REPORT

Can refrigerants with a GWP below 150 be used for split air conditioners in Europe?

June 2022

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Contents

Brief summary

The viability of applying alternative refrigerants with a GWP < 150 to reversible room air conditioning systems (RACS) with nominal cooling capacities below 12 kW is considered. The assessment reflects the proposed revision to the European F-gas regulation. This class of RACS currently uses R410A and R32, whereas alternative refrigerants with GWP < 150 under consideration are primarily R1270, R290 and secondarily R1234yf and R152a; all of which are flammable.

Using the Eurovent database and extending it for additional parameters such as refrigerant charge, physical size and weight and retail price, general characteristics of these products are mapped out with particular attention to the parameters that may be affected by refrigerant selection.

From these data, along with information on the currently available R290 RACS, as well as results from heat exchanger calculations, refrigerant charge for R1270, R290, R1234yf and R152a is estimated for a range of hypothetical models covering a range of 2 – 12 kW and seasonal efficiency levels from 4 to 12.

Information on average, high and extreme thermal loads for conditioned spaces across Europe is also obtained. Combining these thermal loads with the flammable refrigerant charge limits specified within the revised safety standard, IEC 60335-2-40: 2022, provides a framework for determining the applicability of RACS using alternative refrigerants.

Further, outputs from heat exchanger calculations and analysis of compressor product data provides a strong indication as to differences in RACS refrigeration system materials arising from a switch to the alternative refrigerants (whilst maintaining the same seasonal efficiency). Additionally, material requirements associated with compliance to the safety standard are also quantified. Differences in materials and other inputs are used to determine implications of cost, equipment size and lifetime carbon dioxide equivalent (CO_2e) emissions.

The main findings are:

- For the entire RACS capacity range, all seasonal energy efficiency ratios (up to SEER = 12) and average, high and extreme space thermal loads, all the alternative refrigerants can be applied within the charge limits of the standard. With R290, when additional 20 m interconnecting piping is assumed and “over-sizing” due to absence of precisely matched RACS capacities, the charge amount can exceed the upper charge limit for capacities above 10 kW. However, due to its higher LFL, R1270 would not be constrained.
- To achieve the same seasonal efficiency as R410A, additional heat exchanger materials are required for R1234yf and R152a. Compared to R32, additional material is also required for R1270 and R290. The cost implication is relatively small, in the order of a few Euros. The cost implication for additional safety features for R1270 and R290 are also minor, a few Euros, especially when considering higher efficiency products that already use electronic expansion valves.
- Emissions associated with use of the additional materials are negligible, especially when compared with those associated with the lifetime emissions from refrigerants with GWP > 150.
- The cost effectiveness of switching to alternative refrigerants, from R410A or R32, are favourable. With R1270 and R290, emissions reductions are achieved in parallel with lifetime cost reductions. For R152a additional expenditure is likely required but cost-effectiveness is still low. Due to the high costs associated with R1234yf, due to much greater material mass and quantities of expensive refrigerant, cost-effectiveness, especially relative to R32, is high – above that of the European Carbon Trading Scheme – suggesting questionable viability.
- The database, simulations and other sources from which the information was gathered is extensive. The treatment and analysis were thorough, usually being approached both practically (break-down

of real equipment data) and theoretically (upward simulation of components) to check that findings were consistent using different methodologies. Furthermore, where notable uncertainties are associated with any inputs, reasonably pessimistic assumptions were used so as to disadvantage the proposed alternatives. Accordingly, the results and conclusions are considered to have a high level of confidence.

- Discussions with manufacturers and various literature sources indicate a variety of developments related to charge reduction and performance improvements with R1270 and R290, provided sufficient time is available. Adoption of such improvements as well as general technology refinements suggests that future iterations of alternative refrigerant RACS will help further extend their cost-effective applicability.

Main summary

1 Introduction

- The viability of applying selected refrigerants with a GWP < 150 to reversible room air conditioning systems (RACS) with nominal cooling capacities below 12 kW is considered. The assessment reflects the proposed revision to the European F-gas regulation.
- This class of RACS currently use R410A and R32, whereas alternative refrigerants with GWP < 150 under consideration are primarily R1270, R290 and secondarily R1234yf and R152a.
- Application of these alternatives is evaluated with regards to the extended use of flammable refrigerants enabled by the revised safety standard for air conditioners and heat pumps, IEC 60335-2-40: 2022.
- The criteria against which the viability is assessed are:
  - Product safety, through compliance with safety standards, primarily related to refrigerant charge limits necessary for high efficiency RACS.
  - Cost for the consumer, through impact on material costs and whether adoption of the alternatives would result in an adverse increase in cost.
  - Environmental impact, through assessment of carbon dioxide equivalent (CO_2e) emissions
- The assessment is carried out through the use of a publicly-available RACS database (Eurovent) which was extended to include refrigerant charge, product mass and dimensions and pricing. Aspects assessed include performance analysis of the refrigerant-RACS combinations considering heat exchanger and piping design, quantification of mass and dimensions of system components, costs and associated CO_2e emissions.

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Charge limit requirements

- Charge limit requirements of IEC 60335-2-40: 2022 provide a variety of additional measures to enable greater charge quantities to be used within a given room floor area. These are broadly 2 – 3 times the basic charge limits (per unit of floor area).
- Provided the additional mitigation measures are adopted, relatively large room areas and thermal capacities can now be served with A3 and A2 refrigerants.

3 Heating and cooling loads

- Use of appropriate thermal (heating or cooling) loads for the applications where RACS are applied is crucial for a realistic assessment. Thermal loads are used to match a RACS cooling (and/or heating) capacity to a given room size.
- Various studies and industry sources were used to identify appropriate values for across Europe.
- For both heating and cooling, a reasonable average value of 100 W/m^2 was identified, with 150 W/m^2 being regarded is a "high" thermal load. An "extreme" value of 200 W/m^2 – more representative of high ambient regions – was also considered.
- "Over-sizing" of RACS is accounted for, where an exact match between an application's thermal load and capacity is not possible, due to a capacity gap between RACS models; often "the next size up" RACS may be chosen if a model with a close match to the thermal load is unavailable.

4 RACS performance and product data

- To provide RACS baseline data the Eurovent database is used, which includes nominal cooling capacity (NCC), heating capacity, cooling and heating efficiencies and various other values. The database was extended to include refrigerant charge quantities, mass and volume of the RACS and retail price.
- This database amounted to about 2500 split-type RACS, including wall, ceiling cassette, ceiling&floor, floor standing, ducted and console types. Analysis of the data indicates that across all these models, only comprise about 250 different refrigerating systems. Thus, numerous models only differ by colour/ packaging, functional features and so on.
- Seasonal energy efficiency (SEER) values range from 4.5 to 10.5 and seasonal coefficient of performance (SCOP) from 3.5 to 6.5. However, the vast majority of products are between SEER = 5 – 8.5 and SCOP = 4 – 5.
- On average, nominal heating capacity is 15% lower than NCC.
- Broadly, RACS total volume and mass (i.e., IDU + ODU) increase as NCC does. However, for a given NCC, the largest total volume or mass is double that with the lowest volume or mass. There is no clear difference between the volume and mass of R32 and R410A models with the same NCC and SEER.
- Refrigerant charge roughly rises with higher NCC, although, for a given capacity the highest charge quantity can be up to three times that of the lowest charge quantity. This is a strong indication that little regard is given to charge minimisation and that significant reductions are feasible in most cases. For a given NCC, there is no clear variation in charge across the range of SEERs, although overall slightly lower charges are seen with R32 for some models. Refrigerant charge is consistent across all types of split RACS.
- Greatest variation amongst all the parameters is retail price, by up to a factor of seven at the same NCC. There is no discernible influence of SEER on the price and there is not even a correlation

between price and total material mass. Similarly, use of R32 or R410A does not lead to any differences in price.

- Evidently, RACS are seldom designed with regards to minimising refrigerant charge and similarly RACS physical size and mass appear not to be reduced when they could be. This observation is further amplified when considering normalised retail price. Most characteristics of RACS, including price (except refrigerant charge) are not influenced by the switch from R410A to R32. Any contribution that efficiency-affecting components have on cost are eclipsed by other factors such as other technical features and supply-chain profit margins.
- Available data is also compiled for a small selection of R290 RACS, including reversible models from China and Europe and cooling-only from India and South America. Although the number of models is less than 1% of the number of R410A and R32 models in the database, the product data provides a strong indication as to what is achievable with R290 and potentially other alternatives with GWP < 150.

5 Mandated efficiency levels

- Current minimum efficiency is SEER = 4.3 – 4.6 with highest energy efficiency level set to SEER > 8.5.
- Proposed revised minimum efficiency is SEER = 5.5 – 6.0 with highest energy efficiency level set to SEER > 11.5.
- RACS using alternative refrigerants with GWP < 150 must be able to achieve these efficiency levels without incurring adverse costs and increasing CO_2e emissions.

6 Efficiency and alternative refrigerants

- As a first step, alternative refrigerants are assessed with regards to their thermodynamic cycle efficiency. This cycle efficiency represents a theoretically ideal case in absence of thermal and other energetic losses, representing the potential performance that a refrigerant could achieve in absence of practical and economic constrains.
- R410A and R32 exhibit lowest cycle efficiencies, R290, R1270 and R1234yf have about 6 – 7% higher and R152a about 11% higher COP. The rankings apply to both cooling and heating efficiency. R290 and R1270 have about 5 to 15% lower compression ratio – which is associated with higher compressor efficiency – than the other refrigerants. R290, R1270 and R1234yf also have notably lower compressor discharge temperatures, which are usually favoured for compressor and system longevity.
- However, R1270 and R290 have higher suction swept volume than R410A and R32 and R1234yf and R152a higher values still. Swept volume is an indicate of circuit volume flow rates and thus potential flow velocities and circuit pressure drops (although fluid viscosity must also be considered). Assuming the same component (piping, heat exchangers, etc.) sizes, a higher swept volume infers greater pressure drop, leading to a higher rate of efficiency degradation from the ideal thermodynamic cycle. Alternatively, larger, more costly components are used to negate the higher pressure drop.
- For a specified system efficiency (for all refrigerants), tolerable condenser- and evaporator-side losses are determined for which heat exchanger selections and interconnecting pipe sizes are made. Broadly, when targeting high system efficiency according to the proposed revised Ecodesign rules, R1270, R290 and R1234yf can tolerate about 0.5 K and R152a, 1.0 K larger condenser and evaporator temperature differences compared to R410A and R32.

7 Heating capacity of reversible systems

- Across the database, on average nominal rated heating capacity is about 85% of the NCC and across the different RACS models heating capacity varies by up to ±50% of the average.
- Available data for reversible R290 models shows all RACS have a heating capacity greater than NCC and for 3.5 kW NCC models, they can offer higher heating capacity than any of the R410A or R32 models.

8 Approximation of charge amounts

- Fundamental to the assessment is the approximation of required refrigerant charge for RACS using alternative refrigerants, particularly for RACS of efficiencies and NCCs not currently commercially available. In particular for reversible RACS with NCC between 6 – 12 kW and SEER = 8 – 12 across the entire capacity range. This has been achieved through extrapolation of existing (R410A, R32) product data, adjusting for refrigerant properties, results of heat exchanger simulation design analysis and real R290 RACS product data.
- Whilst theoretically, it is supposed that higher efficiency RACS would demand greater refrigerant charge, data for R410A and R32 show huge scatter, implying that (at least at present) systems are not charge-optimised. This is likely due to the unrestrictive charge limits in safety standards and the relatively low cost of refrigerant.
- Conversely, larger capacity RACS (irrespective of efficiency) clearly utilise smaller specific refrigerant charges (charge per NCC), which is due to relatively diminishing internal appendage volumes, such as exchanger headers and compressor chambers.
- A best-fit correlation for lowest specific charge as a function of NCC and SEER is developed from the database. Adjustments are included according to refrigerant density and further refinements based on fitting the correlation pessimistically to data from existing R290 RACS models. Evaporator and condenser working charges from the heat exchanger simulations are used to cross-check variation in R290 specific charge over a range of system efficiencies.
- Further approximations are made for additional interconnecting piping across the range of RACSs.
- For the same NCC and SEER, current R290 models are seen to have a disproportionately lower specific charge (i.e., beyond density effects), which is likely to have been driven by the stringent charge size limitations prescribed in earlier editions of the safety standard.
- Graphs of required charge amount for hypothetical RACS employing alternative refrigerants, incrementally over a range of NCC, SEER and interconnecting pipe lengths are generated.

9 RACS charge requirements in relation to charge limits

- Charge quantities of the hypothetical RACS with incrementally higher SEERs are superimposed on the charge limits from IEC 60335-2-40 are presented, specifically for high and excessive thermal loads and with 0 m and 20 m additional interconnecting piping.
- Under all conditions, R1234yf and R152a fall within the limits of the standard. R290 RACS also fall within the charge limits, except for NCC above 10 kW with 20 m additional piping. In these cases, the RACS charge exceeds the upper charge limit (UCL). Due to the higher LFL of R1270, RACS could be accommodated across all such circumstances.
- Since the UCL is an arbitrary boundary (rather than being strictly linked to any safety function), it could be raised to better accommodate the use of R290 in larger NCC models with additional interconnecting piping.

10 Component material mass and costs

- With refrigerants have differing thermophysical properties, each have distinctive potential impacts on material requirements. Based on a high efficiency 5 kW RACS, main system component material requirements are approximated using simulations and catalogue data, as appropriate, with regards to the target efficiency, corresponding temperature differences and associated pressure drops.

- For system piping, diameter is determined according to a fixed change in saturated refrigerant temperature, corresponding to 0.1 K per metre; thus, those with higher pressure loss and lower saturation pressure usually necessitate a larger diameter and greater material mass, although conversely, wall thickness can be thinner for lower pressure refrigerants in turn reducing or offsetting the mass. Material requirements for R410A, R32 and R1234yf are similar, whereas R1270, R290 and R152a potentially require about 20 – 40% less copper and corresponding cost.
- Analysis of catalogue data for rotary, but also other types of compressors (for perspective) shows that material mass, primarily steel, is almost identical for a given NCC. Similar trade-offs between volume and wall thickness observed with piping similarly apply to compressors. There is no evidence to suggest that there should be any difference in compressor cost amongst the alternative refrigerants.
- Performance of numerous evaporators and condensers designs are simulated and the most appropriate are selected based on target temperature differences and tolerable pressure drops to ensure design capacity with minimum material cost and refrigerant mass, as appropriate. R32 requires least mass, followed by R1270, R290 and R410A, with R152a and R1234yf demanding most materials. The difference between R1234yf and R32 is almost 50% for the evaporator and 100% for the condenser.
- Considering total component cost of the heat exchangers, i.e., including cost for the operating refrigerant mass, skews the ranking, but nevertheless amplifies the difference between R32 and R1234yf; doubling or tripling the differences for mass alone.
- Examination of materials and costs for implementing the safety measures are quantified. On the basis of high efficiency reversible systems, incremental costs for R290 or R1270 are minor, perhaps €1 to €3 and additional material implications negligible (provided production-level output in the 10s or 100s of thousands of units per year). For lower efficiency, cooling-only RACS the additional cost could be greater due to the need for additional shut-off valves, where electronic expansion valves and reversing valves are not present; although for such systems limited releasable charge measures are unlikely to be required due to smaller charge requirements. Almost no such safety-related costs would be necessary for R152a or R1234yf.
- Total incremental cost, also including for shipping and storage of slightly larger physical RACS, indicates R410A, R32, R1270, R290 and R152a within ±€10 of each other. R32 and R1270 have least cost, then R290, R410A and R152a. In contrast is R1234yf, for which the incremental cost is over €100.
- Compared to the average retail price of a 5 kW RACS, the incremental cost of all alternatives is within ±1%, except R1234yf which approaches an increase of 10%. Since the analysis of current products does not show any relationship between SEER, total mass and retail price, it is unlikely that such minor changes arising from use of R1270, R290 or even R152a would result in an observable difference.

11 Greenhouse gas emissions

- CO_2e emissions are calculated according to the differences in materials mass from system construction associated with each alternative refrigerant and the refrigerant emissions themselves during the assumed lifetime of the RACS. Conventional assumptions are used for the latter. Emissions arising from energy consumption are negated since RACS for all alternatives are designed for the same seasonal efficiency.

- Emissions associated solely with the construction materials are around 50 – 90 $kgCO_2e$. Incremental materials emissions associated with the choice of refrigerant are within ±10 $kgCO_2e$ for R410A, R32, R1270 and R290, with R32 being the least and R290 the highest. R152a and R1234yf are responsible for an additional 30 kgCO2e.
- However, considering the GWP effect of refrigerant emissions during in-use and at end of life, the contribution of construction materials is negligible in comparison. R32 contributes about 1200 $kgCO_2e$ and R410A, about 4000 $kgCO_2e$, 30 and 70 times the production emissions. Using a 20 y GWP significantly exaggerates this, doubling the value for R410A and tripling the value for R32 (and R152a). Emissions for R1270, R290 and R234yf are unaffected by the choice of GWP time horizon.
- Considering the incremental costs with respect to emissions reduction, all the alternatives show attractive cost-effectiveness, regardless of whether R410A or R32 are used as the baseline. R1270, R290 and R152a are always below €1/tCO_2e (in fact, negative). However, R1234yf has values of about €30/tCO_2e, being potentially more expensive than credits under the European carbon Trading Scheme.

12 Further considerations

- IDU and ODU noise levels have not been considered in detail. The database indicates no discernible difference between R32 and R410A. previous experience with the switch from R134a to R600a was accompanied with significant reduction in domestic fridge noise levels and this was attributed to lower refrigerant pressure and certain oil use. Therefore, it is unlikely that use of any of the alternatives would result is an increase of noise levels.
- A review of recent articles covering improvement of energy efficiency and charge reduction was carried out, to provide an impression of possible near-term developments. These studies indicate significant improvements are imminent and that the “highest efficiency for least charge” boundary is still some way off.
- Whilst not easily quantifiable, a crucial issue pertinent to the discussion is that of development duration. Although revised designs of RACS using alternative refrigerants, including R1270 and R290, can be realised relatively quickly (a year or two), development of compressors can impose a significant hindrance. Compressor design, optimisation and refinement iterations can take longer and usually have to be done (partially) ahead of RACS development. Scaling-up of extended production of both RACS and compressors can similarly be time-consuming. It is likely to require more than two or three years for most producers to achieve steady output of a range of models.

13 Concluding remarks

- Since required charge amounts of the hypothetical RACS using R290 or R1270 are encompassed by the charge limits from the safety standard, IEC 60335-2-40, it therefore indicates their application is broadly feasible. With the additional interconnecting piping, over-sizing and extreme thermal loads, there is some overshoot for RACS above 9-10 kW. However, this can be addressed through selection of R1270 instead of R290, or more likely, further developments on charge minimisation and possibly changes to the upper charge limit in the longer-term.
- With R1234yf and R152a, application within the constraints of the standard is straight-forwards.
- A switch from R410A or R32 to R1270, R290 or even R152a is cost-effective, where incremental material costs would be less than €5, €10 and €30, respectively, although almost negligible when considering lifetime refrigerant cost. In such cases, any would be well within 1% of the average RACS retail price. Incremental costs including refrigerant for R1270 and R290 are below that of R32, compared to R410A.

- In terms of greenhouse gases, such a switch reduces lifetime emissions regardless of the GWP < 150 alternative refrigerants selected. These emissions reductions are achieved in parallel with lifetime cost reductions.
- The database, simulations and other sources from which the information was gathered is extensive, and the treatment and analysis was thorough and approached with different methodologies. Furthermore, where there is uncertainty associated with any inputs, pessimistic assumptions were used. Thus, the results and conclusions are considered to have a high level of confidence.
- If the market for alternatives with GWP < 150 is as extensive as the current one for R410A/R32, the accompanying increase in the magnitude of research and development for RACS would lead to significant technological advances, providing further improvements in cost-effectiveness.

Nomenclature

Abbreviations

AC	air conditioner
ACL	allowable charge limit
ALRC	active limited releasable charge
COP	Coefficient of performance
EER	Energy efficiency ratio
ETD	Effective temperature difference
ETRS	enhanced tightness refrigeration system
EU	European Union
F-gas	Fluorinated gas
GWP	Global warming potential
HC	hydrocarbon refrigerant
HX	heat exchanger
IAF	integral airflow
IDU	Indoor unit
IEC	International Electrotechnical Commission
LFL	lower flammability limit
NCC	nominal cooling capacity
ODU	Outdoor unit
PLRC	passive limited releasable charge
RACS	room air conditioning system
SCOP	Seasonal coefficient of performance
SEER	Seasonal energy efficiency ratio
SLHX	suction-liquid heat exchanger
UCL	upper charge limit

Symbols

a	a constant
A_{rm}	room floor area [m^2]
b	a constant
c	a constant
C_f	floor concentration [kg m^{-3}]

F	concentration factor [-]
g	a constant
h_0	installation height of lowest refrigerant-containing parts [m]
h_{rm}	room height [m]
L	additional refrigerant piping length [m]
LFL_m	lower flammability limit by mass [kg m^{-3}]
m	an index
m_{ACL}	allowable charge limit of refrigerant [kg]
m_C	system refrigerant charge [kg]
$m_{C,R1}$	charge of refrigerant 1 [kg]
$m_{C,R2}$	charge of refrigerant 2 [kg]
m'_p	refrigerant charge for piping [kg/m]
m_{RC}	releasable refrigerant charge [kg]
m_{UCL}	upper charge limit of refrigerant [kg]
n	an index
Q_c	nominal heating capacity [kW]
Q_e	nominal cooling capacity [kW]
$T_{a,in}$	air inlet temperature [°C]
$T_{a,out}$	air outlet temperature [°C]
$T_{d,sat}$	saturated discharge temperature [°C]
$T_{s,sat}$	saturated suction temperature [°C]
V_{rm}	room volume [m^3]
Δp	pressure drop as refrigerant saturation temperature [K]
$\Delta T_{c,eff}$	condenser effective temperature difference [K]
$\Delta T_{e,eff}$	evaporator effective temperature difference [K]
η_c	heating efficiency [-]
η_e	cooling efficiency [-]
η_o	efficiency at reference condition [-]
η_r	efficiency [-]
μ_c	specific refrigerant charge [kg/kW]
φ	density ratio [-]
ψ	charge matching coadjuvant [-]
ϑ	retained charge coefficient [-]

1 Introduction

1.1 Background

Hydrocarbon refrigerants (HC), such as R290, have excellent performance and negligible global warming potential. Within the context of the Kigali Amendment of the Montreal Protocol and national and regional legislation on fluorinated fluids, such as the EU "F-gas" regulation, there is a desire for reducing the use of hydrofluorocarbons (HFCs). Within this context, HCs are a potentially viable substitute for many applications.

