	Compressor types	Operating mode	Outdoor air temperature	Evaporation temperature	Compressor suction superheat	Evaporator saturation temp. drop	Compressor displacement	Compressor isentropic efficiency	Compressor volumetric efficiency	Discharge line temperature drop	Condensing temperature	Condenser subcooling	Condenser saturation temp. drop	EER	Capacity	System power
			°C	°C	°C	°C	m3/s	-	-	°C	°C	°C	°C	-	kW	kW
R1234ze(E) Water-water	Centrifugal	A/C	30	4.0	5.0	0.5	0.1685	0.85	0.95	5.0	35.0	5.0	0.5	6.34	314.7	49.62
R1234ze(E) Water-water	Centrifugal	A/C	35	4.0	5.0	0.5	0.1685	0.83	0.95	5.0	40.0	5.0	0.5	5.22	300.0	57.44
R1234ze(E) Water-water	Centrifugal	A/C	40	4.0	5.0	0.5	0.1685	0.81	0.95	5.0	45.0	5.0	0.5	4.36	285.1	65.39
R1234ze(E)	Centrifugal	A/C	45	4.0	5.0	0.5	0.1685	0.79	0.95	5.0	50.0	5.0	0.5	3.68	270.0	73.47

Water-water																

Table 1.15 and Table 1.16 show the cycle parameters for the medium H/P chillers with scroll/screw and centrifugal compressors, respectively. The only difference between this data and the small H/P chillers is the higher capacity and extra power of 2.5 kW.

Table 1.15 – Medium chiller H/P cycle parameters (Scroll/Screw)

Refrigerant	Compressor types	Operating mode	Outdoor air temperature	Evaporation temperature	Compressor suction superheat	Evaporator saturation temp. drop	Compressor displacement	Compressor isentropic efficiency	Compressor volumetric efficiency	Discharge line temperature drop	Condensing temperature	Condenser subcooling	Condenser saturation temp. drop	EER	Capacity	System power
			°C	°C	°C	°C	m3/s	-	-	°C	°C	°C	°C	-	kW	kW
R1234ze(E) Air-water	Scroll Screw	H/P	8.3	2.3	5.0	1.0	0.14926	0.75	0.95	5.0	40.0	5.0	0.5	5.36	300.0	55.94
R1234ze(E) Air-water	Scroll Screw	H/P	1.7	-4.3	5.0	1.0	0.14926	0.70	0.95	5.0	40.0	5.0	0.5	4.27	242.6	56.85
R1234ze(E) Air-water	Scroll Screw	H/P	-8.3	-14.3	5.0	1.0	0.14926	0.60	0.95	5.0	40.0	5.0	0.5	3.24	173.0	53.34
R1234ze(E) Air-water	Scroll Screw	H/P	-15	-21	5.0	1.0	0.14926	0.55	0.95	5.0	40.0	5.0	0.5	2.72	138.1	50.84
R290 Air-water	Scroll Screw	H/P	8.3	2.3	5.0	1.0	0.08281	0.75	0.95	5.0	40.0	5.0	0.5	5.29	300.0	56.71
R290 Air-water	Scroll Screw	H/P	1.7	-4.3	5.0	1.0	0.08281	0.70	0.95	5.0	40.0	5.0	0.5	4.23	254.0	59.98
R290	Scroll	H/P	-8.3	-14.3	5.0	1.0	0.08281	0.60	0.95	5.0	40.0	5.0	0.5	3.25	195.3	60.13

Air-water	Screw															
R290 Air-water	Scroll Screw	H/P	-15	-21	5.0	1.0	0.08281	0.55	0.95	5.0	40.0	5.0	0.5	2.74	164.6	60.17
R1234ze(E) Water-water	Scroll Screw	H/P	-15 to 8.3	4.0	5.0	0.5	0.14042	0.76	0.95	5.0	40.0	5.0	0.5	5.71	300.0	52.50
R290 Water-water	Scroll Screw	H/P	-15 to 8.3	4.0	5.0	0.5	0.07887	0.76	0.95	5.0	40.0	5.0	0.5	5.63	300.0	53.26

Table 1.16 – Medium chiller H/P cycle parameters (Centrifugal compressors)