Split-type room air conditioning systems (RACS) consume and emit a significant proportion of HFCs due to widespread global usage; stationary AC is responsible for about one-third of GWP-weighted HFC emissions (RTOC, 2018).

Since before 2000, there have been frequent attempts to use HCs in RACS (e.g., Colbourne, 2021). However, introduction of the revised product standard IEC 60335-2-40 in 2003, with its obstructive requirements, resulted in major difficulties for implementing HCs. This was largely due to the allowable charge limits (ACL), which constrain the amount of refrigerant per unit of room floor area. A recently approved revision of this standard offers renewed possibilities.

The proposed European F-gas regulation[1] includes new placing on the market prohibitions, including for stationary split air-conditioning and split heat pump equipment: "split systems of a rated capacity of up to and including 12 kW containing, or whose functioning relies upon, fluorinated greenhouse gases with GWP of 150 or more, except when required to meet safety standards". This prohibition is proposed to apply from 1st January 2027. Some industry lobby groups have unsurprisingly objected to major elements of the proposal, arguing that there are inadequate alternatives for such sub-sectors.[2, 3]

There are several alternative refrigerants would may be considered to address this prohibition. Whilst there are several pure HCs suitable as refrigerants and numerous blends, those of primary interest are R290 and R1270. Also, with relatively low GWP are R152a and R1234yf, which are also considered. All of these alternatives are flammable (class A3, A2 or A2L). The GWP (RTOC, 2018), safety class

[1] https://ec.europa.eu/commission/presscorner/detail/en/IP_22_2189
[2] https://www.fluorocarbons.org/news/trade-associations-respond-to-f-gas-proposal/
[3] https://epeeglobal.org/wp-content/uploads/2022/04/Joint-industry-Press-Release-on-F-gas-Regulation-proposal-5-April-2022.pdf

and lower flammability limit (LFL) (ISO 817: 2014) of these refrigerants, as well as those currently widely used for RACS (R410A and R32) are listed in Table 1.

Some studies in the literature have extended such an analysis to many other alternative refrigerants, including a variety of mixtures. For example, Yu et al. (2021), Heredia-Aricapa et al. (2020), Devecioğlu (2017), Schultz (2019), etc. examined an extensive number of such mixtures, but for those with a GWP < 150, none appear feasible to compete with the refrigerants listed above. The only other refrigerant of potential interested would be R161, which is reported elsewhere to offer attractive performance and other such characteristics (e.g., Wu et al., 2012; Padalkar et al., 2015). However, at present it is not formally classified as a refrigerant (in ISO 817: 2014), due to ongoing toxicity questions and therefore its suitability and acceptance as a refrigerant remains open.

Table 1: GWPs, safety classification and LFL of refrigerants under consideration

GWP	R410A	R32	R1270	R290	R1234yf	R152a
GWP (100 y)	2100	750	<1	<1	<1	148
GWP (20 y)	4400	2600	<1	<1	1	545
Safety class	A1	A2L	A3	A3	A2L	A2
LFL [kg/m^3]	–	0.307	0.046	0.038	0.297	0.130

The objective of the present study is to identify whether such a proposal for the F-gas regulation is viable or not (as argued by the HFC stakeholders). Within this context “viability” is broadly a subjective concept. On one hand, the proposal is viable because air conditioning of spaces can still be provided with or without F-gases (with a GWP < 150), but there may be cost, environmental and convenience implications. On the other hand, the proposal may be regarded as not viable, since it could cause at least some disruption (however large or small) to the RACS sector, maybe leading to higher costs, less convenience, fewer sales and loss of profit. Therefore, some tangible criteria must be applied.

1.2 Viability criteria

Viability criteria may be based upon the financial, safety and “inconvenience” impact to stakeholders throughout the producer-to-user chain. If the viability is to be assessed, it must involve defined and quantifiable parameters. In this regard, the following criteria are considered.

Extent of required R&D for manufacturers

RACS are continually under a revision cycle and (another) change of refrigerant would be combined with such an R&D processes. Further, developments are not carried out solely related to one aspect (such as refrigerant); improvements addressing efficiency, reliability, noise, cost reduction, functionality, etc., are carried out simultaneously. It is not practical or realistic to isolate this one aspect from other R&D activities and therefore the general implications associated with integration of an alternative refrigerant with GWP < 150 cannot easily be isolated.

Inconvenience for the supply-chain

Manifestation of inconvenience if often cited as a barrier to implementation of alternative refrigerants. However, some stakeholders have argued that the additional training, knowledge, awareness, etc. of suppliers and installers can be beneficial (e.g., Rajadhyaksha et al., 2015). For example, higher levels of competence during selection and installation, more precise matching of RACS to the application thermal load, better servicing, etc. is more favourable to the end user and improves product reputation.

Conversely, there may be instances where it is not feasible for the proposed RACS product to be installed (e.g., when using a large charge of higher flammability refrigerant), thus causing consternation and inconvenience to the seller and end user. (However, as is shown later – section 9 – this issue is far less likely with the introduction of the new safety standard.)

Product safety

Product safety is one of the key reported concerns associated with the adoption of flammable and higher flammability refrigerants. Accordingly, application is to be considered with respect to the new RACS safety standard, IEC 60335-2-40. However, it may be noted that despite more tolerant requirements than previous editions of the standard, the degree of stringency imposed by the standard is beyond what flammability risk assessments may deem necessary.

Competency of technicians

Although a portion of the RACS installer base may be less well trained and often conduct activities in a “slap-dash” manner, there is an increasing importance for technicians to carry out refrigerant handling practices in a responsible manner, even when non-flammable refrigerants are involved. Poor service practices lead to a variety of other safety hazards, poor system performance, adverse functioning and reduced efficiency and greater refrigerant-related and energy-related emissions. There is an obligation for all technicians to increase competency, irrespective of the introduction of low GWP and/or flammable refrigerants.

Cost for the consumer

A crucial factor for manufacturers and retailers is the cost of RACS to the consumer, since it is the consumer that dictates the success of their business. Adverse changes to the first cost of products may compromise the appeal of products and, largely due to reputational effects, higher on-going service and maintenance costs can similarly be detrimental. Switching to an alternative refrigerant – whilst maintaining a given efficiency – infers possible cost implications to system components, additional safety features and subsequent lifetime costs. As such, these need to be examined.

Environmental impact

The primary purpose of switching to low GWP alternatives is to reduce environmental impact, particularly CO2e emissions. There are numerous sources of such emissions, including those associated with production of construction materials, transportation and leakage of refrigerants over the product lifetime. Monetary value is increasingly applied to carbon emissions, or more precisely, the avoidance of emissions. Therefore, it is important to consider whether any additional emissions associated with the production offsets gains achieved by reducing those arising from lifetime leakage and how these relate to the costs of adopting alternatives with GWP < 150.

Considering the assessable aspects from this list, the criteria to be quantified and evaluated are:

- Product safety, through compliance with safety standards, primarily related to refrigerant charge limits necessary for high efficiency RACS.
- Cost for the consumer, through impact on material costs and whether adoption of the alternatives would result in an adverse increase in cost
- Environmental impact, through assessment of carbon dioxide equivalent emissions

From a societal perspective and within the context of the drive to address climate change, the latter two criteria can be combined and expressed as a cost-effectiveness in terms of cost per unit reduction of CO2-equivalent emissions.

1.3 Methodology and data-sources

The methodology adopted follows the general sequence:

- Summarise refrigerant charge limits in revised safety standard
- Establish heating and cooling thermal loads in RACS applications
- Characterise RACS performance and construction aspects using available databases
- Identify performance characteristics of alternative refrigerants
- Remarks on heating performance of reversible systems
- Develop empirical method to approximate RACS charge amount (based on capacity and efficiency)
- Compare estimate charge amounts for alternative refrigerants with safety standard charge limits
- Quantify material masses, component volumes and associated costs for alternative refrigerants, including shipping and storage
- Estimate production and lifetime emissions associated with the alternative refrigerants
- Discuss the trade-off between cost-effectiveness, safety limitations and possibly other practical implications, such as implementation time

To provide a baseline for the assessment, against which the impact of applying the alternatives can be gauged, demands comprehensive data on existing RACS products. For this, data is extracted from the Eurovent database for air-to-air reversible split air conditioners of less than 12 kW nominal cooling capacity (Eurovent, 2022). However, some key values (refrigerant charge, weight, dimensions and price) are not included in the database, so additional details were obtained from product literature. However, this additional data could not be found for about one-third of the models. All of the products in the database are stated as using R410A or R32 only. It is also noted that in numerous cases, the performance values stated on product sheets and in manuals differed from those listed in the Eurovent database; in such cases, those values from the database were selected for the analysis.

To enable adjustments and validation of conversion exercises, available data for a small number of R290 models was also obtained. These models are mostly lower capacity, which is due to the low historical ACLs. No RACS models for R1234yf or R152a have been found, so the assessment for these fluids is based solely on their properties and characteristics, using established methods. Furthermore, interviews and discussions were held with several major international manufacturers to better understand RACS product development.

For brevity, the numerical assessment is based on a specific RACS model:

- Wall-mounted type

- High efficiency SEER = 12 (assumed to have fixed-point EER = 6.5)
- Hypothetical models from 2 kW to 12 kW at 1 kW intervals
- Detailed consideration of a nominal cooling capacity of 5 kW
- No additional interconnecting piping (beyond the standard 5 m) and additional 20 m

The findings for this generic model are considered to be representative of equivalent models with capacities from 2.5 kW up to 12 kW.

2 Charge limit requirements

Hitherto, the main hindrance imposed by the air conditioner and heat pump safety standard, IEC 60335-2-40, are constraints in refrigerant charge size limits, being a function of IDU installation height and room area. Since RACS are normally selected according to its cooling capacity (or heating capacity for reversible systems in colder climates), there can be a conflict between the size of charge required for the refrigeration system thermal capacity and the size of charge afforded by the room size. For instance, if a 25 m^2 room has an estimated heat load 3.5 kW and an allowable charge limit of 400 g, but the 3.5 kW RACS has a refrigerant charge of 500 g, then its use would be contrary to the rules within the safety standard, whereas a RACS with 300 g would be acceptable. A detailed discussion of this is provided in Colbourne et al., 2000 and Colbourne and Suen, 2021).

In contrast to earlier editions, the recently approved revision (IEC 60335-2-40, 2022) permits larger quantities of flammable refrigerants per unit of room floor area. Greater quantities of refrigerant are allowed on the condition of additional mitigation measures intended to lower concentrations of refrigerant leaked into the room. Essentially these mitigation measures include improved system tightness, provision of airflow to disperse leaks and integration of valving to limit the amount of refrigerant that could leak from the system. In summary:

- Enhanced tightness refrigeration system (ETRS), where assumed leak rate is much smaller than non-ETRS. In this case, allowable charge limit (ACL) is equation (1).

  $$m_{ACL} = F \times LFL \times h_0 \times A_{rm} \quad (1)$$

  where the concentration factor, F = 0.35.
- Systems which use integral airflow (IAF), where indoor unit fan operates continuously or in response to leak detection. Systems may be ETRS or non-ETRS; this only affects the required minimum airflow rate to disperse a leak. The ACL is equation (2).

  $$m_{ACL} = F \times LFL \times h_{rm} \times A_{rm} \quad (2)$$

  where the concentration factor, F = 0.50.
- Limited releasable charge, where, if the releasable charge can be determined by test, the resulting mass can be assumed rather than the charged amount (equation 3). This can be considered to fall into two categories:
  - “Passive” limited releasable charge (PLRC), which typically accounts only for the mass retained in refrigerant oil and the system volume at atmospheric pressure, and
  - “Active” limited releasable charge (ALRC), which employs features such as safety shut-off valves to hold charge within the outdoor unit in response to leak detection.

$$m_{RC} \cong (1 - \vartheta) \times m_C \quad (3)$$

where the retained charge coefficient, ϑ, may be around 0.8 – 0.9 for PLRC and anywhere from 0.05 to 0.75 for ALRC, based on experiments. For ALRC, the smaller the internal volume of the indoor part of the system (relative to the whole system) and the faster the response time of the leak detection system, the lower ϑ will be.

- ACL calculation for the basic method (as included in previous editions of the standard) is equation (4).

$$m_{ACL} = 2.5 \times LFL^{1.25} \times h_0 \times \sqrt{A_{rm}} \quad (4)$$

Overriding all of these ACLs is an upper charge limit (UCL) of 26×LFL, corresponding to about 1 kg of R290, 1.2 kg of R1270 and 3 kg of R152a. There is no rational basis for this limit, except that it provides some sort of "comfort boundary" to those involved with drafting and approving the standard (Colbourne et al., 2000).

Quantification of these charge limits for R290 with respect to room area where the RACS is installed, are shown in Figure 1, where for ALRC cases it is pessimistically assumed ϑ = 0.4. It can be seen that most new charge limits (i.e., ETRS, IAF and ALRC) are above the basic ones for floor, wall and ceiling units, although for floor (ETRS) charge remains limited on account of the low positioning of the IDU. However, using IAF or ALRC options (of combined) overcome such limits. For very small rooms (< 10 – 15 m^2) the ETRS options are less advantageous than the basic ones, although this is largely a consequence of the different implicit assumptions of release rate; the basic method effectively assumes a diminishing leak rate with smaller capacity RACS whereas ETRS assumes a fixed value irrespective of RACS size.

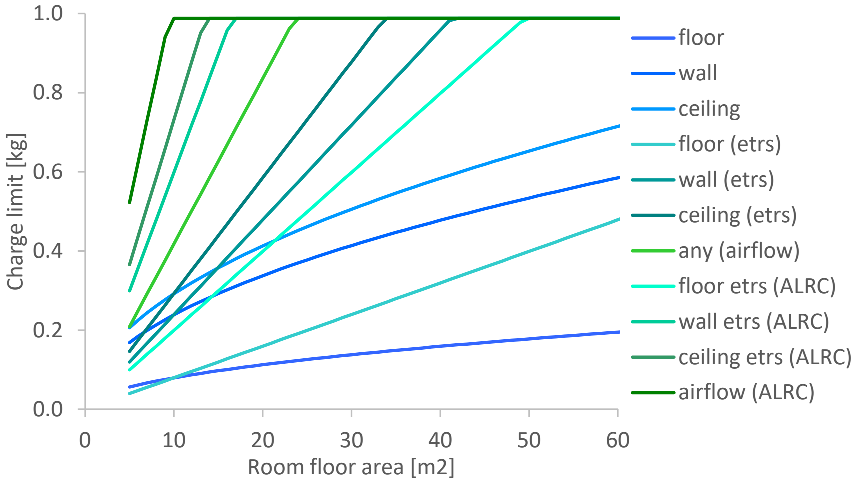


Figure 1: R290 system charge limits as a function of room floor area

Figure 2 translates Figure 1 into charge limit as a function of cooling (or heating) capacity, where a thermal load of 200 W/m^2 has been assumed. Expressing the charge limits in this way provides more relevance to the application, although the same observations can be made as with room area. However, such a graph can be used to compare charge limits with actual charge quantities in RACS; this is carried out in subsequent sections.

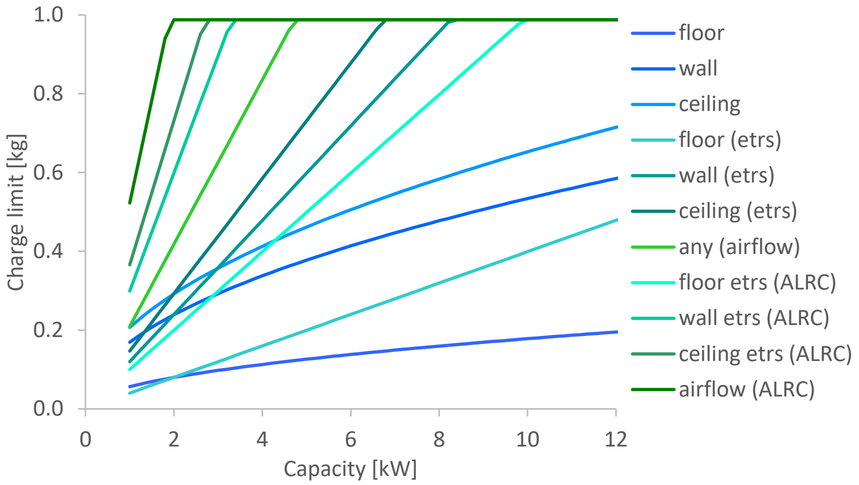


Figure 2: R290 system charge limits as a function of thermal load, assuming 200 W m^{-2}

One important observation to remark on, is that when the additional mitigation measures are applied, it is the UCL that eventually imposes the overriding constraint. This can be from rooms as small as 10 m^2 and capacities as low as 2 kW.

3 Heating and cooling loads

Critical to the assessment of viable charge quantities is the thermal load (heating or cooling) of a space, which determines the size of RACS to be selected and installed. The greater the thermal load, the larger the RACS capacity. For a fixed room area, a greater thermal load implies more refrigerant per unit of floor area and thus potentially more constraining charge limits are.

There are various studies (e.g., Persson and Werner, 2015; Kemna, 2014; Zangheri et al., 2014) reporting on average heating and cooling loads across Europe, spanning the range of climate conditions and building characteristics (age, construction, size, purpose, etc.). Across these studies, a heating load and cooling load of 100 W/m^2 exceeds the maximum typical average value even in Southern Europe.

Studies that looked at the statistical distribution of room thermal loads indicate that the highest are seldom 40% higher than the average (e.g., Cui et al., 2017; Zhang et al., 2017). So, where the highest regional values of, say, 100 W/m^2 are determined, individual cases exceeding 150 W/m^2 are extremely rare. Exceptions, where much higher-than-average loads occur is in regions with relatively low average values (say, 5 – 20 W/m^2) and would thus always be well below 100 W/m^2 anyway.

Other sources exist such as "rules of thumb" which provide rough guides to values usually employed. For instance, BSRIA (2021) provides thermal load as listed in Table 2.

Table 2: Rule-of-thumb thermal loads[4]

Purpose	Thermal load for cooling [W/m^2]	Thermal load for heating [W/m^2]
Hotels	150	n/a
Offices	90	70
Restaurants	200	n/a
Retail establishments	140	100
Residential	70	60

[4] One application with exceptionally high thermal loads is data-centres, which require in the order of 1500 W/m^2 of cooling. However, these are usually served by dedicated evaporative or adiabatic ("free-ish") cooling systems and are not considered relevant in the current context.

According to these sources, charge quantities will be assessed considering a thermal load for cooling of 100 W/m^2, 150 W/m^2 and 200 W/m^2 to represent extreme cases.

In terms of thermal load for heating (applicable to when reversible RACS are used for space heating purposes) the largest nominal heating demand across Europe is about 150 W/m^2, being for Prague. For more northern regions, such as Helsinki, maximum heating demand is lower (about 110 W/m^2), which is due to better thermal construction of buildings. Although, for most cases the maximum thermal load for heating does not exceed 100 W/m^2. Thus, as with cooling, the same values of 100 W/m^2 and 150 W/m^2 are considered and 200 W/m^2 for extreme cases.

With regards to matching NCC and thermal load, there is also a consideration of over-sizing of RACS following estimation of a room(s) thermal load. For instance, where the estimated thermal load on a room is 5.5 kW, but only RACS of nominal 5.0 kW or 6.0 kW capacity are available, installers may select the 6.0 kW model to ensure against customer dissatisfaction during the times of peak thermal load. Thus, for a 46 m^2 room taken to have a specific load of 120 W/m^2, the RACS selection would effectively be for 130 W/m^2. As a result, the refrigerant quantity within the room would correspond to, say, 4.2 g/m^3 of room volume instead of 3.5 g/m^3 if the 5.0 kW RACS was selected or 3.8 g/m^3 if a 5.0 kW model were available.

Across the range of RACS in the Eurovent database, the average increment in NCC is 0.14 kW, so if end users have a sufficiently wide choice from all product ranges, precise selection should usually be possible and over-sizing would be avoided. However, where for incremental capacity ranges where few models exist, capacity gaps should be recognised. Figure 3 shows the capacity gaps across the RACS within the database, where there are too few interposing models to consider. Depending upon the reference capacity, these gaps are between 5 – 15% of the reference NCC, except at about 8.5 kW where the gap is almost 30%. Taking the hypothetical models of 1 kW incremental NCCs, Figure 4 shows the variation in “selected” RACS capacity for the particular thermal load. This assumes the RACS is selected to match the capacity to the closest value. According to interviews with RACS application engineers, this is typical practice.

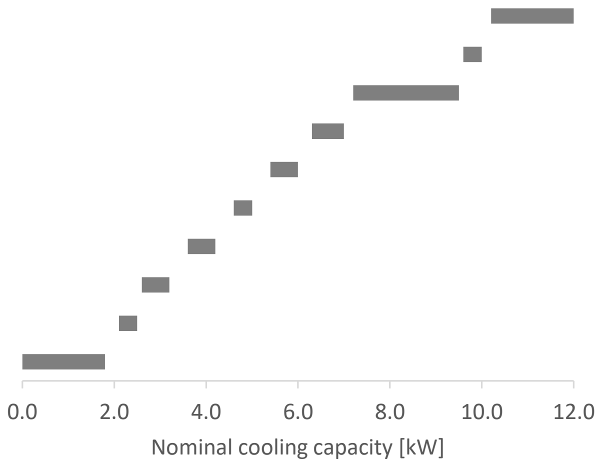


Figure 3: Gaps in NCC of RACS, that could lead to over-sizing

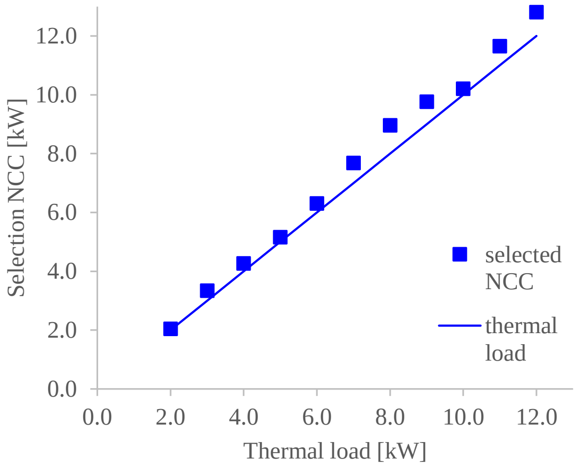


Figure 4: Nominal cooling capacity of selected models, for a given thermal load, accounting for gaps in RACS capacity

4 RACS performance and product data

The Eurovent database holds extensive data for registered RACS. It includes certified performance data (thermal capacity, efficiency, etc.) for cooling and heating modes, including part-load conditions, electrical inputs and noise level data. However, the database does not generally include data on refrigerant charge amounts or product weight or dimensions or costs/prices. Therefore, these latter data have to be extracted from product sheets and retail internet sites.

Amongst the nearly 2500 models, a large number are evidently repetitions of the same refrigerating system (same compressor, HXs, housing size, etc.). Based on discrete capacity and efficiency ratings and total housing size, it is estimated that there are only about 250 different refrigerating systems. In other words, about there are about 10 variations associated with each refrigerating system. Amongst these variations are differences in housing colour and aesthetic designs, functionality, product names (e.g., for targeting at different end use categories), level of air filtering and so on. In many cases, the same IDU is match to several different ODUs and vice versa.

Initially, an overview of product data is presented to help provide an impression of the range and characteristics of the products. For brevity, data for wall-mounted split-type RACS is discussed, although assessment of other types is considered subsequently.

Recently, RACS have increasingly been introduced with R32, due to the F-gas regulation introducing a placing on the market prohibition for refrigerants with GWP > 750 with AC systems charged with less than 3 kg. Hereafter, RACS product data is compared for those using R410A and R32 in order to identify any characteristic differences that may be linked to respective refrigerant properties.

Available data for R290 models is addressed later in section 4.6.

4.1 Efficiency

Figure 5 shows the relationship between current RACS products across the nominal cooling capacity range.
On average, fixed-point efficiency diminishes at a rate of about 15% per kW. Although there is wide scatter, the general trend is that smaller capacity models have higher efficiency. A similar trend was

observed in Figure 6 with the heating capacity and heating efficiency, although the reduction in efficiency with larger products was less at about 5% per kW.

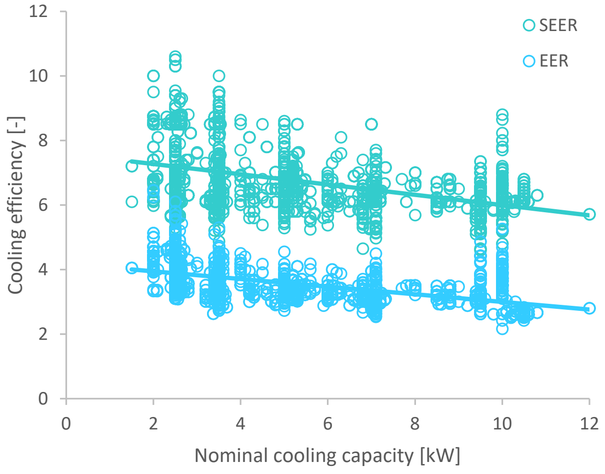


Figure 5: Relationship between RACS cooling efficiency and nominal cooling capacity

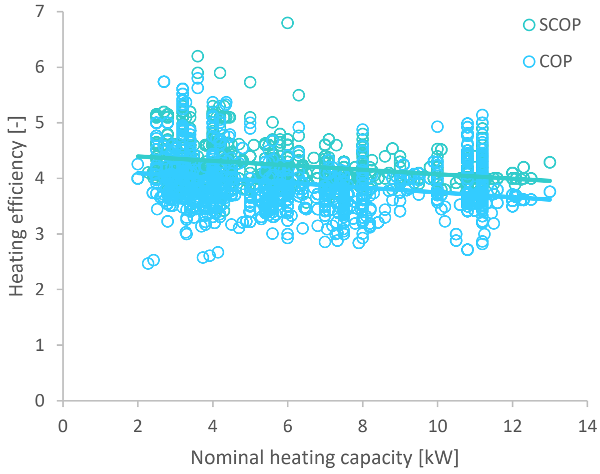


Figure 6: Relationship between RACS heating efficiency and nominal heating capacity

SEER for other types of RACS (Figure 7) tends to be lower than that of wall-types, although mainly at smaller NCC levels. Above about 5 – 6 kW, there is no distinction.

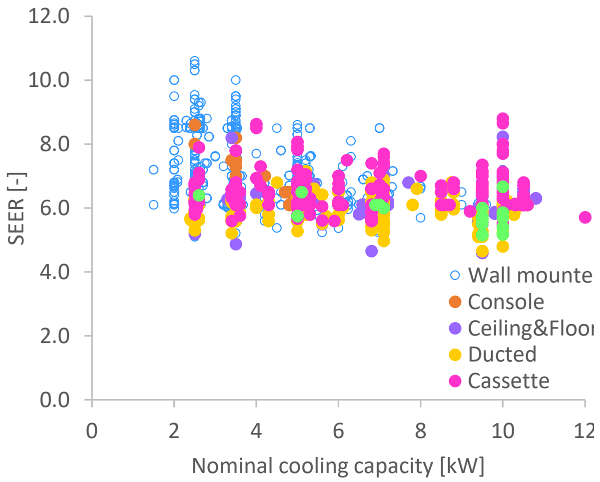


Figure 7: Comparison of SEER across various types of RACS

Figure 8 shows fixed-point nominal efficiency (EER) and corresponding seasonal efficiency (SEER) for each model. It can be seen that for each fixed-point efficiency, products can have a range of SEER; for instance, an EER of 4 may have SEER from 6 to 10. Vertical clusters of data-points typically correspond to incremental SEER steps according to energy labels; for instance, a vertical cluster can be seen at a SEER of 8.5, according to energy efficiency class A+++. Actual SEER is dictated by circuit design and control methods. Across the database, the highest EER was 6.45 and SEER of 10.6. Note that the product with highest EER is not necessarily the one with highest SEER.

In Figure 9, a similar relationship between fixed-point heating efficiency (COP) and seasonal heating efficiency (SCOP) is also seen, although the overall variation in SCOP (about 3.5 to 5.5) is narrower than COP (about 2.5 to 5.5). As with cooling efficiency, that the product with highest COP is not that with highest SCOP. Furthermore, products with high SEER do not always correspond with those of high SCOP. Apart from control strategies, the variation between RACS' EER/SEER and COP/SCOP is largely affected by distribution between IDU and ODU surface area of HXs.

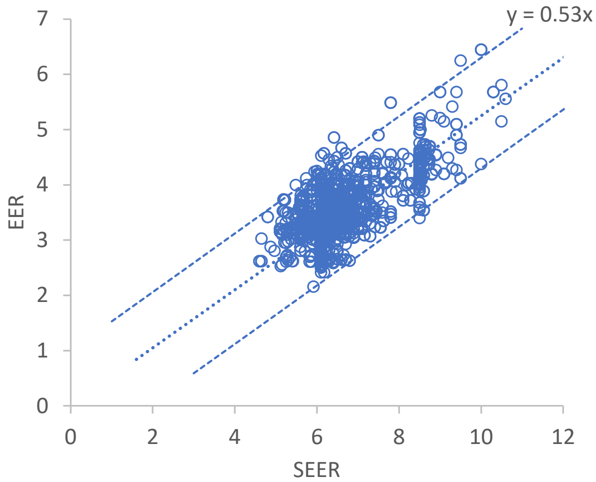


Figure 8: Comparison of EER and SEER of models

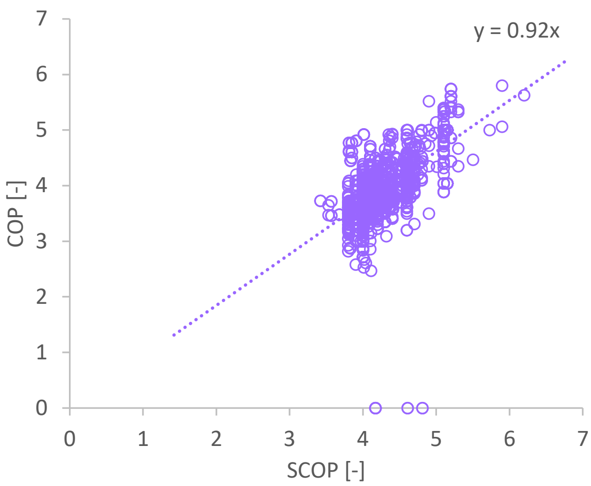


Figure 9: Comparison of COP and SCOP of models

4.2 Cooling and heating capacity

Within the "<12 kW reversible" category, the smallest models are 2.0 kW, whilst the largest are about 11 kW. There are around 1100 models to about 3.5 kW, about 500 between 3.5 – 6.5 kW and 6.5 – 10 kW and about 250 above 10 kW of NCC.

For reversible systems, another important factor is that the RACS must achieve a certain heating capacity.
A comparison of RACS cooling and nominal heating capacity is shown in Figure 10. On average reversible RACS provide a heating capacity 15% below the NCC, although scattered over a wide range, i.e., some models have heating capacity as low as 50% of the NCC, whereas other's heating capacity is over 30% higher than NCC. Across the various other types of RACS, there is also no observable difference in the ratio of heating to cooling capacity (Figure 11).

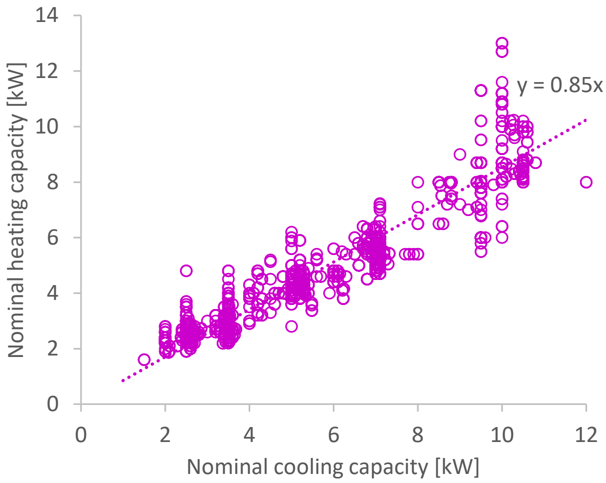


Figure 10: Comparison of nominal heating and cooling capacity

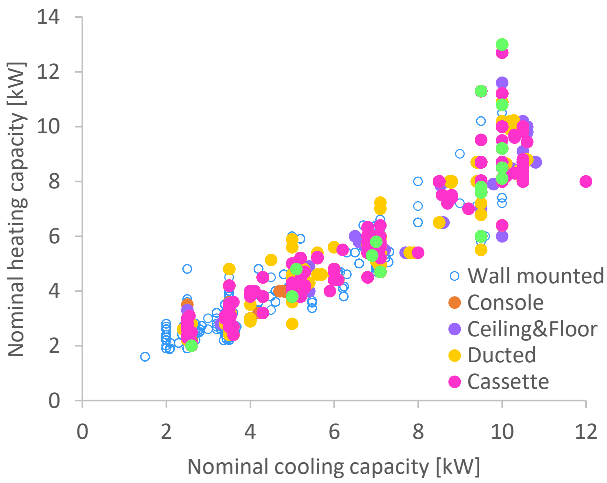


Figure 11: Comparison of nominal heating and cooling capacity for different types of RACS

4.3 Size (volume and mass)

The total volume, i.e., the sum of the indoor and outdoor units (interconnecting pipe and remote controllers, etc. are neglected) are shown in Figure 12. Larger NCC units usually correspond to greater volume, although smaller NCC models seem to be no less than 0.13 m^3. Scatter is quite wide, where for a given NCC, total volume extends across ±0.1 m^3. For instance, the volume of 5 kW models can range from about 0.15 m^3 to more than double, at 0.35 m^3.

Similar patterns are seen for total mass (IDU +ODU mass, including suppled interconnecting piping only) in Figure 13. Mass seldom drops below 20 kg for any NCC and across the range of NCC, for any capacity the mass is at least ±20 kg. For 2 to 4 kW models, the highest mass is more than double the lowest weight.

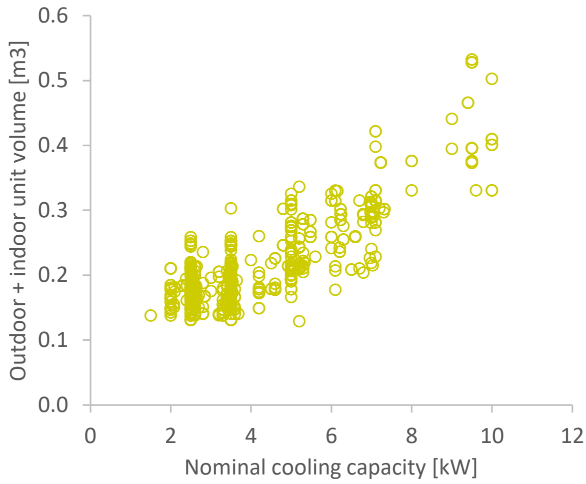


Figure 12: Total (IDU +ODU) volume

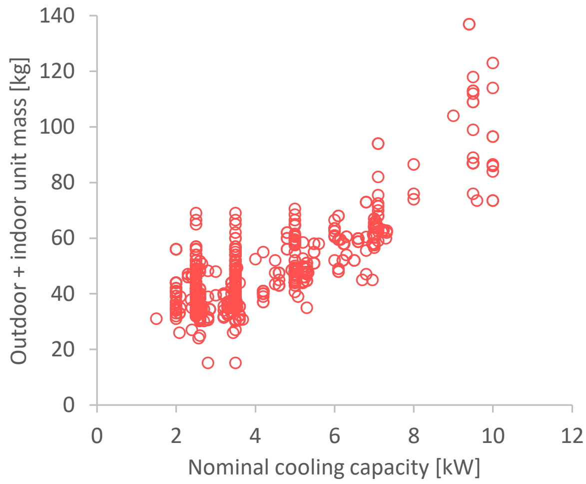


Figure 13: Total (IDU +ODU) mass

The same data is shown in Figure 14 and Figure 15 where it is seen that generally for RACS other than wall-types, both the physical volume and mass are greater. This is generally due to the larger, bulkier IDUs.

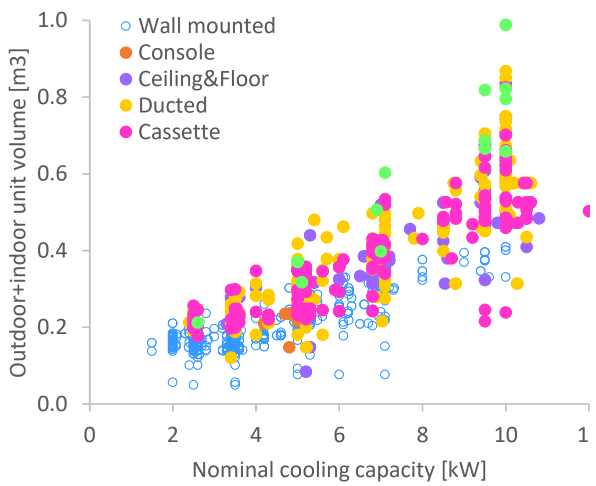


Figure 14: Total (IDU +ODU) volume for different types of RACS

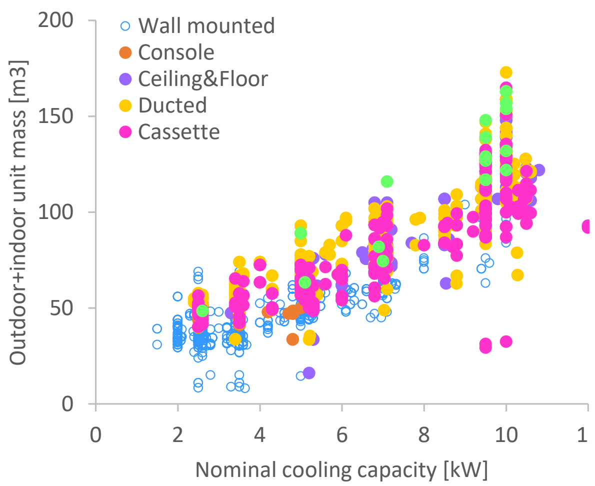


Figure 15: Total (IDU +ODU) mass for different types of RACS

Examining the differences between R410A and R32, Figure 16 plots the specific volume (volume of IDU and ODU divided by NCC) against SEER. Apart from a slight shift of a small number of products to higher SEER, the distribution between R410A and R32 is not notably different. Some R32 models have greater, some have smaller volume. Similar observations apply to Figure 17, which plots specific mass (mass of IDU and ODU divided by NCC) against SEER. From this data, it cannot be concluded that use of R32 leads to distinctly smaller RACS.

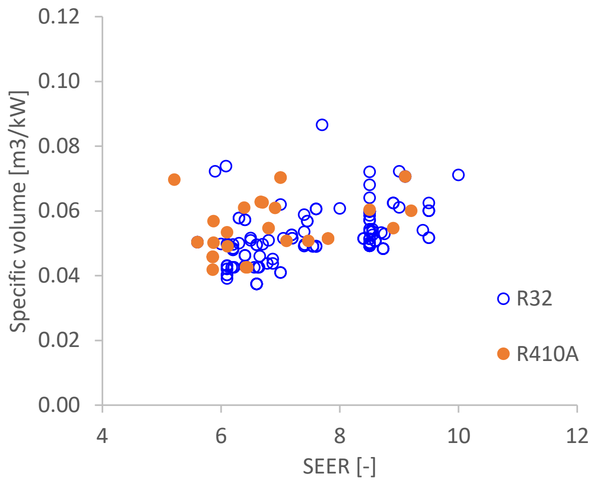


Figure 16: Comparison of specific volume between R410A and R32 for 3.4 – 3.6 kW NCC models

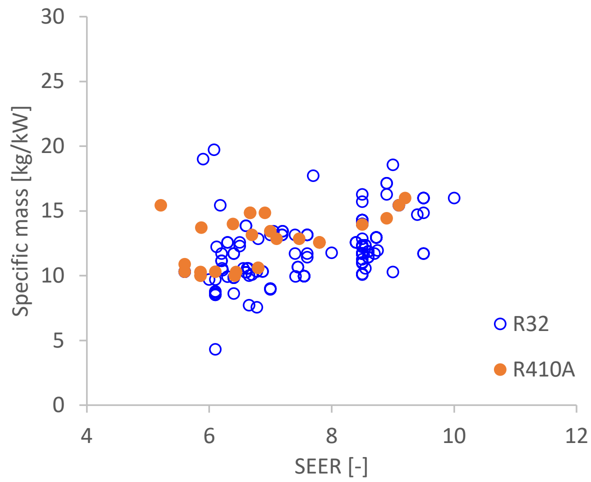


Figure 17: Comparison of specific mass between R410A and R32 for 3.4 – 3.6 kW NCC models

4.4 Refrigerant charge

Figure 18 provides refrigerant charge. Again, this follows the characteristics of the volume and mass data, where models with 1.5 to 4.5 kW have a charge of no less than about 0.4 kg. Otherwise, the charge ranges across ±0.5 kg for smaller NCC models up to about ±1.0 kg for larger models. In Figure 19, data for R410A models has been removed and the refrigerant charge limit, below which minimum room size does not apply (i.e., 6 × LFL, for A2L refrigerants) is indicated as a dashed line. For almost all RACS below about 6.5 kW fall below this limit, whereas above about 7 kW most have larger charges. However, there are some RACS of highest NCC, 10 kW, that remain below that charge limit. Taking a typical additional charge of about 30 g/m for interconnecting piping, an extra 20 m would require 0.6 kg, taking the charge of most units larger than 5 kW above the 6 × LFL limit.

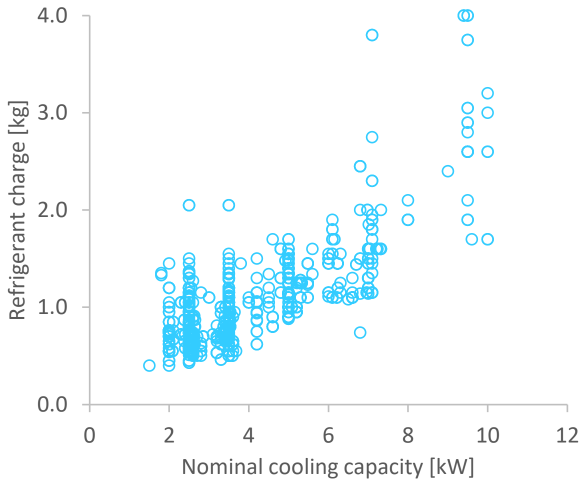


Figure 18: Refrigerant charge for various models

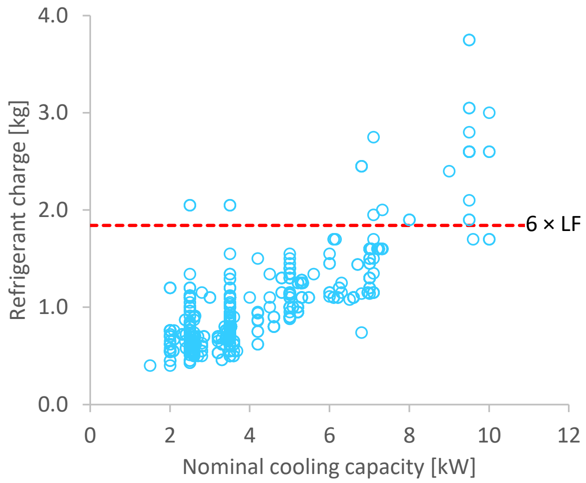


Figure 19: Refrigerant charge for R32 models only

Specific charge for the two refrigerants is in Figure 20, again for units of 3.4 – 3.6 kW NCC. Whilst there is broad scatter, even with R32 having both the highest and lowest values for certain SEER, an approximate tendency can be observed for R410A to have a higher specific charge. Considering the lowest charge RACS, R32 RACS have up to 30% less refrigerant mass than R410A. Difference in charge solely due to density difference is small, less than 10%., thus, the observable lowering of charge with R32 is also likely due to HX design coupled with a general focus on minimising charge on account of flammability.