Refrigerant	Compressor types	Operating mode	Outdoor air temperature	Evaporation temperature	Compressor suction superheat	Evaporator saturation temp. drop	Compressor displacement	Compressor isentropic efficiency	Compressor volumetric efficiency	Discharge line temperature drop	Condensing temperature	Condenser subcooling	Condenser saturation temp. drop	EER	Capacity	System power
			°C	°C	°C	°C	m3/s	-	-	°C	°C	°C	°C	-	kW	kW
R1234ze(E) Water-water	Centrifugal	H/P	-15 to 8.3	4.0	5.0	0.5	0.14295	0.85	0.95	5.0	40.0	5.0	0.5	6.25	300.0	48.01

Table 1.17 and Table 1.18 show the cycle parameters for the large A/C chillers with scroll/screw and centrifugal compressors, respectively. Ammonia generally uses reciprocating and screw compressors, so centrifugal compressors were only considered for R1234ze(E). The extra power for large chillers was assumed to be 6 kW.

Table 1.17 – Large chiller A/C cycle parameters (Scroll/Screw compressors)

Refrigerant	Compressor types	Operating mode	Outdoor air temperature	Evaporation temperature	Compressor suction superheat	Evaporator saturation	Compressor displacement	Compressor isentropic	Compressor volumetric	Discharge line temperature drop	Condensing temperature	Condenser subcooling	Condenser saturation	EER	Capacity	System power

Honeywell

						temp. drop		efficiency	efficiency				temp. drop			
			°C	°C	°C	°C	m3/s	-	-	°C	°C	°C	°C	-	kW	kW
R1234ze(E) Water-water	Scroll Screw	A/C	30	4.0	5.0	0.5	0.44211	0.75	0.95	5.0	40.0	5.0	1.0	5.11	789.06	154.40
R1234ze(E) Water-water	Scroll Screw	A/C	35	4.0	5.0	0.5	0.44211	0.70	0.95	5.0	45.0	5.0	1.0	4.23	750.01	179.52
R1234ze(E) Water-water	Scroll Screw	A/C	40	4.0	5.0	0.5	0.44211	0.60	0.95	5.0	50.0	5.0	1.0	3.55	710.41	206.08
R1234ze(E) Water-water	Scroll Screw	A/C	45	4.0	5.0	0.5	0.44211	0.55	0.95	5.0	55.0	5.0	1.0	3.00	670.22	234.35
R717 Air-water	Scroll Screw	A/C	30	4.0	5.0	0.5	0.18815	0.75	0.95	5.0	40.0	5.0	1.0	4.87	766.86	157.31
R717 Air-water	Scroll Screw	A/C	35	4.0	5.0	0.5	0.18815	0.70	0.95	5.0	45.0	5.0	1.0	4.10	750.01	182.90
R717 Air-water	Scroll Screw	A/C	40	4.0	5.0	0.5	0.18815	0.60	0.95	5.0	50.0	5.0	1.0	3.49	732.99	209.80
R717 Air-water	Scroll Screw	A/C	45	4.0	5.0	0.5	0.18815	0.55	0.95	5.0	55.0	5.0	1.0	3.01	715.76	238.13
R1234ze(E) Water-water	Scroll Screw	A/C	30	4.0	5.0	0.5	0.42126	0.76	0.95	5.0	35.0	5.0	0.5	5.71	786.76	137.76

R1234ze(E) Water-water	Scroll Screw	A/C	35	4.0	5.0	0.5	0.42126	0.74	0.95	5.0	40.0	5.0	0.5	4.69	750.00	160.06
R1234ze(E) Water-water	Scroll Screw	A/C	40	4.0	5.0	0.5	0.42126	0.72	0.95	5.0	45.0	5.0	0.5	3.90	712.76	182.87
R1234ze(E) Water-water	Scroll Screw	A/C	45	4.0	5.0	0.5	0.42126	0.70	0.95	5.0	50.0	5.0	0.5	3.27	675.01	206.23
R717 Water-water	Scroll Screw	A/C	30	4.0	5.0	0.5	0.18422	0.76	0.95	5.0	35.0	5.0	0.5	5.66	766.35	135.29
R717 Water-water	Scroll Screw	A/C	35	4.0	5.0	0.5	0.18422	0.74	0.95	5.0	40.0	5.0	0.5	4.70	750.02	159.63
R717 Water-water	Scroll Screw	A/C	40	4.0	5.0	0.5	0.18422	0.72	0.95	5.0	45.0	5.0	0.5	3.96	733.52	185.24
R717 Water-water	Scroll Screw	A/C	45	4.0	5.0	0.5	0.18422	0.70	0.95	5.0	50.0	5.0	0.5	3.38	716.84	212.20