Consideration is also given to the charge required for different types of RACS. Figure 21 shows the distribution of specific charge for various types of RACS against NCC. Whilst it can be seen that there are a greater number of non-wall types covering the larger NCC range, there is no indication that console, ceiling&floor, ducted or cassette type RACS use notably more or less refrigerant charge. As such, subsequent analysis based on wall-type data is considered representative of all tougher types.

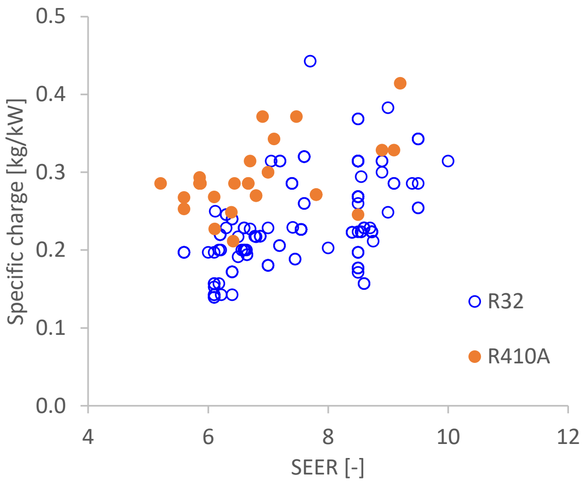


Figure 20: Comparison of specific charge between R410A and R32 for 3.4 – 3.6 kW NCC models

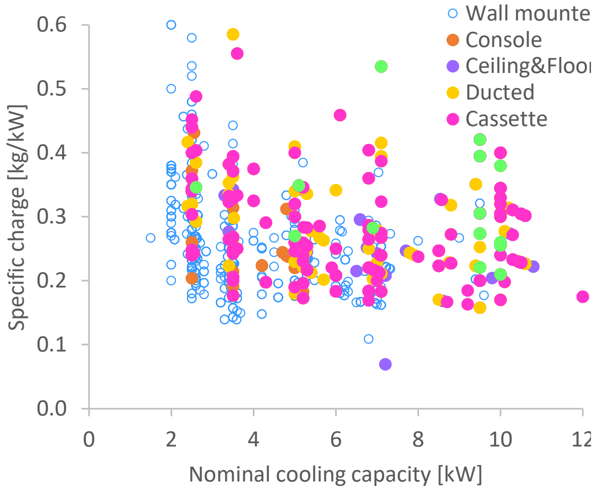


Figure 21: Comparison of specific charge across various types of RACS

4.5 Retail price

Retail prices were gathered and treated as described in Annex B. This normalised retail price in Figure 22 is seen to present the widest variance of all examined parameters at any given NCC. For smaller NCC models, lowest price tends to be around €350, but can extend up to about €2500. Range of price seems to narrow as NCC increases, but still remains at over more than €1500 for the largest NCC.

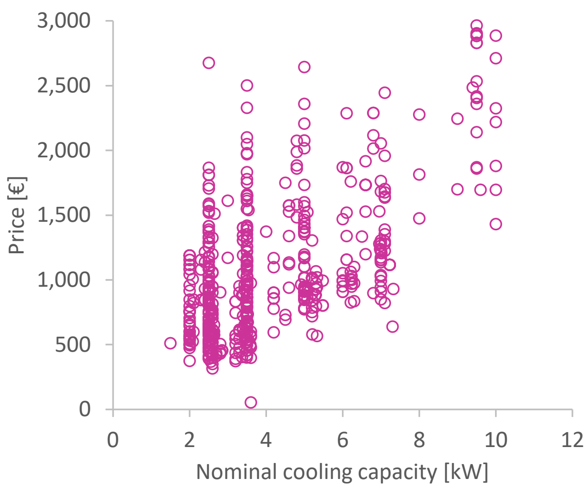


Figure 22: Normalised retail price for models

The specific price for all RACS is plotted in Figure 23 against SEER, for various increments of NCC, where there is considerable scatter. It is not possible to discern any trend between efficiency (for a given NCC range) and specific price. For instance, for 2.5 kW models, the price ranges from €150/kW to above €600/kW for RACS with SEER = 5.5 and SEER = 8.5. Any additional cost associated with features for improving efficiency are obscured by other price-influencing factors.

A similar comparison in Figure 24 uses total material mass as the cost denominator. Theoretically, it may be expected that if the price of RACS were dependent upon material mass a narrow constant relationship would be found against SEER. Conversely, wide scatter can again be observed indicating no functional link between price and mass material of the RACS.

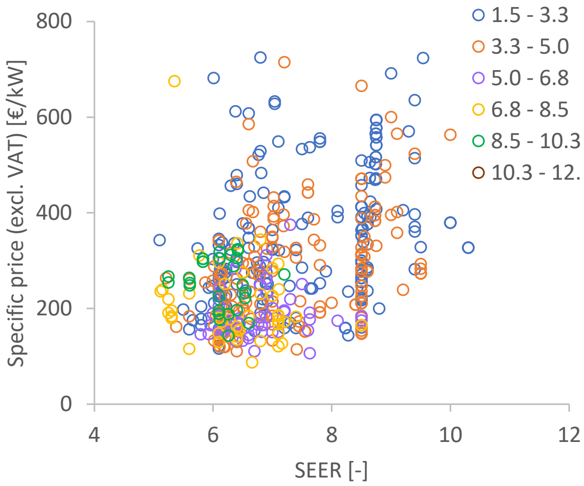


Figure 23: Variation of specific price with SEER for various NCC increments

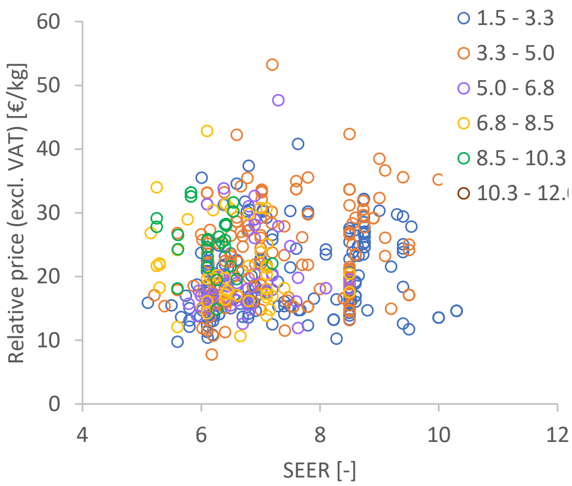


Figure 24: Variation of relative price with SEER for various NCC increments

Figure 25 compares specific price of R410A and R32 products. As with RACS specific volume and mass, there are some R32 models at the lower end, but equally some exceeding the price of R410A. Again, the impact of the refrigerant switch is inconclusive.

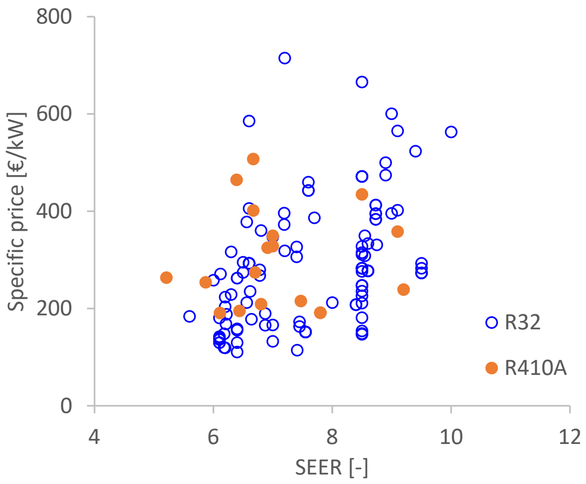


Figure 25: Comparison of specific price between R410A and R32 for 3.4 – 3.6 kW NCC models

It may be concluded that neither refrigerant nor efficiency level have any discernible influence on the retail process of RACS. Theoretically, an increased efficiency infers more costly components which should increase price. However, these observations suggest that other factors, such as electronics and control features and gimmicks, regional pricing philosophies, branding and producer, importer and retailer margins dwarf the contributions of material aspects.

4.6 R290 RACS

For comparative purposes, available data for R290 RACS was also gathered, as listed in Annex E. Various characteristics are included in the data, although not price. This is partly due to the vastly different econo-geographical regions where the RACS are manufactured and sold, likely rendering the reported values incompatible to the values obtained from the European economic area. Further, due to the hugely different economies of scale for the production of the RACS, compared to those with R410A and R32 manufactured by multinational enterprises producing models in the order of millions per annum, any comparison would be misrepresentative.

In terms of the physical construction of the R290 RACS, though, Figure 26 shows that the specific charge is significantly reduced below R32 and particularly R410A.

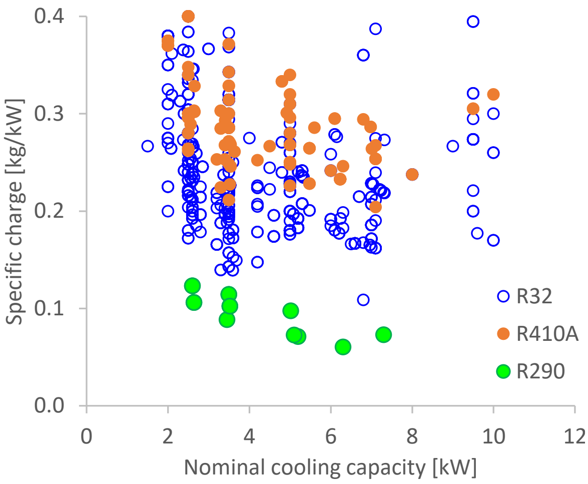


Figure 26: Comparison of specific charge between R410A and R32 with R290 models

Figure 27 and Figure 28 compare the total specific volume and specific mass of R410A and R32 models against R290. Generally, R290 models appear to be below the average values indicating similar values sized RACS can be developed when switching to alternatives.

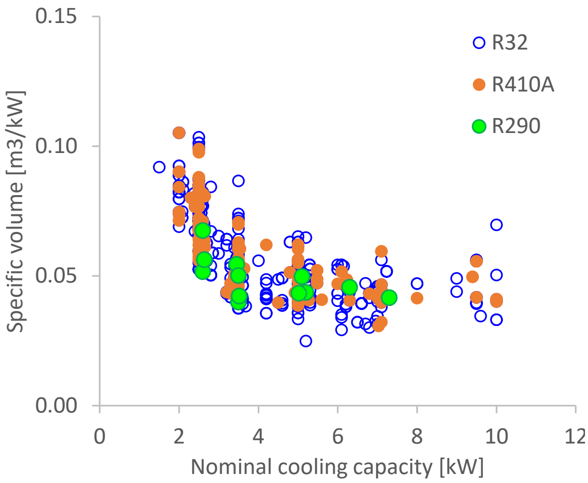


Figure 27: Comparison of specific volume between R410A and R32 with R290 models

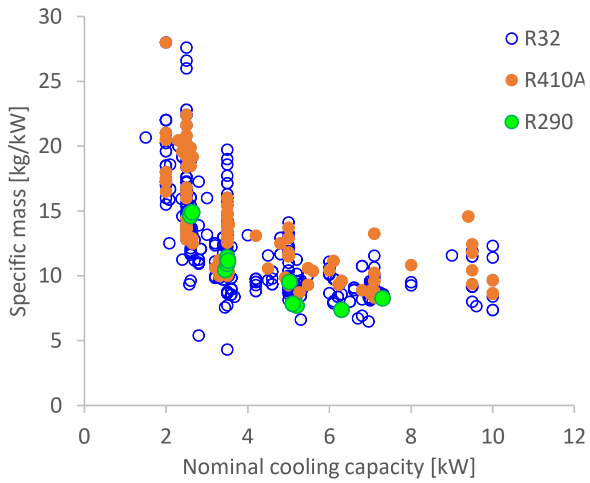


Figure 28: Comparison of specific mass between R410A and R32 with R290 models

5 Mandated efficiency levels

As with many other regions, European legislation prescribes minimum efficiency of RACS and associated efficiency levels for energy labelling. Currently, minimum efficiency (SEER) is 4.6 (< 6 kW) or 4.3 (6 – 12 kW) if the refrigerant used has a GWP > 150, otherwise 4.14 (< 6 kW) or 3.87 (6 – 12 kW) (EU, 2012). The 10% lower boundary for GWP < 150 represents the offset in CO_2e emissions associated with refrigerant leakage. Energy labels range from G (SEER < 2.6 and SCOP < 1.9) incrementally up to A and then to A+++ (SEER > 8.5 and SCOP > 5.1) (EU, 2011). With reference to the Eurovent database, the highest efficiency model below 6 kW is currently SEER = 10.6 and above 6 kW is SEER = 8.8 (Figure 5).

It is anticipated that with the next revision of the EU Ecodesign regulation, minimum efficiency and energy label levels will be as proposed by Huang et al. (2018); Table 3. It is observed that 969 (or 94%) of the 1029 wall-type models in the current list, would meet these proposed criteria. Future RACS models with GWP < 150 refrigerants must be able to achieve the forthcoming anticipated minimum efficiency levels and ideally exceed the highest efficiency energy labels.

Table 3: Proposed revised efficiency levels for Eco-design regulation

Efficiency level	Cooling		Heating	
	SEER	Equiv. EER	SCOP	Equiv. COP
Minimum (< 6 kW)	6.0	2.2 – 4.2	4.0	2.8 – 4.8
Minimum (6 – 12 kW)	5.5	1.9 – 3.9	3.0	1.8 – 3.8
A	≥ 11.5	5.1 – 7.1	≥ 6.2	4.8 – 6.8
B	9.7 to <11.5	4.1 – 7.1	5.5 to <6.2	4.2 – 6.8
C	8.1 to <9.7	3.3 – 6.1	4.9 to <5.5	3.6 – 6.2
D	6.8 to <8.1	2.6 – 5.3	4.3 to <4.9	3.1 – 5.6
E	5.7 to <6.8	2.0 – 4.6	3.8 to <4.3	2.6 – 5.1

6 Efficiency and alternative refrigerants

Ordinarily, refrigerating system efficiency is termed “coefficient of performance” (COP) and is the ratio of useful thermal flux (evaporating or condensing capacity) to the energy used to drive the system (compressor power). This may be extended to the “coefficient of system performance” (COSP), where the energy used to drive the system also includes electrical power for controllers, fan motors, crankcase heaters and so on.

Within the performance test standard, EN 14511 (2018), the system efficiency in cooling mode is termed “energy efficiency ratio” (EER) and is defined as the total cooling capacity divided by the effective power input, which includes that for the compressor, fans, controls, etc. System efficiency in heating mode is assigned the initialism “COP” and is similarly defined as the total heating capacity divided by the effective power input (during heating mode operation). EN 14511 also specifies the operating conditions for full-load measurements. Additionally, systems must also be evaluated for part-load performance, which follows EN 14825 (2018). Along with part-load tests being conducted at lower outdoor temperatures, the seasonal efficiency or SEER is determined. Similarly, seasonal heating efficiency or SCOP is also defined in a similar manner.

Whilst implications of refrigerant selection on SEER and SCOP cannot be easily analysed due to the complexities of isolating refrigerant properties from transient mechanisms within the various components of the refrigeration cycle, efficiency implications will be addressed for full-load/fixed-point conditions, with the assumption that the conclusions translate to part-load and seasonal temperature conditions. Further, it is noted that the auxiliary sources of electrical power consumption (fan motors, controls, etc.) are unrelated to refrigerant selection – including those associated with safety features (see section 10.5) – and therefore need not be considered for the efficiency assessment.

In analysing efficiency with respect to the alternative refrigerants, the following elements are considered:

- Thermodynamic cycle efficiency
- Component pressure losses
- Heat exchanger heat transfer performance (effects within the compressor and piping is neglected)

First, Table 4 lists calculated cooling and heating cycle efficiencies, as well as compression ratio, based on an evaporating temperature of +13.5°C and condensing temperature of +48.5°C (representing a temperature difference of 13.5 K in both HX, between refrigerant and air temperatures as specified in EN 14511).

R290, R1270 and R1234yf have higher cooling and heating cycle efficiencies, than both R410A and R32. R152a has much higher efficiencies, still. R290 and R1270 also have lower compression ratios, which potentially lead to higher compressor efficiencies. Whilst these should not be regarded as practical values as they neglect system losses, they are nevertheless important as they indicate the extent of potential efficiency, such as what can be gained from system optimisation.

Table 4: Thermodynamic cycle performance of selected refrigerants

Parameter	R410A	R32	R1270	R290	R1234yf	R152a
Cooling capacity [kW]	5.00	5.00	5.00	5.00	5.00	5.00
Heating capacity [kW]	5.79	5.77	5.74	5.73	5.73	5.70
Cooling COP [-]	6.35	6.50	6.78	6.87	6.83	7.15
Heating COP [-]	7.35	7.50	7.78	7.87	7.83	8.15
Swept volume [m^3/h]	2.56	2.35	3.65	4.35	5.85	5.89
Compression ratio [-]	2.47	2.48	2.33	2.37	2.59	2.72
Discharge temperature [°C]	72.6	83.9	64.6	60.6	54.7	67.3

Conditions: Evaporating temperature: 27°C – 13 K = 13.5°C; superheat: 10 K; condensing temperature: 35°C + 13.5 K = 48.5°C; subcooling: 5 K; compressor efficiency: 100%; no circuit pressure losses; interconnecting piping is adiabatic.

In order to characterise system components (HX, piping, etc.), the corresponding “tolerable” evaporating and condensing temperatures should be determined. This is done to obtain an equal target system efficiency for all refrigerants. The resultant parameters are then used subsequently for HX selections.

The tolerable equivalent saturated temperature difference for each refrigerant can be determined for each refrigerant to help achieve the target cycle efficiency. Here, the effective temperature difference (ETD) for the evaporator and condenser are defined as equations (5) and (6), respectively.

$$\Delta T_{e,eff} = \frac{T_{a,in} + T_{a,out}}{2} - T_{s,sat} \quad (5)$$

$$\Delta T_{c,eff} = T_{d,sat} - \frac{T_{a,in} + T_{a,out}}{2} \quad (6)$$

where $T_{a,in}$ and $T_{a,out}$ are the inlet and outlet air temperatures of the respective HX, $T_{s,sat}$ is the saturated suction (evaporator outlet) temperature and $T_{d,sat}$ is the saturated discharge (condenser inlet) temperature. An additional nominal 0.5 K saturated temperature pressure drop is assigned to all refrigerants on the high side and low to account for interconnecting piping.

For each refrigerant, the tolerable ETD is calculated, assuming the prescribed system efficiency. A fixed-point efficiency of EER = 6.5 has been selected (broadly corresponding to a SEER = 12 – 13), to represent a RACS efficiency beyond the highest proposed forthcoming Ecodesign energy label. To achieve this EER, the corresponding condenser and evaporator ETD are calculated for each alternative refrigerant. The applicable cycle points are illustrated in Figure 29.

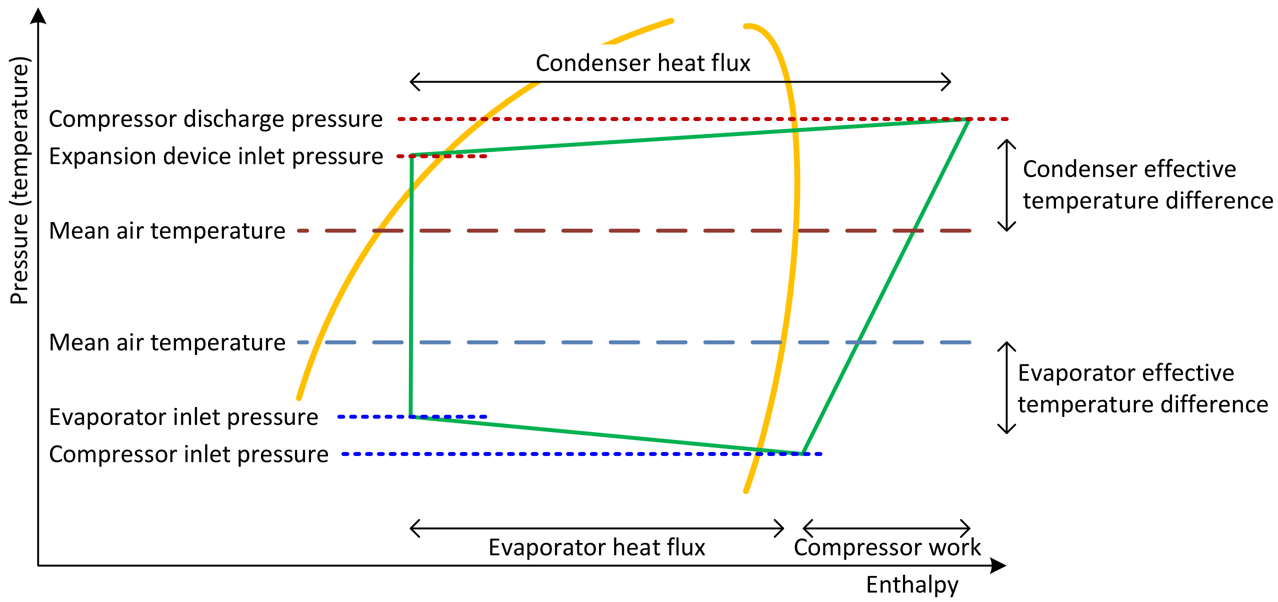


Figure 29: Cycle diagram indicating effective temperature differences

Corresponding ETD was determined for all refrigerants (as listed in ISO 817: 2014) and the results for the calculation are shown in Figure 30 (according to a target EER of 6.5); the alternative refrigerants presently under consideration are identified. Values are plotted against saturation pressure of the refrigerant. Broadly, it can be seen that refrigerants with a lower saturation pressure can tolerate a slightly higher ETD.

The plot in Figure 31 is for the ETD over a range of target COPs (based on equal ETD assigned to evaporator and condenser). All refrigerants behave in a similar manner, where smaller ETDs correspond to higher COPs. Lower pressure refrigerants (R1234yf and R152a) tolerate larger ETDs whereas higher pressure refrigerants consistently require smaller ETDs. For any given refrigerant, with a fixed thermal flux a smaller ETD demands a larger heat exchanger. Depending upon the refrigerant, a smaller ETD may be applied (i.e., relatively larger HX) to the evaporator or condenser, but since all present systems are likely reversible, an equal weighting is applied to both HX. (For example, whilst R410A favours a greater proportion of the total HX surface area for the evaporator, R152a is better suited to assigning more of the area to the condenser.) For lower target COPs the difference in tolerable ETD across the selected refrigerants is about 2 K, whereas for higher target COPs it is about 1 K. Practically, this means that for higher target efficiencies, the rate of increase in HX size is greater for higher pressure refrigerants, or, as minimum efficiencies increase, higher pressure refrigerants will demand increasingly larger HXs, relative to lower pressure refrigerants.

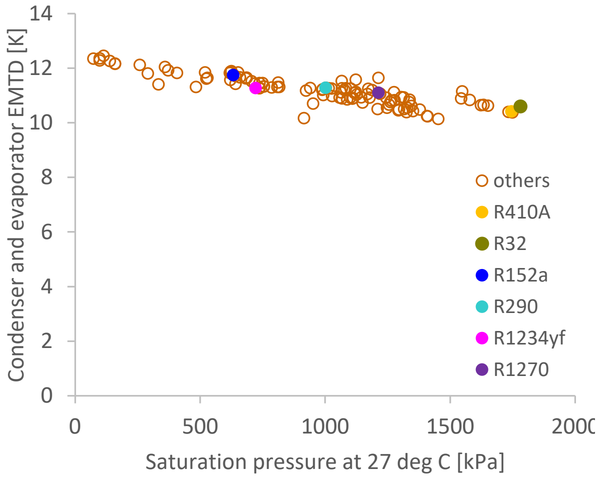


Figure 30: Effective temperature difference

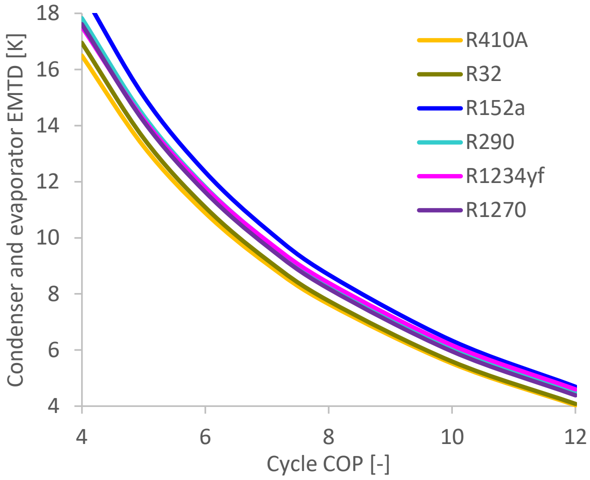


Figure 31: Effective temperature difference for selected refrigerants over a range of target COPs

Table 5 provides the precise values from Figure 30 for the refrigerants of interest. This shows that R32 can tolerate a 0.2 K greater ETD in either HX than R410A, whereas R290, R1270 and R1234yf can tolerate around 0.7 – 0.9 K and R152a, about 1.3 K. In other words, the latter four refrigerants can accept a slightly higher ETD in the evaporator and condenser when aiming for the same efficiency level, which effectively helps compensates for the comparatively higher pressure drop of these refrigerants (see section 10.4). Note that the lower pressure refrigerants tend to be able to tolerate a lower saturation (corresponding to compressor suction) temperature because they have a higher cycle efficiency and can thus accept greater losses when reaching the target efficiency.

Table 5: ETD and saturated suction and discharge temperatures for achieving a fixed-point EER of 6.5

	R410A	R32	R1270	R290	R1234yf	R152a
$\Delta T_{e,eff}$ [K]	9.96	10.05	10.50	10.64	10.64	11.00
$\frac{T_{a,in}+T_{a,out}}{2}$ [°C]	19.8	19.8	19.8	19.8	19.8	19.8
$T_{s,sat}$ [°C]	9.83	9.65	9.14	8.97	8.98	8.50
$\Delta T_{c,eff}$ [K]	9.96	10.05	10.50	10.64	10.64	11.00
$\frac{T_{a,in}+T_{a,out}}{2}$ [°C]	40.0	40.0	40.0	40.0	40.0	40.0
$T_{d,sat}$ [°C]	50.06	50.05	50.50	50.64	50.64	51.00

For the refrigerants considered, the degradation in COP with increasing pressure drop can be approximated as equation (7).

$$\frac{\eta_r}{\eta_0} = 1 + g \times \Delta p \qquad (7)$$

where the constant g is 0.036 for both evaporator and condenser side and Δp is the pressure drop expressed as change in saturation temperature [K]. Thus, a 1.5 K pressure loss corresponds to 5% drop in COP. Conversely, R32 can tolerate an additional 0.9 K pressure drop, 3.7 K for R152a, 2.2 K for R290 and for R1270, 1.9 K, compared to R410A.

These values are used subsequently to select appropriate HX in order to assess influence of refrigerant, component mass, volume and associated costs and emissions.

7 Heating capacity of reversible systems

As indicated in section 3, reversible RACS are used for heating as well as cooling purposes. In more northerly regions, it is likely that the heating function is of greater importance than cooling. Therefore, it is important to understand whether RACS with alternative refrigerants could provide adequate heating capacity.

The cycle calculations in Table 4 indicate a heating capacity for the various alternative refrigerants all within ±1% of each other.

A practical assessment is shown in Figure 32, where RACS cooling and nominal heating capacities as shown in Figure 10 are compared against those of R290 models. On average, conventional refrigerant (R32, R410A) models provide about 15% lower heating capacity than NCC, although this is within a ±20% band. Some models provide a heating capacity substantially less than the NCC. Data for R290 models show they provide some of the highest relative heating capacities, with none being less than the NCC. Some models provide heating capacities in excess of 50% greater than the cooling capacities. The R290 products shown are of a smaller size (< 4kW), but this is due to the constraints of the charge limits within the existing safety standard (IEC 60335-2-40, edition 6). In principle, the heating relative to cooling capacity scales up linearly for larger capacity models (proportionally larger compressors, heat exchangers, piping, etc.). Having high heating capacity models with R290 does not pose a technical barrier.

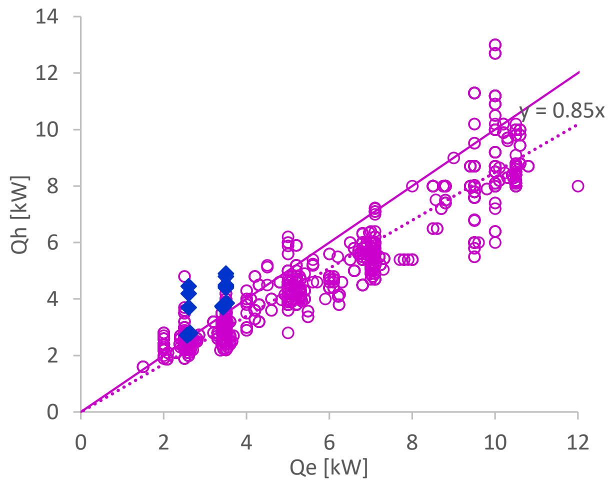


Figure 32: Comparison of heating and cooling capacity, including R290 models (blue diamonds)

In practice, the heating capacity of a RACS (relative to the NCC) is determined by compressor selection and HX design, in particular the distribution of area between IDU and ODU and control strategies. These factors have vastly more influence over heating capacity than refrigerant selection.

The literature includes some data for cooling and heating capacities for R290 in an AC systems. Some studies show a modest increase in heating capacity relative to cooling capacity of a few percent (e.g., Xu et al., Ding et al.) and others (e.g., Li et al., 2020) show heating capacity almost double that of cooling mode.

It is concluded that R1270 (and R290) reversible system do not present any risk of diminished heating capacity.

8 Approximation of charge amounts

It is intended to estimate the refrigerant charge of systems using R290, across the range of RACS capacity sizes and efficiency levels. For this, RACS charge quantities are treated on the basis of specific charge (μ); the ratio of initial refrigerant charge to NCC. This enables the charge to be expressed more clearly in relation to the size of the system under consideration. Specific charge across the database has been plotted against efficiency and NCC in order to identify patterns. Whilst the data could be expressed against EER or SEER, SEER has been chosen as the objective parameter since it is this that which product efficiency is to be gauged; see section 5. (Arguably, fixed-point EER has more of a functional relationship to specific charge, however, across the range of products, where a variety of compressor efficiencies and HX designs will be present, the usual dependencies will likely be obscured, just as much as with SEER.)

Refrigerant charge for products in the Eurovent database, where charge size had been extracted externally from product datasheets, are shown in Figure 33 and Figure 34 over a range, partitioned by NCC and efficiency, respectively. Note that for the 2 – 3% of models which adopt a 7 m or 7.5 m standard piping length, charge amounts were normalised to 5 m, according to their manuals' charge adjustment for additional piping.

8.1 Specific charge for R410A and R32

Figure 33 plots specific charge against NCC across a range of several incremental SEER values. Best-fit curves are included for each range of SEER. Evidently, there is wide scatter amongst the products, where there are a given SEER range, specific charge can be low or high; the largest specific charge (for a given NCC and SEER range) can be two or three times that of the smallest. Whilst a definite trend can be seen in terms of higher specific charge for smaller NCC products, the influence of efficiency on specific charge is not clear. There is a tendency for specific charge to diminish as NCC increases, not only for the entire dataset, but also for each SEER range, as seen with the best-fit curves.

Ordinarily such a trend may not be expected (double the NCC corresponds to double the HX area, double the HX volume and thus double the refrigerant charge). However, as system NCC increases, peripheral elements such as the relative volume of HX headers, compressor internal volumes, oil charge, controller/sensor volumes and so on diminish, thereby leading to an overall reduction in specific charge.

Figure 34 plots specific charge against SEER across a range of several incremental ranges of NCC values and includes corresponding best-fit lines. There is wide scatter and any lumped relationship between specific charge and SEER is impossible to discern. Indeed, the best-fit lines for each range of NCC show both increase and decrease of specific charge with higher SEER.

These observations are in contrast to the Ecodesign report (Huang et al., 2018), where a figure (their "Fig. 9") shows a clear linear correlation between specific charge and efficiency, with little scatter; a linear increase of about 0.09 kg per incremental increase of EER. It is likely that the small dataset used by Huang et al. originated from a single manufacturer thus reflecting an internal design approach. Indeed, narrowing the Eurovent data to individual manufacturers' products was found to provide far less scatter and clearer correlations than that seen in Figure 34. This is likely attributable to manufacturer's individual design strategies.

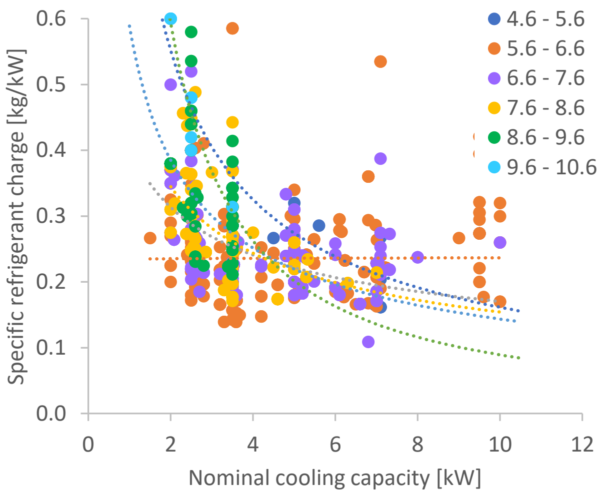


Figure 33: Specific refrigerant charge against NCC, across several incremental ranges of SEER

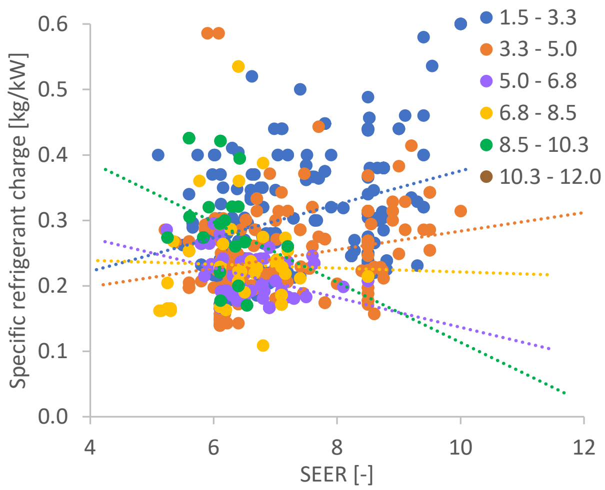


Figure 34: Specific refrigerant charge against SEER across several incremental ranges of NCC

Accordingly, explanations for the wide scatter is likely to include the range of design approaches used across different manufacturers and product groups. For R32 and particularly R410A, there is little motivation for charge minimisation, except for the minor benefits associated with limited cost reduction. Conversely, with A3 refrigerants, considerable efforts must be exerted to achieve charge minimisation if allowable refrigerant charge limits were to be satisfied.

Nevertheless, physically there should be a link between higher efficiency and a larger specific charge. Assuming that a system uses the highest efficiency compressor available, HX are designed and optimised to achieve the highest air-side heat transfer coefficients, HX refrigerant tubing diameter, internal surface, circuitry strategy, etc. have been refined as far as possible and system controllers have been enhanced for the operating conditions, then simply increasing HX surface area is a remaining approach for increasing system efficiency. Such an increase of HX surface area corresponds to a larger refrigerant-side volume and thus refrigerant mass.

Whilst Ecodesign (Huang et al., 2018) offers a best-fit for R32 units of 3.5 kW NCC, considering the current expanded dataset, it is not possible to obtain such a convenient correlation using either SEER or EER; the extent of scatter resulted in highly skewed correlations for each NCC grouping. In order to extract some relationship between specific refrigerant charge and SEER from the data, minimum μ_c were extracted from each range of data. For instance, Figure 35 provides minimum μ_c for each range of SEER and similarly Figure 36 for each range of NCC.

It may be supposed that at least some manufacturers opt to attain the minimum necessary refrigerant charge for some products, either for cost and/or environmental impact reasons. Therefore, amongst the dataset it may be assumed that at least some products represent designs based on minimally-optimised refrigerant charge. Accordingly, rational curve-fits are included in Figure 35 and Figure 36. Note that these minimal values do not correspond with the lowest SEER (Figure 35) or highest NCC (Figure 36), as would be expected. This implies there remains further optimal charge minimisation to be achieved. Nevertheless, the best-fit curves shown in Figure 35 and Figure 36 have been used as the basis for estimating specific charge.

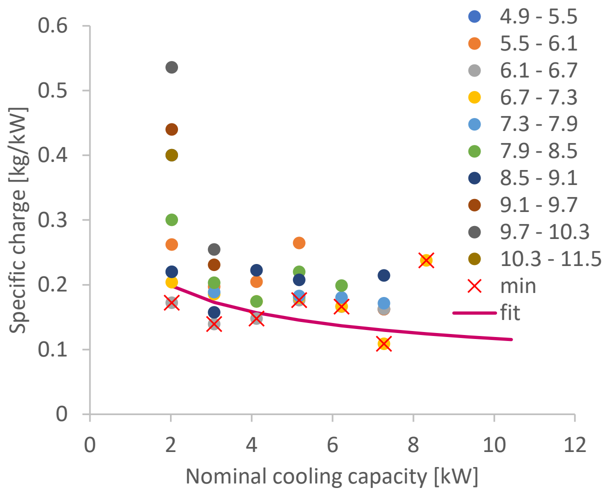


Figure 35: Minimum specific refrigerant charge against NCC, across incremental ranges of SEER

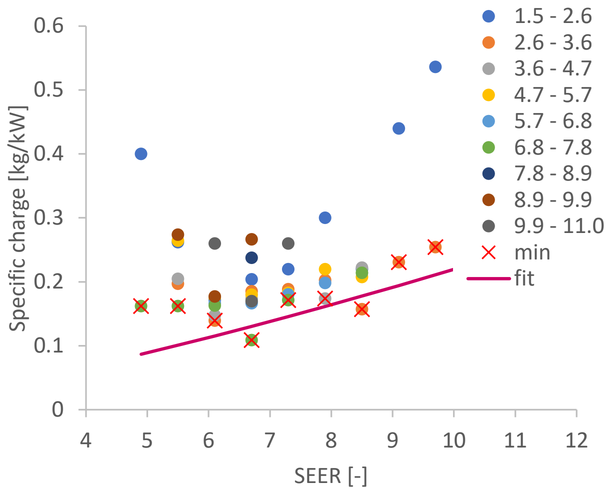


Figure 36: Minimum specific refrigerant charge against SEER across incremental ranges of NCC

Further, it is pertinent to remark on the sample number for certain data-points as an explanation for why the curve fit does not consistently match the minimum μ_c datapoints. In Figure 36 the best-fit curve is seen to lie beneath the minimum values at the three highest SEER values, arguably suggesting that the curve reflects unrealistically low μ_c. However, as shown in Table 6, these datapoints represent only small sample sizes (38, nine and seven), where the chance that there are models based on minimally-optimised refrigerant charge is low. By comparison, the values lying below the best-fit are based on sample sizes of 222 and 227 datapoints and thus, much more likely to include models which have been minimally-charge optimised. Thus, the best-fit curves are considered to represent the state-of-the-art in minimally-optimised refrigerant charge.

Table 6: Number of models associated with each range of SEER

SEER range	4.9 – 5.5	5.5 – 6.1	6.1 – 6.7	6.7 – 7.3	7.3 – 7.9	7.9 – 8.5	8.5 – 9.1	9.1 – 9.7	9.7 – 10.3	10.3 – 11.5
No. of models	8	43	256	222	139	47	227	38	9	7

The best-fit in Figure 35 and Figure 36 are represented by equations (8) and (9), respectively.

$$\mu_c = a \times \eta_e^n \tag{8}$$

$$\mu_c = b \times Q_e^m \tag{9}$$

where a = 0.011, n = 1.3, η_e is SEER, b = 0.25, m = -0.33 and Q_e is NCC.

Thus, a more general curve-fit approach was used, in the form of equation (10), to account for both NCC and SEER.

$$\mu_c = c \times \eta_e^n \times Q_e^m \tag{10}$$

where a = 0.1, n = 0.65 and m = -0.4.

To ensure the formula has validity. the following conditions were deemed appropriate and were broadly expected to be satisfied:

- Highest efficiency requires greatest specific charge.
- Specific charge reduces with increasing NCC.
- Lowest value resulting from equation (10) should not be below the lowest value for the corresponding efficiency increment (at any NCC).
- Match the average decline over NCC.

Equation (10) is superimposed on the data from Figure 35 and Figure 36 as shown in Figure 37 and Figure 38, respectively, using lower and upper ranges of NCC (1.5 to 12 kW) and SEER (4.6 to 12). Nearly all of the minimum specific charges are seen to be captured within these upper and lower bounds; the only outliers are those associated with very small sample sizes from the dataset.

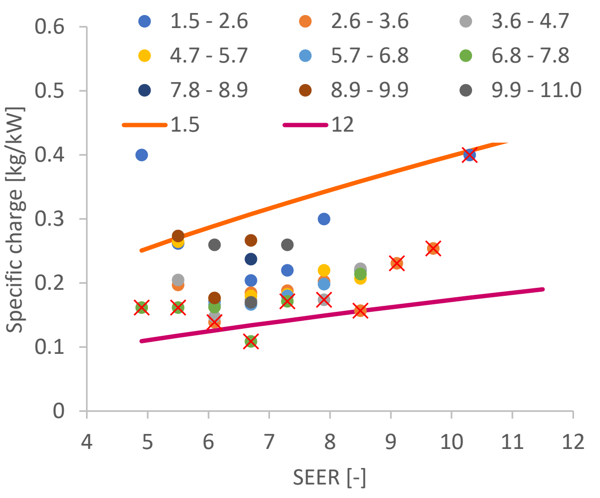


Figure 37: Minimum specific refrigerant charge against NCC, with equation (10) for 1.5 and 12 kW

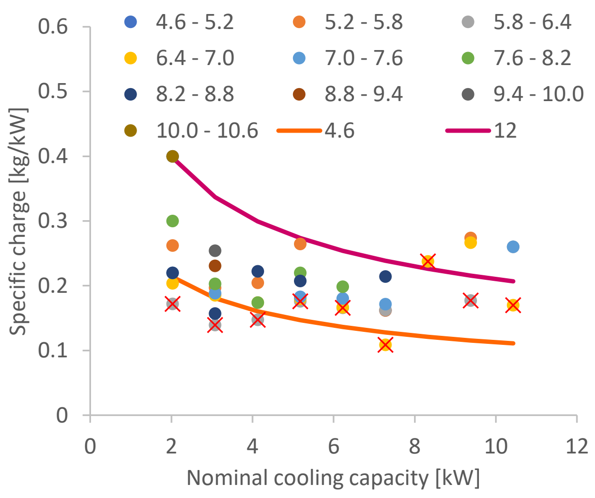


Figure 38: Minimum specific refrigerant charge against SEER, with equation (10) for 4.6 and 12

8.2 Specific charge for alternative refrigerants

Whilst equation (10) is based on R410A and R32 RACS models and may be considered to adequately represent the available data, their applicability should be extended to the alternative refrigerants. Due to the limitations outlined in section 1 and 0, though, there are relatively few R290 models available against which equation (10) can be qualified (and none for R1270, R1234yf or R152a).