Table 1.18 – Large chiller A/C cycle parameters (Centrifugal compressors)

Refrigerant	Compressor types	Operating mode	Outdoor air temperature	Evaporation temperature	Compressor suction superheat	Evaporator saturation temp. drop	Compressor displacement	Compressor isentropic efficiency	Compressor volumetric efficiency	Discharge line temperature drop	Condensing temperature	Condenser subcooling	Condenser saturation temp. drop	EER	Capacity	System power
			°C	°C	°C	°C	m3/s	-	-	°C	°C	°C	°C	-	kW	kW

R1234ze(E) Water-water	Centrifugal	A/C	30	4.0	5.0	0.5	0.42126	0.85	0.95	5.0	35.0	5.0	0.5	6.35	786.76	123.81
R1234ze(E) Water-water	Centrifugal	A/C	35	4.0	5.0	0.5	0.42126	0.83	0.95	5.0	40.0	5.0	0.5	5.23	750.00	143.36
R1234ze(E) Water-water	Centrifugal	A/C	40	4.0	5.0	0.5	0.42126	0.81	0.95	5.0	45.0	5.0	0.5	4.37	712.76	163.22
R1234ze(E) Water-water	Centrifugal	A/C	45	4.0	5.0	0.5	0.42126	0.79	0.95	5.0	50.0	5.0	0.5	3.68	675.01	183.42

Table 1.19 and Table 1.20 show the cycle parameters for the medium H/P chillers with scroll/screw and centrifugal compressors, respectively.

Table 1.19 – Large chiller H/P cycle parameters (Scroll/Screw)

Refrigerant	Compressor types	Operating mode	Outdoor air temperature	Evaporation temperature	Compressor suction superheat	Evaporator saturation temp. drop	Compressor displacement	Compressor isentropic efficiency	Compressor volumetric efficiency	Discharge line temperature drop	Condensing temperature	Condenser subcooling	Condenser saturation temp. drop	EER	Capacity	System power
			°C	°C	°C	°C	m3/s	-	-	°C	°C	°C	°C	-	kW	kW
R1234ze(E) Air-water	Scroll Screw	H/P	8.3	2.3	5.0	1.0	0.37315	0.75	0.95	5.0	40.0	5.0	0.5	5.37	749.99	139.61
R1234ze(E) Air-water	Scroll Screw	H/P	1.7	-4.3	5.0	1.0	0.37315	0.70	0.95	5.0	40.0	5.0	0.5	4.27	606.48	141.88

R1234ze(E) Air-water	Scroll Screw	H/P	-8.3	-14.3	5.0	1.0	0.37315	0.65	0.95	5.0	40.0	5.0	0.5	3.25	432.53	133.10
R1234ze(E) Air-water	Scroll Screw	H/P	-15	-21	5.0	1.0	0.37315	0.60	0.95	5.0	40.0	5.0	0.5	2.72	345.15	126.84
R717 Air-water	Scroll Screw	H/P	8.3	2.3	5.0	1.0	0.16234	0.75	0.95	5.0	40.0	5.0	0.5	5.39	750.01	139.21
R717 Air-water	Scroll Screw	H/P	1.7	-4.3	5.0	1.0	0.16234	0.70	0.95	5.0	40.0	5.0	0.5	4.31	620.33	143.87
R717 Air-water	Scroll Screw	H/P	-8.3	-14.3	5.0	1.0	0.16234	0.65	0.95	5.0	40.0	5.0	0.5	3.30	457.79	138.56
R717 Air-water	Scroll Screw	H/P	-15	-21	5.0	1.0	0.16234	0.60	0.95	5.0	40.0	5.0	0.5	2.78	373.80	134.49
R1234ze(E) Water-water	Scroll Screw	H/P	-15 to 8.3	4.0	5.0	0.5	0.35105	0.76	0.95	5.0	40.0	5.0	0.5	6.02	750.01	124.60
R717 Water-water	Scroll Screw	H/P	-15 to 8.3	4.0	5.0	0.5	0.15358	0.76	0.95	5.0	40.0	5.0	0.5	5.74	749.98	130.71

Table 1.20 – Large chiller H/P cycle parameters (Centrifugal compressors)

Refrigerant	Compressor types	Operating mode	Outdoor air temperature	Evaporation temperature	Compressor suction superheat	Evaporator saturation temp. drop	Compressor displacement	Compressor isentropic efficiency	Compressor volumetric efficiency	Discharge line temperature drop	Condensing temperature	Condenser subcooling	Condenser saturation temp. drop	EER	Capacity	System power
			°C	°C	°C	°C	m3/s	-	-	°C	°C	°C	°C	-	kW	kW

R1234ze(E) Water-water	Centrifugal	H/P	-15 to 8.3	4.0	5.0	0.5	0.35735	0.85	0.95	5.0	40.0	5.0	0.5	6.49	750.0	115.50

5. Results and Discussions

Table 1.21 shows the total energy consumption, electricity costs and CO_2 emissions for both the HFC/HFO and NIK refrigerants. The results for CO_2 avoidance and electricity cost reduction over 20 years comparing HFC/HFO refrigerants and NIK solutions are shown in Figure 1.1. The results are also presented in Table 1.22. Every sector, except for the small chillers, shows both a reduction in CO_2 emissions and electricity cost. The main contributor is the light commercial heat pump sector with values inflated by the installation numbers which are projected to increase significantly with the replacement of gas furnaces/boilers.

Table 1.21 – Total energy consumption, electricity costs and CO_2 emissions for HFO refrigerants vs. NIK alternatives over a 20-year period

Commercial sector	Annualized Energy Consumption		Total Electricity Cost Lifetime (0.15 €/kWh)		Total Electricity Cost Lifetime (0.49 €/kWh)		Lifetime CO_2 Emissions	
	GWh		Billion €		Billion €		Mt	
	HFC/HFO	NIK	HFC/HFO	NIK	HFC/HFO	NIK	HFC/HFO	NIK
Light Commercial A/C	189615	225298	28.4	33.8	92.9	110.4	81.7	96.9
Light Commercial H/P	1980247	2031261	297.0	304.7	970.3	995.3	855.7	873.5
Small Chillers A/C	14520	14760	2.2	2.2	7.1	7.2	6.3	6.4
Small Chillers H/P	241379	241353	36.2	36.2	118.3	118.3	103.8	103.8
Medium Chillers A/C	81024	89407	12.2	13.4	39.7	43.8	35.0	38.5
Medium Chillers H/P	1693292	1724383	254.0	258.7	829.7	844.9	728.2	741.5
Large Chillers A/C	208237	219942	31.2	33.0	102.0	107.8	90.0	94.7
Large Chiller H/P	61025	61176	9.2	9.2	29.9	30.0	26.2	26.3
Total	**4469339**	**4607580**	**670.4**	**691.2**	**2189.9**	**2257.7**	**1926.9**	**1981.6**