As a first step, equation (10) may be compared against the available data for the small number of R290 products and adjusted with a factor φ, being the ratio of liquid densities of the two refrigerants, $\varphi = \rho_{R2}/\rho_{R1}$. Experience with converting HCFC and HFC systems to HC shows that using this liquid density ratio at condensing temperature provides a reasonable approximation. Whilst φ differs according to whether the original refrigerant is assumed to be R410A (φ = 0.49) or R32 (φ = 0.53) (Refprop, 2020), an average value based on the proportion of respective models in the database is used; φ = 0.52. Thus equation (11) can be applied to R290 (and R1270) models and latterly to R1234yf and R152a.

$$\mu_c = \psi \times \varphi \times c \times \eta_e^n \times Q_e^m \tag{11}$$

where φ = 0.52, a = 0.1, n = 0.65, m = -0.4 and ψ = 0.85 and is a coadjuvant to help better match the R290 RACS data to the correlation.

Equation (11) is compared against specific charge for actual R290 products (listed in Annex E), as shown in Figure 39 (with the coadjuvant, ψ = 1). The calculation overestimates the specific charge for these products. Accordingly, it is adjusted downwards, with ψ = 0.85, which can be considered as a fair representation (Figure 40). Note that the 18 kW product is a cooling-only ducted split model and may not necessarily be representative of reversible system, but is included here to help provide some indication of the validity of the approach to larger NCCs. Apart from this particular case, using equation (11) with ψ = 0.85 seems to provide a reasonable representation of specific charge, although still an overestimation in some cases. For the lowest charge product, ψ may be set as low as 0.65 to 0.70. Such significant reduction in refrigerant charge for R290 models can be attributed to rigorous R&D activities of the manufacturers, driven by the need to lower refrigerant charge to below the ACL imposed by earlier editions of IEC 60335-2-40. Conversely, RACS using R410A and R32 have not been subjected to such technical pressures.

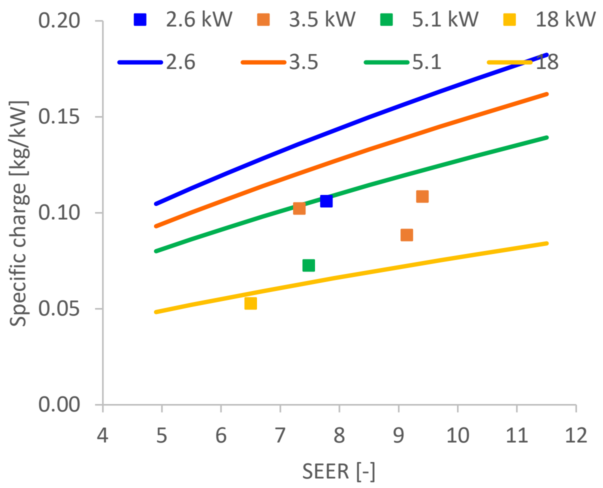


Figure 39: Comparison of R290 product specific refrigerant charge with equation (11)

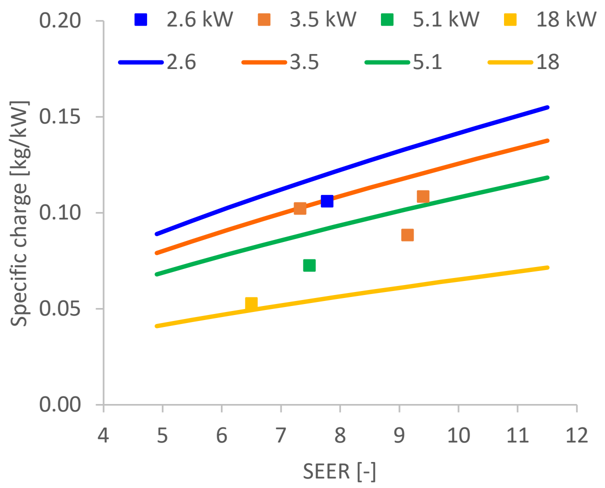
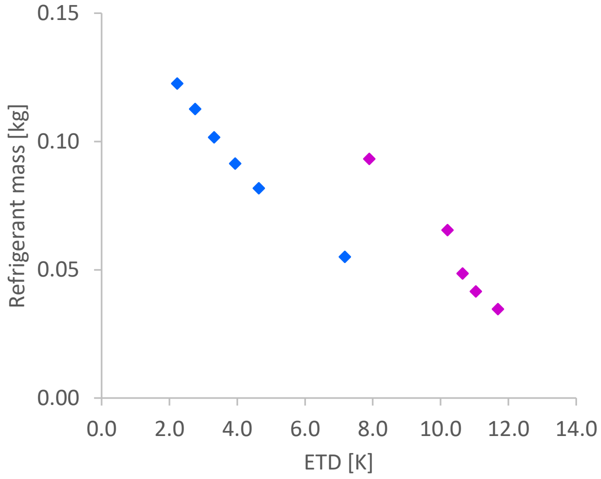


Figure 40: Adjustment of equation (11) to better match specific charge of R290 products

Lastly, as a cross-check, the output of equation (11) has been compared against the required R290 charge obtained from the HX simulations (see section 10.4). Operating mass for the evaporator and condenser were obtained for the under- and over-sized HX (for the design capacity); see Figure 41. Best-fit curves were obtained, from which operating refrigerant mass was calculated for each ETD required to achieve a given cycle efficiency (EER), as in Figure 30 and Figure 31. A nominal system charge for a 5 kW NCC and EER = 6.5 was obtained from equation (11) and adjusted for higher or lower EER using the best-fit curves. The resulting R290 specific charges are plotted in Figure 42 for two cases: one where the majority of the change in ETD is given to the evaporator and one given to the condenser. It can be seen that the behaviour exhibited by equation (11) is consistent with that based on HX simulation, which gives further confidence that the formula is adequately representative.



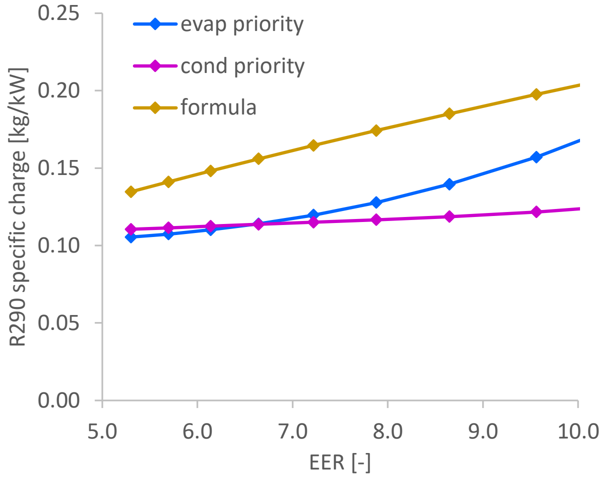


Figure 41: Evaporator and condenser operating charges for different designs

Figure 42: Comparison of equation (11) against charge results based on HX simulations

For cases with R1234yf and R152a, equation (11) may be used but with φ = 1.12 and 0.93, respectively, to account for refrigerant properties and ψ = 1 since there is little need for rigorous charge reduction.

8.3 Charge for interconnecting piping

In addition to initial system charge, RACS may require extra refrigerant to account for interconnecting piping in excess of the standard 5 m. This is defined by the size of the pipe connections and includes both the suction line and the (two-phase) delivery line. Additional charge values were averaged across typical interconnecting line sizes for 3.5 kW – 20 kW models and expressed in equation (12).

$$m'_p = \varphi \times (2.7 + 1 \times Q_e) \quad (12)$$

For example, for a 3.5 kW R290 RACS with 20 m of extra piping requires an additional 65 g, 95 g for a 6 kW unit and a 12 kW unit would need about 160 g.

Finally, total system charge with a given additional interconnecting pipe length, L [m], is from equation (13).

$$m_c = \mu_c \times Q_e + m'_p \times L \quad (13)$$

8.4 Example charge amounts

Estimated charge amount for the alternative refrigerants in a series of hypothetical RACS is shown in Figure 43, Figure 44, Figure 45 and Figure 46 across a range of NCC and efficiency levels, including with an additional 20 m interconnecting piping.

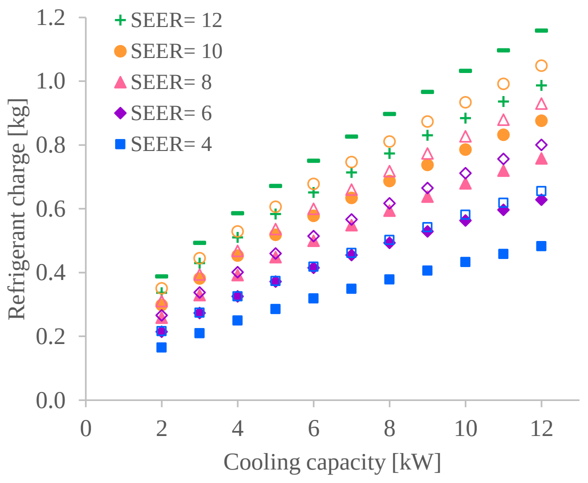


Figure 43: Charge amount for hypothetical 1 – 12 kW R1270 models at a range of SEER levels, with 0 m (filled) and 20 m (empty markers) additional interconnecting piping.

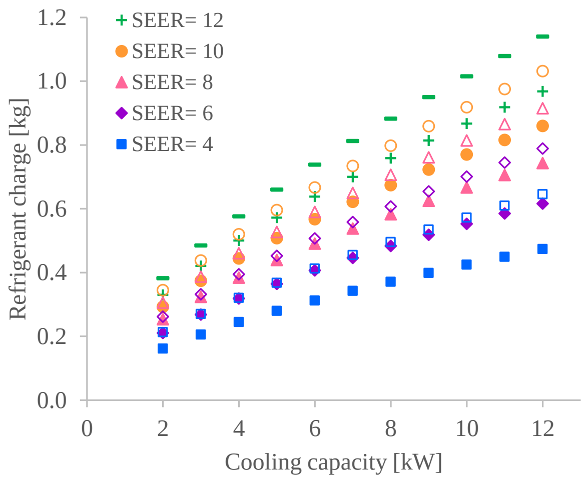


Figure 44: Charge amount for hypothetical 1 – 12 kW R290 models at a range of SEER levels, with 0 m (filled) and 20 m (empty markers) additional interconnecting piping.

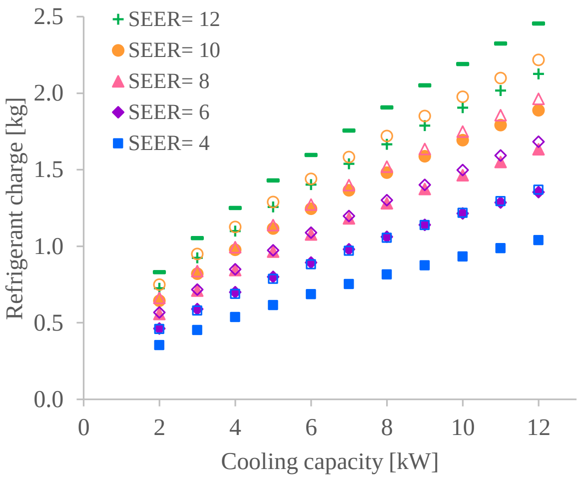


Figure 45: Charge amount for hypothetical 1 – 12 kW R1234yf models at a range of SEER levels, with 0 m (filled) and 20 m (empty markers) additional interconnecting piping.

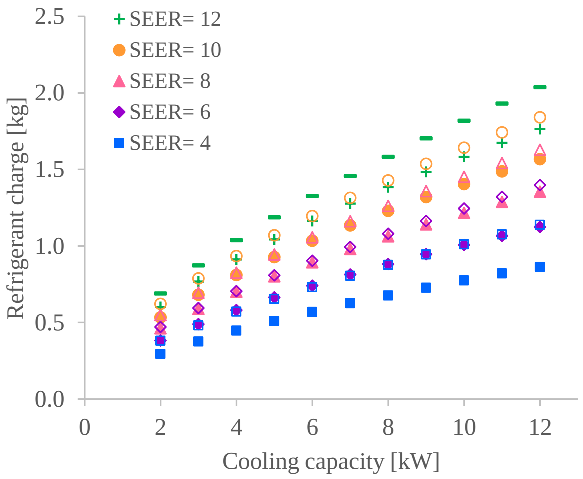


Figure 46: Charge amount for hypothetical 1 – 12 kW R152a models at a range of SEER levels, with 0 m (filled) and 20 m (empty markers) additional interconnecting piping.

9 RACS charge requirements in relation to charge limits

The applicability of refrigerant charge required for RACS products (section 8) can be gauged by considering them in light of the charge limits imposed by safety standards (section 0). This is carried out by comparing the charge limits and the required charge amounts, with regards to the assumed thermal load for the conditioned space (section 3).

Specifically:

- With R290
  - Assuming standard 5 m interconnecting piping
  - Additional 20 m interconnecting piping
  - Additional 20 m interconnecting piping and assumed future charge optimisation approaches
- With R1270
  - Additional 20 m interconnecting piping
- With R152a
  - Additional 20 m interconnecting piping

These are carried out for “medium” (0.15 kW/m^2) and “high” (0.20 kW/m^2) thermal loads. Given its high LFL, such an assessment with R1234yf is not considered necessary. As used in section 0, RACS employing active limited releasable charge (ALRC) are assumed to pessimistically release 40% of their charge, i.e., retaining 60% in the system following a leak.

Figure 47 and Figure 48 superimpose the hypothetical R290 RACS onto the graph of the basic charge limits only. Main observations are:

- Floor RACS are not feasible under any circumstances.
- Only lower SEER would be feasible as wall or ceiling RACS.
- Higher SEER are not possible for any RACS.

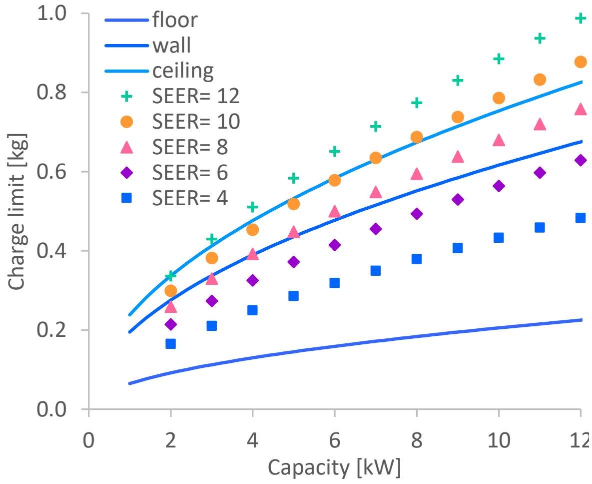


Figure 47: R290 charge assessment with basic charge limits, using medium thermal loads

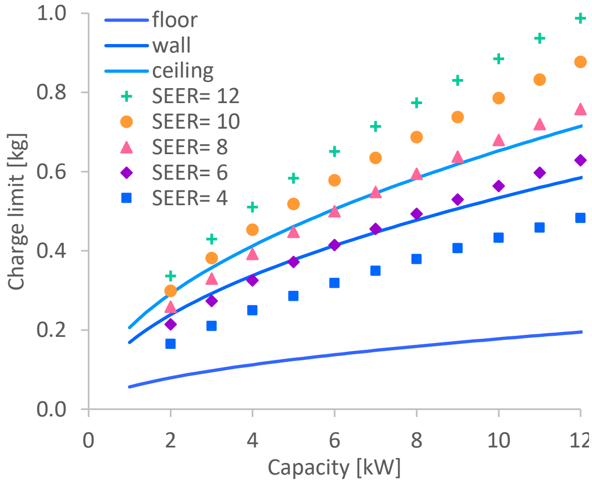


Figure 48: R290 charge assessment with basic charge limits, using high thermal loads

Figure 49 and Figure 50 superimpose the hypothetical R290 RACS onto the graph with ETRS charge limits.

- Floor RACS are again not feasible for almost all circumstances.
- With wall and ceiling RACS, nearly all low and high SEER are applicable
- The exceptions are the lowest NCC models with high SEER

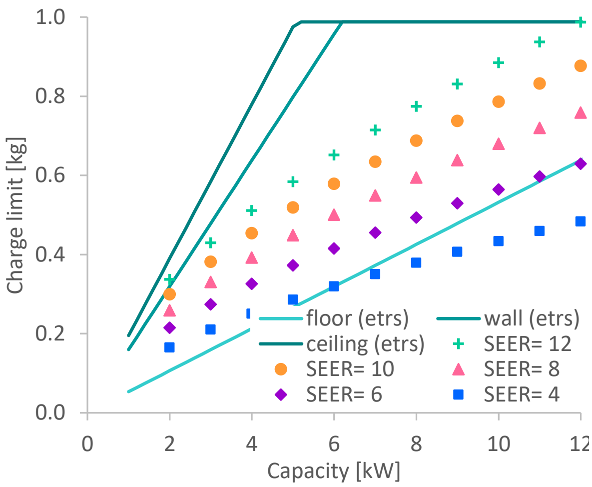


Figure 49: R290 charge assessment with ETRS charge limits, using medium thermal loads

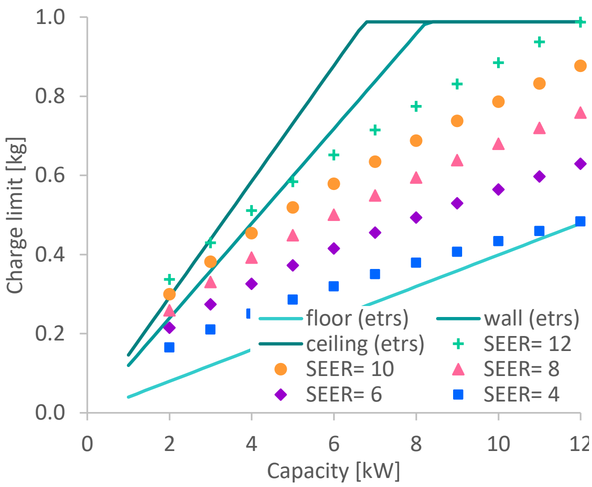


Figure 50: R290 charge assessment with ETRS charge limits, using high thermal loads

Figure 51 and Figure 52 superimpose the hypothetical R290 RACS onto the graph with ETRS charge limits, using ALRC.

- Floor RACS are generally feasible for all SEER levels, except for higher SEER in lower NCC models.
- All high and low SEER levels are feasible with both wall and ceiling RACS.

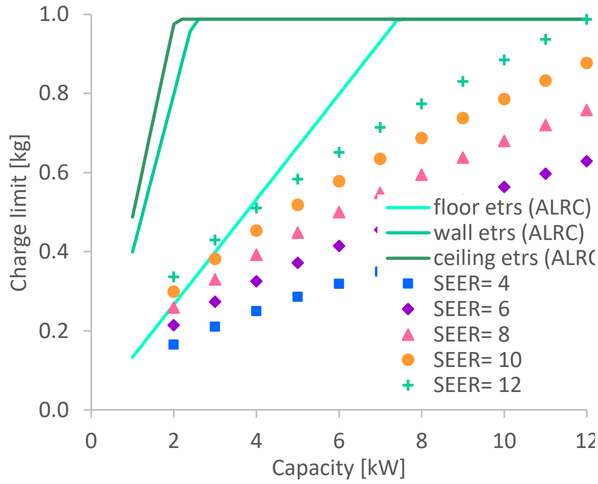


Figure 51: R290 charge assessment with ETRS limits employing ALRC, using medium thermal loads

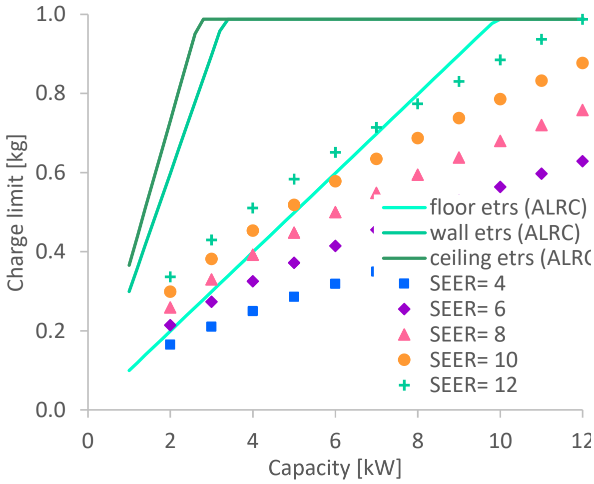


Figure 52: R290 charge assessment with ETRS limits employing ALRC, using high thermal loads

Figure 53 and Figure 54 superimpose the hypothetical R290 RACS onto the graph with IAF charge limits, with and without use of ALRC.

- Regardless of the type of RACS (floor, wall, ceiling), all high and low SEER levels are feasible.