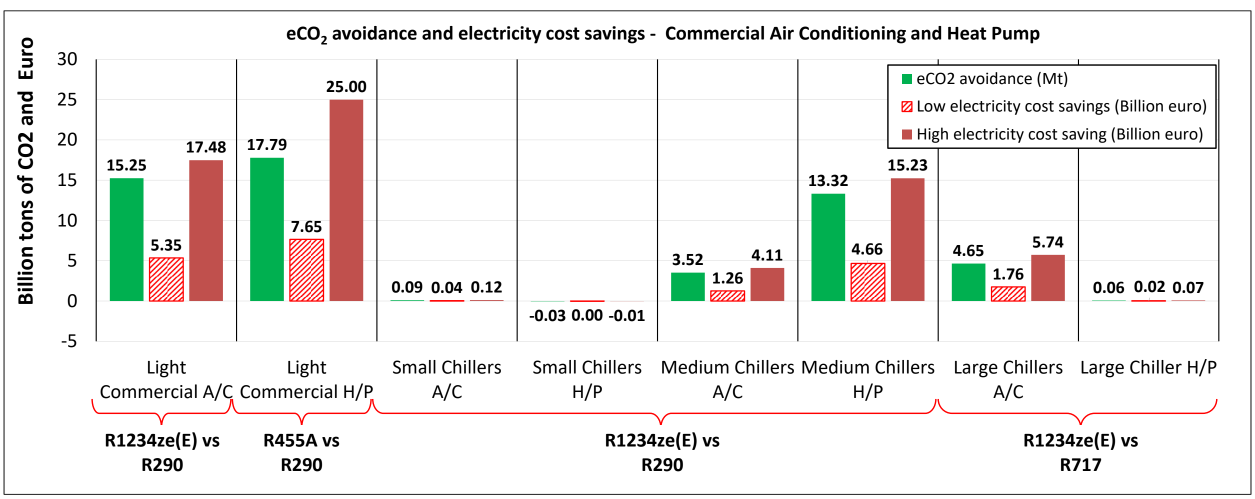

Figure 1.1 - CO_2 avoidance and electricity cost savings of HFC/HFO refrigerants vs. NIK alternatives over a 20-year period

Table 1.22 – CO_2 avoidance energy savings and electricity cost savings of HFC/HFO refrigerants vs. NIK alternatives over a 20-year period

Commercial sector	eCO_2 avoidance	Energy Savings	Electricity Cost Savings (0.15 €/kWh)	Electricity Cost Savings (0.49 €/kWh)
	Mt	GWh	Billion €	Billion €
Light Commercial A/C	15.25	35684	5.35	17.48
Light Commercial H/P	17.79	51014	7.65	25.00
Small Chillers A/C	0.09	240	0.04	0.12
Small Chillers H/P	-0.03	-26	0.00	-0.01
Medium Chillers A/C	3.52	8382	1.26	4.11
Medium Chillers H/P	13.32	31090	4.66	15.23
Large Chillers A/C	4.65	11706	1.76	5.74
Large Chiller H/P	0.06	152	0.02	0.07
Total commercial sector	**54.66**	**138242**	**20.74**	**67.74**

The only sector where R290 shows lower emissions and power consumption is for the small chillers. The main reason is in this specific sector both systems use a basic A/C-H/P cycle with a scroll compressor, condenser, expansion device and evaporator. For this specific case R290 can outperform R1234ze(E), especially in low temperature heating conditions (<-5°C). If the small chillers were to use more sophisticated cycle architectures, such as an economizer with two-stage compression, R1234ze(E) would outperform R290. Another possible HFO solution for small H/P chillers would be R455A with IHX which should also outperform R290. For medium and large chillers, the HFO solutions can outperform R290 and R717 because of the higher isentropic efficiencies from centrifugal R1234ze(E) compressors.

R290 and R717 still have safety concerns in these large capacity applications with high charges that will require strict safety guidelines in order to prevent any fatal accidents, while R1234ze(E) with its A2L classification, per ASHRAE 34, would not have as severe safety requirements and could have overall lower capital and operational costs.

6. Conclusions

This investigation showed that by using HFO refrigerants it's possible to significantly reduce CO_2 emissions and energy consumption of the commercial A/C and H/P sector when compared to completely migrating to NIK solutions, such as R290 and R717. The analysis used performance parameters that agreed with literature and catalog data.

Most sectors showed a reduction in emissions and energy consumption, except for the small chillers, where R290 and R1234ze perform very similarly with a slight edge to R290 in heat pump due to its better properties at low ambient temperatures.

Overall, by allowing the use of HFO refrigerants it's possible to avoid 54.66 million tons of eCO_2 emissions and save 20.74 to 67.74 billion euros over a span of 20 years.

This analysis assumed the current technologies for HFC/HFO refrigerants, which haven't been as thoroughly researched as the NIK solutions, R290 and R717. Section 2d includes a brief statement on the future technologies that could improve efficiency and capacity for HFC/HFO refrigerants.

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