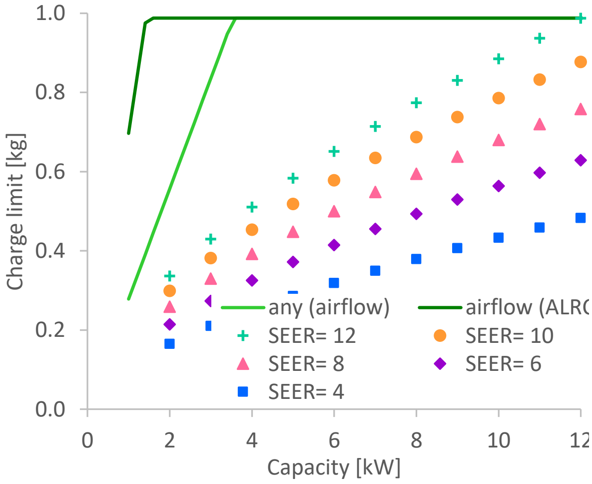


Figure 53: R290 charge assessment with IAF limits including ALRC, using medium thermal loads

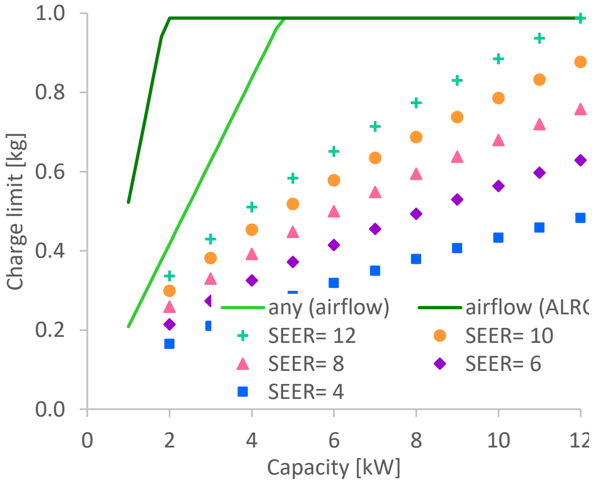


Figure 54: R290 charge assessment with IAF limits including ALRC, using high thermal loads

It is observed in Figure 49, Figure 51 and Figure 53 that for the largest NCC models with highest SEER, the charge is about the same as the upper charge limit (UCL), regardless of the heat load. This may pose a concern for product development for such situations where additional interconnecting piping is required between the IDU and ODU.

Figure 55 superimposes the hypothetical R290 RACS onto the graph of ETRS and IAF charge limits, with and without ALRC, but where the system charge amount is increased (as detailed in section 8.3) to account for an additional 20 m of piping.

- Charge amount of higher SEER levels exceed the UCL.
- Also, for RACS with smaller NCC, the allowable charge limits (ACL) for wall and ceiling ETRS cases are also exceeded, where either IAF and/or ETRS with ALRC would have to be used.

Addressing the larger NCC models with additional piping would require increasing UCLs or identifying a route under the horizontal standards (ISO 5149, EN 378) where the UCL is about 1.5 kg.

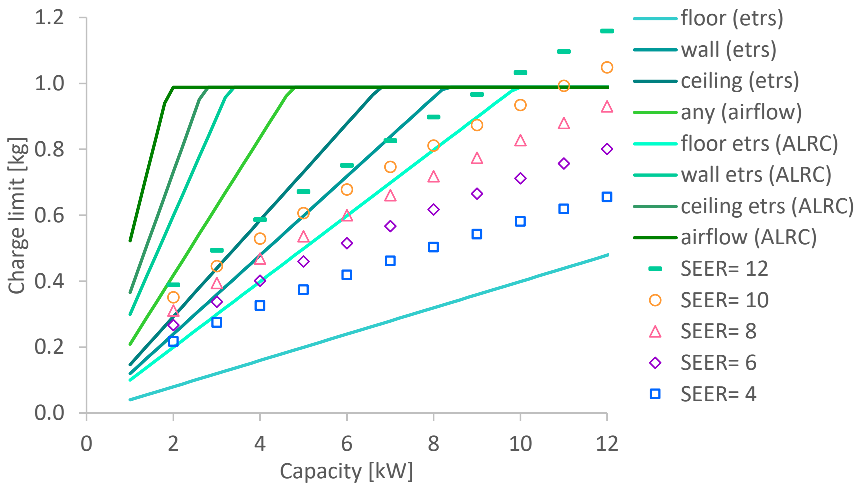


Figure 55: R290 charge assessment with ETRS limits, IAF limits and ALRC, using high heat load and 20 m additional interconnecting piping

A further option would to be to employ R1270, with an LFL about 20% higher than R290. Figure 56 repeats Figure 55, but using R1270. Here, all RACS cases are encompassed by IAF or ETRS with and without ALRC.

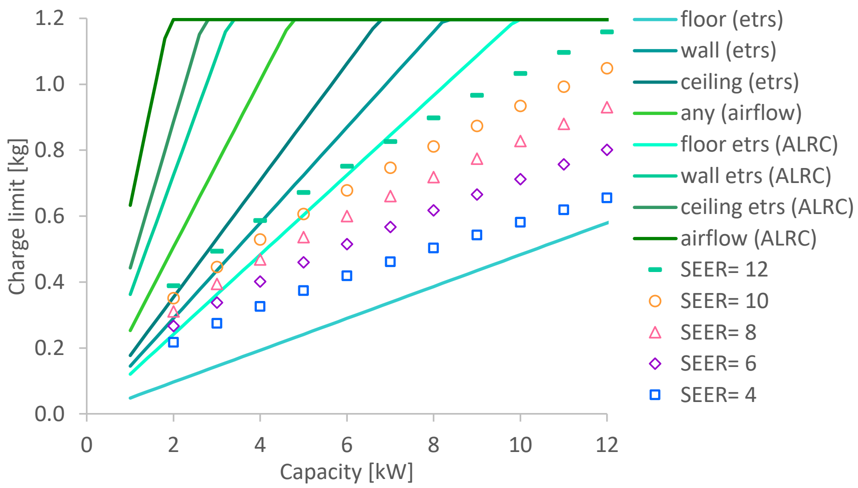


Figure 56: R1270 charge assessment with ETRS limits, IAF limits and ALRC, using high heat load and 20 m additional interconnecting piping

Figure 57 similarly repeats Figure 55 and Figure 56, but with R152a. The LFL of R152a is about 3.5 times that of R290. In this case, all RACS cases are encompassed by IAF or ETRS, regardless of ALRC.

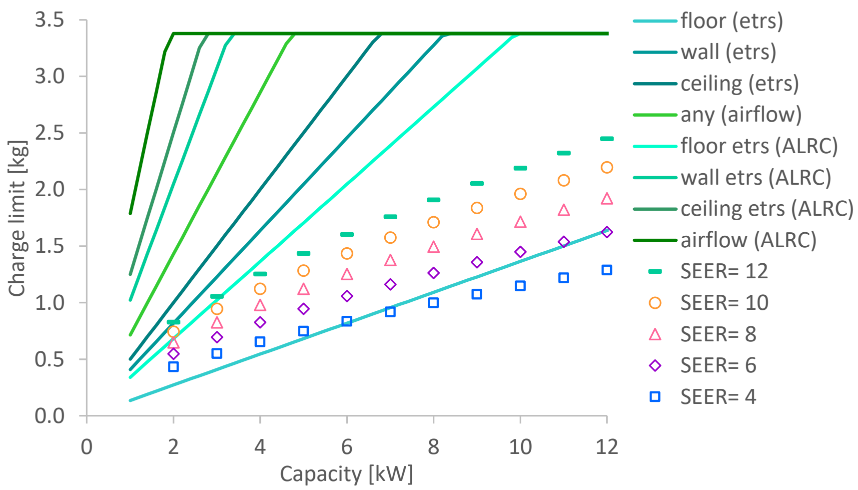


Figure 57: R152a charge assessment with ETRS limits, IAF limits and limited releasable charge, using high heat load and 20 m additional interconnecting piping

In general, RACS with alternative refrigerants with GWP < 150 can satisfy average, high and even extreme thermal loads. Neglecting cost and environmental implications (see sections 10 and 11), R1234yf and R152a can easily satisfy the application requirements. Use of R290 approaches the application boundary for very high efficiency models and NCC above about 10 kW. Having +20 m interconnecting piping with these RACS exceeds the UCL within IEC 60335-2-40. On the other hand, due to its higher LFL, use of R1270 enables all such systems to fall below the UCL and thus never goes beyond this application boundary.

For smaller NCC with higher efficiency, use of certain mitigation measures can lead to R290 RACS exceeding the ACL, especially for extreme thermal loads. Thus, manufacturers would need to be able to anticipate the maximum demand of the space that a unit could be installed in, when choosing the mitigation measures. Alternatively, applying IAF and ALRC for all models would act as a sort of "catch all".

10 Component material mass and costs

Quantifying the relative impact on the consumption of construction materials, considering cost and emissions implications, is important when considering alternative refrigerants. Accordingly, a detailed assessment of changes in material requirements due to differences in HX, compressor, piping and other RACS components arising from a switch of refrigerants, has been carried out. This has been executed through analysis of component catalogue data, previous implementation projects and detailed design and performance simulation of HXs.

According to Huang et al. (2018b), material composition of RACS (and approximate material cost) is plastics: 18% (€1 per kg), steel: 45% (€1 per kg), copper: 17% (€6 per kg), aluminium: 7% (€3 per kg) and the remainder as “miscellaneous”. Broadly, the cost of materials corresponds to about €2.1 per kg of AC and this indicates that the material cost of AC is responsible for 4 – 19% of the retail price (excluding tax). The remaining 80 – 95% may be accounted for by research and development, manufacturing whole unit and components), storage and distribution, business costs such as sales and marketing, warrantees and of course company profit. As such, a change of, say, 10% in AC material mass would correspond to about 1 – 2% change in product price.

10.1 Piping

Refrigerant piping is part of finned-tube heat exchangers, for linking system components, including interconnecting piping between the indoor and outdoor units. In general, pipe size is selected to provide a tolerable pressure drop (in terms of equivalent change in saturation temperature). Figure 58, Figure 59 and Figure 60 shows results of calculations for piping for all refrigerants listed in ISO 817, plotted over saturation pressure corresponding to 0°C as a reference.

For each, refrigerant mass flow is calculated based on 25°C and 10 kW cooling capacity and the internal diameter (Figure 58) is determined according to a pressure drop equivalent to 0.1 K/m for that refrigerant. As a general trend, lower pressure refrigerants demand a larger pipe diameter, which is primarily due to 0.1 K corresponding to a smaller frictional pressure loss than for higher pressure refrigerants. For a given saturation pressure, the scatter arises from different thermophysical properties of the refrigerants, such as density and viscosity.

Within knowledge of the pipe diameter and its expected maximum operating pressure (here, taken as that corresponding to 65°C), the pipe wall minimum thickness can be calculated. The method prescribed in EN 14276-2 (2020) is used, assuming seamless copper tube at 100°C. For a fixed pipe diameter, the thickness increases smoothly with greater pressure. However, the scatter occurring in Figure 59 does so because of the variations in pipe diameter already seen in Figure 58.

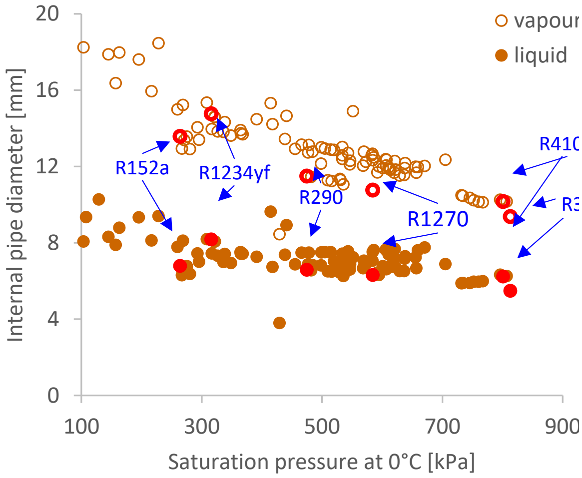


Figure 58: Internal pipe diameter for various refrigerants, assuming 25°C, 10 kW refrigerating capacity and 0.1 K/m pressure drop

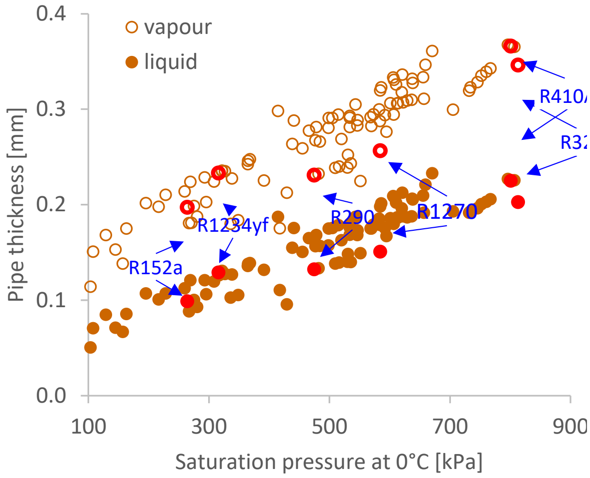


Figure 59: Pipe thickness for Figure 58, based on a maximum operating pressure corresponding to 65°C

Knowing the diameter and thickness allows the mass of copper to be calculated, as shown in Figure 60. Broadly, the higher the saturation pressure, the greater the material mass required. Although higher pressure refrigerants enjoy smaller diameters, they still require thicker walls; generally, the smaller diameter does not offset the increased mass associated with the thicker walls. Some exceptions do arise, such as with R1234yf and R410A, where the higher viscosity and smaller enthalpy difference (leading to higher mass flow rates) result in disproportionately greater pressure drops.

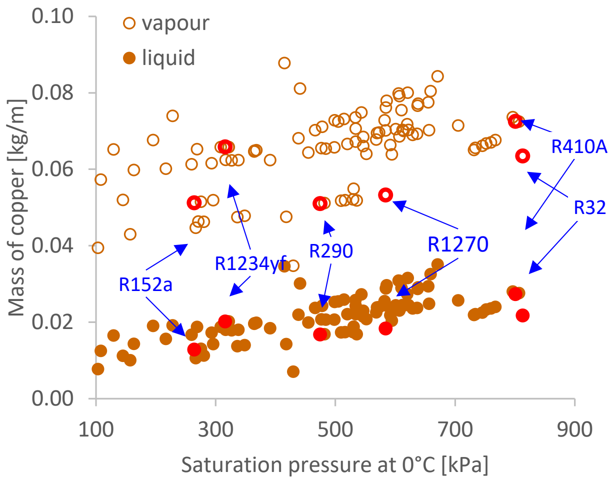


Figure 60: Comparison mass of copper per metre piping for various refrigerants

A summary of the results for the selected conditions are presented in Table 7, listing outside diameter and mass of copper. Switching from R410A to any of the alternative refrigerants always results in lower mass of copper. R32 requires 10% less, R1270 and R290, about 30 – 40% less, R1234yf, between 10 – 25% less and 30 – 50% less for R152a. All refrigerants, except R1234yf, require less mass than R32.

It is noted, however, that refrigeration pipe is usually supplied in incremental diameters and usually, two, three or four thicknesses, so optimal selection for a given refrigerant is seldom possible. Moreover, at least for lower pressure cases, overly thin pipes are avoided since further protection is usually required against external impacts, damage, etc.

Table 7: Tube diameter and mass per metre

Refrigerant		R410A	R32	R1270	R290	R1234yf	R152a
Vapour	Outside diameter [mm]	10.9	10.1	11.3	12.0	15.2	14.0
	Mass [kg/m]	0.073	0.063	0.053	0.051	0.066	0.051
	Cost [€/m]	0.58	0.50	0.42	0.41	0.53	0.41
Liquid	Outside diameter [mm]	6.7	5.9	6.6	6.8	8.4	7.0
	Mass [kg/m]	0.027	0.022	0.018	0.017	0.02	0.013
	Cost [€/m]	0.22	0.18	0.14	0.14	0.16	0.10

10.2 Compressors

As seen in Table 4, the alternative refrigerants have different operating pressures and swept volumes, which implies differences in the compressor design and construction. Consideration may be given to identify whether variations in material requirements and associated costs also differ. An exercise is carried out to identify the possible changes in compressor mass and volume associated with alternative refrigerants.

Smaller RACS almost exclusively use hermetic rotary compressors. Catalogue data from three different manufacturers has been collated for the same class of compressor and for different refrigerants. Analysis of the data reveals implications associated with adopting other alternative refrigerants. Figure 61 compares the specific mass (compressor mass divided by nominal cooling capacity at standards conditions). Comparing compressors from the same manufacturer for high pressure (R410A) and medium pressure (R22 or R407C) refrigerants, no difference is observed. In some cases, high pressure refrigerants are associated with greater mass whereas in other cases, greater mass is for the medium pressure refrigerants. Specifically, despite R407C having over 1.5 times the swept volume of R410A, the required mass is usually within ±3%.
It is therefore reasonable to regard the compressor displacement as having no discernible impact upon the mass of the compressor. Indeed, the same trade-off between size and wall thickness, as discussed for pipe mass – similarly applies to R290, R1270, R1234yf and R152a. Similarly, motor materials (copper, rare earth metals, etc.) would not change for the same shaft power.

The same conclusions may be drawn from the data for compressor specific volume (shell volume divided by nominal cooling capacity); Figure 62. Again, there is no clear difference between the high and medium pressure refrigerant. Based on this data it is concluded that the same would be applicable to the other alternative refrigerants under consideration.

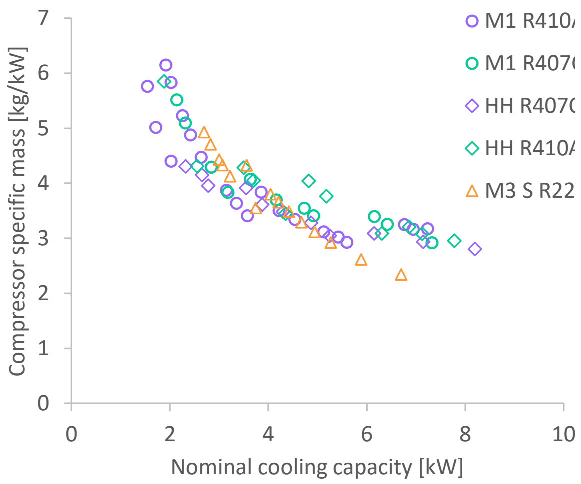


Figure 61: Comparison of rotary compressor specific mass for R410A, R22 and R407C

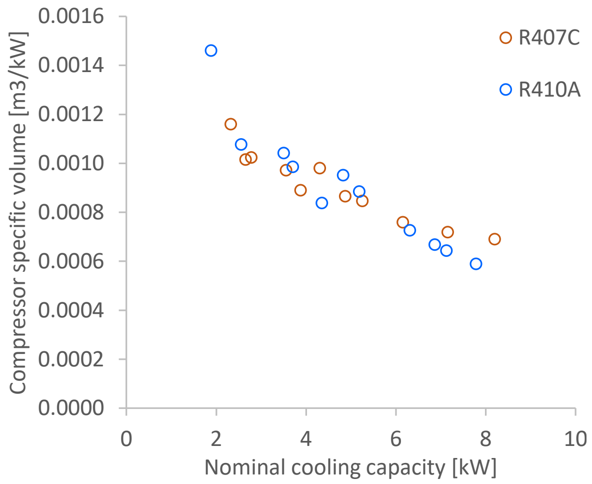


Figure 62: Comparison of rotary compressor specific volume for R410A, R22 and R407C

Figure 63 shows the variation of compressor oil volume for high and medium pressure refrigerants. Again, there is no distinguishable difference between the two refrigerants. Furthermore, due to the desire to minimise refrigerant charge for class A3 refrigerants, additional efforts are made in the development of R290 compressors to reduce oil charge (e.g., Gao et al., 2012; Gao et al., 2015; Zhang et al., 2014; Wu and Chen, 2015).

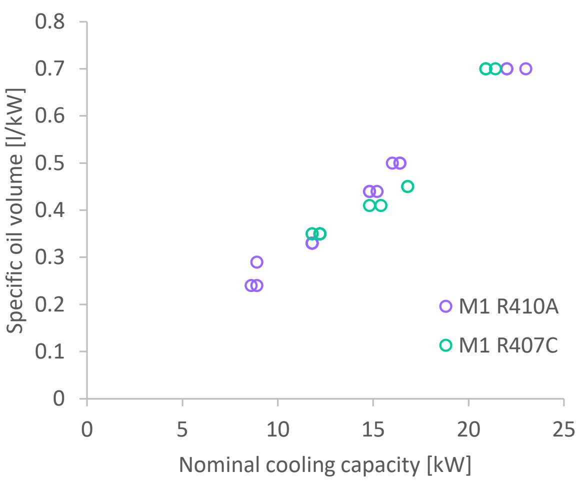


Figure 63: Comparison of rotary compressor specific oil volume for R410A, R22 and R407C

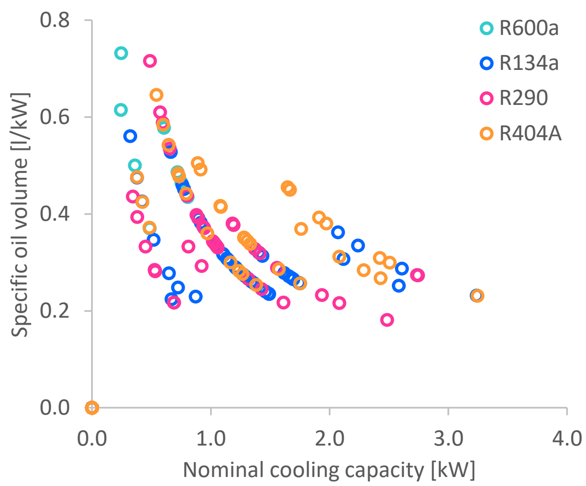


Figure 64: Comparison of hermetic reciprocating compressor specific oil volume for various refrigerants

Carrying out the same assessment on hermetic reciprocating compressors for refrigerants R404A, R290, R134a and R600a (Figure 64, Figure 65 and Figure 66), there is also no consistent differentiation between specific mass and specific volume across these refrigerants. This further provides confidence in the conclusion that the refrigerant characteristics do not impose a cost or dimensional impacts on the compressor characteristics.

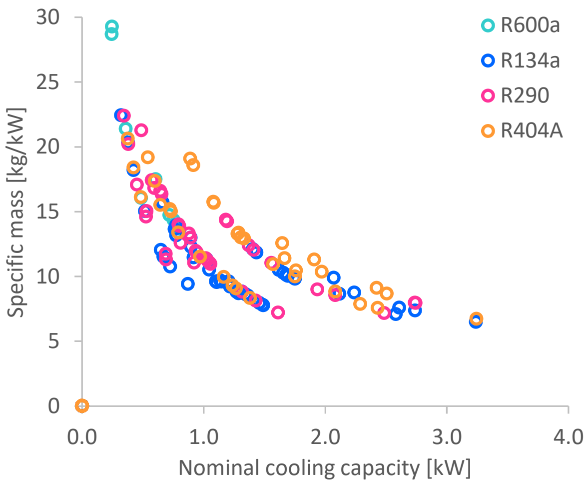


Figure 65: Comparison of hermetic reciprocating compressor specific mass for various refrigerants

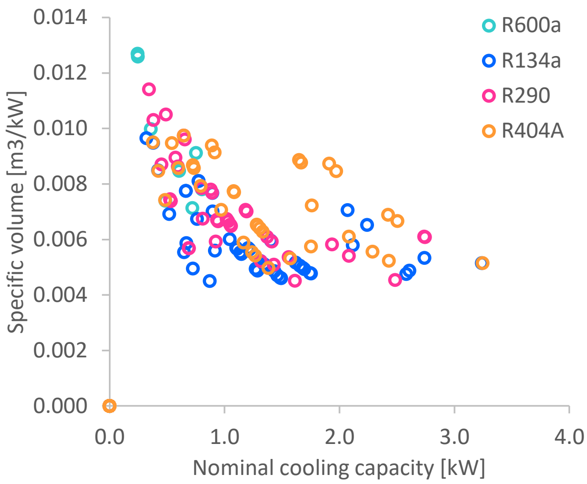


Figure 66: Comparison of hermetic reciprocating compressor specific volume for various refrigerants

In conclusion, there is no evidence to suggest that a shift to an alternative refrigerant (with lower pressure) would lead to a substantive change in compressor mass or volume or quantity of oil and as such, no impact on cost. There would be no change to the size of the unit or expenditure on materials. Furthermore, considering that usually, ODUs generally have significant internal free space and that an ODU housing may be used for two, three or even four different NCC models, it is unlikely that any minor differences in compressor volume would pose an impact.

Compressor development is a continuous process, involving numerous iterations of refinements for improving efficiency, reliability and cost reduction. Whichever refrigerants are used on a larger-scale in RACS, the compressors will benefit from this continuous development.

10.3 Expansion devices, valves and other line components

Expansion devices may include capillary tubes, short-tube restrictors, thermostatic and electronic expansion valves (EEV). Most higher efficiency models use EEVs.

Refrigerant type has a negligible influence in expansion device cost and size. Arguably the connections may differ slightly (see section 10.1 on piping) but the vast majority of the EEV materials are related to its function and are unrelated to the refrigerant pressure or such properties.

The same considerations and conclusions apply to other valves and line components, such as solenoid valves, reversing valves and hand valves.

10.4 Heat exchangers

The construction of the primary HX – evaporator and condenser – can be notably influenced by refrigerant selection and the desired contribution to system efficiency. HXs are designed or selected to help achieve a desired system efficiency. Different construction characteristics affect their performance and these in turn often infer cost implications, in terms of mass of materials (copper, aluminium), features (rifled tubes and textured fins) and manufacturing processes.

The majority of reversible RACS employ finned-tube type HX, which will be the focus in the present work.

However, within this narrow scope, there still exists a variety of different HX designs; tube shapes and sizes, tube alignments, circuitries, air-side enhancements, internal enhancements with different refrigerants and so on, the optimal of which can differ for each specific refrigerant. There are numerous strategies applied for examining the design, rationale and methodology of complex HX circuitry (e.g., Joppolo et al., 2015; Cotton et al., 2018; Wu et al., 2012; Li et al., 2018; Li et al., 2021). However, for brevity, within the scope of the current work HX analysis is conducted on the basis of relatively basic designs. It is considered that the conclusions arising from this would be representative of the optimised and refined designs expected from RACS manufacturers. For this exercise, HX performance is assessed using IMST-ART simulation software[5], where a number of IDU and ODU HXs are simulated, based on standard fixed-point rating conditions.

[5] http://www.imst-art.com/?page_id=67

HX design and selection is not only based on thermophysical properties but other parameters that relate to the application and safety considerations. In terms of application and safety considerations, with a non-flammable refrigerant the objective may solely be lowest HX mass. With an A3 refrigerant, the primary objective may be smallest refrigerant charge (whilst maintaining a pressure drop that will not lead to degradation of efficiency below the target level), which could be to the detriment of material mass and/or physical volume. Conversely, R410A has the luxury to choose the HX providing smallest mass and size (without exceeding the target pressure drop), irrespective of the refrigerant charge (although there is an approximate correlation between HX mass and refrigerant charge). With lower flammability yet more costly refrigerants, such as R1234yf, there remains a motivation to minimise charge, i.e., for economic reasons. However, due to its inherent high pressure drop, larger HX must usually be selected (if the efficiency target is to be met) and accordingly refrigerant and material mass are unavoidably high.

Crucially, the HX analysis is carried out on the basis of the system balance-points detailed in Table 5, to account for the cycle efficiencies of the alternative refrigerants. Furthermore, whilst a NCC of 5 kW has been used (to represent the largest capacity of the high population products), the findings are deemed to be extrapolatable to other NCCs. The outputs from selecting the most appropriate HX design include mass of copper, aluminium and operating refrigerant charge.

10.4.1 Indoor unit HX (evaporator)

Evaporator designs consistent typical split RACS wall type IDUs were applied, with a target thermal capacity of 5 kW. The baseline characteristics and subsequent design variations are listed in Table 8. Output data is presented graphically in Annex D for each of the alternative refrigerants.

Table 8: Evaporator configurations

Parameter	Base	Variations
Tube configuration	U, staggered	
No tubes [-]	2 × 14	2 × 14, 16 … 32
No circuits [-]	6	2, 4, 5, 6, 8, 10
Width [m]	0.8	
Nominal outside diameter [mm]	5.5	6.0, 6.5, 7.0, 7.5
Tube thickness [mm]	0.5	

Airflow rate [m^3/h]	750	

Assuming the manufacturer intends to retain the exiting frame plate size, the evaporator width is retained throughout. Only tube diameter, number of tubes and circuitry is varied.

Objective parameter is the saturated outlet temperature of the refrigerant from the evaporator ($T_{e,sat}$). Other than the direct effect of the refrigerants thermophysical properties on heat transfer coefficients and pressure drop, HX length, tube diameter and number of circuits affect the ETD. The suitable HX design was selected to provide a close match between $T_{e,sat}$ at 5 kW and the target ETD, as listed in Table 5. A tolerance of ±0.1 K is afforded to the selection, as this can often lead to a "better" choice (based on material cost, for example).

According to the cycle efficiencies in Table 4, "tolerable" efficiency deterioration due to HX performance (and also piping pressure loss) may be estimated in order to satisfy the same efficiency for all refrigerants (assumed to be fixed-point EER of 6.0, assumed to correspond to a SEER of 12; see Figure 8).

Table 9: Values corresponding to evaporator balance points

	R410A	R32	R1270	R290	R1234yf	R152a
Tube diameter	6.5	6.0	6.0 (7.0)	6.0	6.0 (7.0)	6.25
No of tubes	24	20	24 (20)	24	30 (32)	28
No of circuits	6	5	6 (4)	6	10 (8)	7
Interpolation	1	1	1/2	1	1/3	1
Pressure drop [K]	0.52	0.67	1.30	1.33	1.59	1.79
Mass of metal [kg]	5.2	4.1	4.9 (4.3)	4.9	6.1 (7.3)	5.9
Refrigerant mass [kg]	0.123	0.075	0.047	0.042	0.115	0.072
Coil volume [m3]	0.0086	0.0072	0.0079	0.0086	0.0111	0.0101
Component cost [€]	30.7	23.6	26.8	28.2	39.6	34.3

10.4.2 Outdoor unit HX (condenser)

Condenser designs consistent typical split RACS wall type IDUs were applied, with a target thermal capacity of about 6 kW. The baseline characteristics and subsequent design variations are listed in Table 10. Output data is presented graphically in Annex C for each of the alternative refrigerants.

Table 10: Evaporator configurations

Parameter	Base	Variations
Tube configuration	U, staggered	
No tubes [-]	2 × 12	2 × 14, 16 … 32
No circuits [-]	2	2, 3, 4, 5, 6, 8
Width [m]	0.85	
Nominal outside diameter [mm]	5.0	5.0, 5.5, 6.0, 6.5
Tube thickness [mm]	0.5	
Airflow rate [m3/h]	1301	

Assuming the manufacturer intends to retain the exiting frame plate size, the condenser width is retained throughout. Only tube diameter, number of tubes and circuitry is varied.

Objective parameter is the saturated inlet temperature of the refrigerant to the condenser ($T_{c,sat}$). Other than the direct effect of the refrigerants thermophysical properties on heat transfer coefficients and pressure drop, HX length, tube diameter and number of circuits affect the ETD. The suitable HX design was selected to provide a close match between $T_{c,sat}$ at 6.1 – 6.2 kW and the target ETD, as listed in Table 5. A tolerance of ±0.1 K is afforded to the selection, as this can often lead to a "better" choice (based on material cost, for example).

According to the cycle efficiencies in Table 4, "tolerable" efficiency deterioration due to HX performance (and also piping pressure loss) may be estimated in order to satisfy the same efficiency for all refrigerants (assumed to be fixed-point EER of 6.0, assumed to correspond to a SEER of 12; see Figure 8).

Table 11: Values corresponding to condenser balance points

	R410A	R32	R1270	R290	R1234yf	R152a
Tube diameter	6.5 (6.0)	5.5 (6.5)	5.0 (6.5)	5.5 (6.5)	6.5	5.5
No of tubes	14 (12)	12 (13)	16 (18)	20 (18)	24	24
No of circuits	2	2	4 (3)	5 (3)	6	8
Interpolation	1/2	1/3	1/3	1	1	1
Pressure drop [K]	0.85 (1.50) 1.18	1.05 (0.59) 0.87	0.82 (0.58) 0.72	0.48 (0.74) 0.48	0.44	0.25
Mass of metal [kg]	4.45 (3.53) 3.99	3.53 (4.45) 3.90	4.51 (5.72) 4.99	5.87 (5.72) 5.87	7.6	7.0
Refrigerant mass [kg]	0.196 (0.115) 0.156	0.090 (0.154) 0.116	0.051 (0.106) 0.073	0.075 (0.100) 0.075	0.297	0.126
Coil volume [m3]	0.0128 (0.0110) 0.012	0.0110 (0.0128) 0.012	0.0147 (0.0165) 0.015	0.0183 (0.0165) 0.018	0.022	0.022
Component cost [€]	23.9 (17.4) 20.7	16.4 (22.2) 18.7	19.5 (27.2) 22.6	26.3 (27.2) 26.3	53.7	31.7

10.5 Costs of safety features

When shifting from an A1 or A2L refrigerant to another refrigerant that is flammable, further constraints on charge limits may be invoked and additional costs may be incurred in order to apply further mitigation measures. Annex A provides a detailed overview of the likely costs associated with compliance with the requirements to address flammability within IEC 60335-2-40. A summary of those costs is listed in Table 12.

Table 12: Summary of cost implication associated with safety measures

Safety measure	Cost implication	Cost for 5 kW RACS using A3 [€]
Refrigerant quantity limits	None	€0
Charge minimisation	Negative – usually leads to lower refrigerant and material cost	€0
Limited releasable charge	Negligible up to cost of sensors and valve(s)	€0 (high efficiency, reversible) to €20 (cooling only)
Integral airflow	Negligible up to cost of sensors	€0
Leak detection	Sensors, controller	€2
No ignition sources	Variable, but usually negligible for RACS	€0

Safety measure	Cost implication	Cost for 5 kW RACS using A3 [€]
Enhanced tightness	Negligible, if production numbers are > 10,000's	€1
Marking and instructions	Negligible	€0

As seen in Figure 2, greatest increases in ACL are achieved through use of IAF and ALRC. Since RACS are assumed to be reversible throughout, they employ a reversing valve, which can also be used for ALRC to prevent backflow of refrigerant to the indoor unit. Thus, only a shut-off valve is required in the liquid line. For higher efficiency models, this can be satisfied with an EEV, otherwise a solenoid valve would be needed; at a cost of €15 – 30, depending upon the line size. For both ALRC and IAF, leak detection is necessary. Costs associated with the controller are negligible, but sensors (ultrasonic or gas) cost anything from €1 upwards; employing three ultrasonic sensors for the leak detection system could cost €3. Thus, to switch to an A2 or A3 refrigerant, the costs incurred for safety features would unlikely exceed €3 or €33 when ALRC is applied (for cooling only, lower efficiency models), depending upon the mitigation strategy and RACS capacity.

10.6 Overall considerations on material mass

Mass of materials from section 10 have been summed and included in Table 13. Material mass includes first charge for each system and the primary metals associated with piping, compressor, HXs, valves and housings. Materials associated with plastics, insulation, electronics and so on have been neglected since there is unlikely to be any significant variation arising from refrigerant choice.

Material costs are based on standard values per kg, as listed in metal exchange internet sites (June 2022). Product material costs are these multiplied by the corresponding material masses. Refrigerant prices vary widely, depending upon region, quantity purchased, supplier and other factors. Listed costs are considered to be representative for Europe in May 2022. Whilst the majority of RACS are manufactured outside Europe, any products containing F-gases are still subject to quotas so associated costs are considered to be lumped in with the product cost. Within the safety costs, the higher contributions, such as for a solenoid valve are not applicable since the system is assumed to be reversible (and thus has a reversing valve) and high efficiency (and thus employs an EEV).

Additional shipping costs are based on any greater volume of system components arising from use of an alternative refrigerant. For example, where a larger condenser is required, the additional shipping cost (currently about €74 per m^3 for a container from East Asia to Europe) is applied to the additional condenser volume. Similarly, for storage, a cost corresponding to €18 per m^3 per year has been applied (assuming the RACS are in storage for one year). The storage cost is highly variable depending upon location and size of storage facility, but since it is a relatively minor contribution, variations can be deemed negligible.

For comparison, a baseline cost is included, according to $\cong 650 \times Q_e^{-0.5}$. As seen in Figure 22, the retail price covers a huge range and is largely unrelated to efficiency, so the baseline cost is simply based on the median.

Refrigerant cost is separated into two categories: “bulk” according to manufacturer purchases (i.e., assigned to the first fill) and “service” as for technicians providing top-up or repair (i.e., applied to the refrigerant used for servicing during the remainder of the RACS lifetime). Service refrigerant cost also applies for filling additional interconnecting piping. Recovered refrigerant at end of life is not considered to have a value. Pricing data is taken from Öko-Recherche (2022) and commercial sources where data was absent.

Table 13: Summary of material mass and associated costs

Item		R410A	R32	R1270	R290	R1234yf	R152a
Material mass	Refrigerant mass [kg]	1.38	1.27	0.58	0.57	1.48	1.23
	Mass of steel [kg]	18	18	18	18	18	18
	Mass of aluminium [kg]	5.5	4.8	5.8	6.5	8.6	7.7
	Mass of copper [kg]	6.2	5.7	6.3	6.8	8.2	7.7
Material costs	Refrigerant – bulk [€/kg]	14	10	2	2	45	4
	Refrigerant – service [€/kg]	22	18	8	8	66	10
	Steel [€/kg]	1.5	1.5	1.5	1.5	1.5	1.5
	Aluminium sheet [€/kg]	2.5	2.5	2.5	2.5	2.5	2.5
	Copper tube [€/kg]	8.0	8.0	8.0	8.0	8.0	8.0
Product costs	Refrigerant [€]	37	26	4	4	125	12
	Steel [€]	27	27	27	27	27	27
	Aluminium sheet [€]	14	12	14	16	21	19
	Copper tube [€]	49	46	51	54	66	61

Item		R410A	R32	R1270	R290	R1234yf	R152a
	Safety features [€]	0	0	3	3	0	1
Additional shipping cost [€]		0.1	-0.1	0.2	0.5	1.0	0.9
Additional storage cost [€/y]		0.0	0.0	0.1	0.1	0.2	0.2
Total incremental additional cost [€]		128	111	99	105	240	122
RACS baseline price [€]		1453	1453	1453	1453	1453	1453
Incremental cost (ref. R410A) [€]		0	-17	-28	-23	113	-6
Adjusted RACS price [€]		1453	1437	1425	1431	1566	1448
Relative		100.0%	98.8%	98.0%	98.4%	107.8%	99.6%

Incremental cost is relative to the average cost of an R410A RACS. From Figure 67, it is seen that R32, R1270 and R290 all have lower incremental cost than R410A, whilst R152a has a similar incremental cost. Conversely, R1234yf shows a significant increase, which is primarily dictated by the high refrigerant cost. Although the material masses for R1270 and R290 are greater than R32 and R410A, the lower refrigerant costs help contribute to offsetting. Lifetime "top-up" costs associated with refrigerant leakage are about equal to the first fill cost. Considering the anticipated rise in price of F-gases over the next decade, it is likely that the incremental costs for the alternatives would reduce over time.

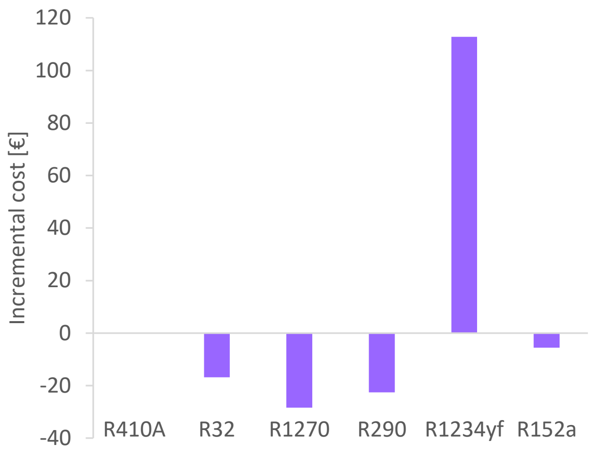


Figure 67: Incremental material cost relative to R410A

These incremental costs may also be considered relative to manufacturing net profit margin for RACS. Whilst such data is not freely available, general information reports that for large domestic appliances, net profit margins are generally around the range of 5 – 10% of the retail price. Thus, for the example case under consideration, this could be in the order of €70 – 150 and thus the adoption of R1234yf would be financially unattractive.

11 Greenhouse gas emissions

Emissions from production of materials and lifetime usage are listed in Table 14, where overall results are given for GWPs using both 20-year and 100-year time horizon. Material mases are as in Table 13.

Emission factors for production of materials are as reported in common literature sources. The literature reports a wide range of values for production of refrigerants, influenced by factors such as production route, age of plant and of course, source of funding for the study. Representative values are taken from Johnson (2011). Material production emissions are again based on the product of emission factors and mass of materials. Lifetime emissions consider only annual leakage and end-of-life releases of refrigerant, according to IPCC guidelines and application reports (i.e., SKM Enviros, 2012). Emissions associated with electrical energy use for the operation of the RACS are not included as they are deemed to be the same for all alternatives since the system is designed for equal seasonal efficiency; there is no reason for differences in electricity consumption amongst RACS using different refrigerants.

Table 14: Summary of emissions

	Item	R410A	R32	R1270	R290	R1234yf	R152a
Material mass	Refrigerant mass [kg]	1.4	1.3	0.6	0.6	1.5	1.2
	Mass of steel [kg]	18.0	18.0	18.0	18.0	18.0	18.0
	Mass of aluminium [kg]	5.5	4.8	5.8	6.5	8.6	7.7
	Mass of copper [kg]	6.2	5.7	6.3	6.8	8.2	7.7
Production emission factors	Refrigerant [kgCO2/kg]	15	10	1.5	1.5	40	5
	Steel [kgCO2/kg]	2.2	2.2	2.2	2.2	2.2	2.2
	Aluminium sheet [kgCO2/kg]	7.1	7.1	7.1	7.1	7.1	7.1
	Copper tube [kgCO2/kg]	3.4	3.4	3.4	3.4	3.4	3.4
Material production emissions	Ref't production emissions [kgCO2]	20.6	12.7	0.9	0.9	59.1	6.2
	Steel emissions [kgCO2]	39.6	39.6	39.6	39.6	39.6	39.6
	Aluminium emissions [kgCO2]	39.1	34.1	40.9	45.9	60.9	55.0
	Copper emissions [kgCO2]	20.8	19.2	21.4	22.9	27.7	25.8
	Total production emissions [kgCO2]	120.2	105.5	102.7	109.3	187.3	126.5
	Incremental product emissions [kgCO2]	0.0	-14.7	-17.5	-10.9	67.1	6.3

	Item	R410A	R32	R1270	R290	R1234yf	R152a
Lifetime emissions	Annual leakage [%/y]	5%	5%	5%	5%	5%	5%
	EOL emissions [%]	80%	80%	80%	80%	80%	80%
	Lifetime [y]	12	12	12	12	12	12
	Lifetime emissions (100 y) [kgCO2]	4046	1240	0	0	2	221
	Total emissions (100 y) [kgCO2]	4166	1346	103	109	189	348
	Lifetime emissions (20 y) [kgCO2]	8477	4607	1	1	8	941
	Total emissions (20 y) [kgCO2]	8597	4712	103	110	196	1068

A summary of the results is shown in Figure 68 and Figure 69 using 100-year and 20-year ITH. For R410A and R32 the refrigerant-related emissions dominate and even for R152a, they are more than double the production-related emissions. Any differences associated with greater or less mass of construction materials amongst the various alternative refrigerants are comparatively minor.

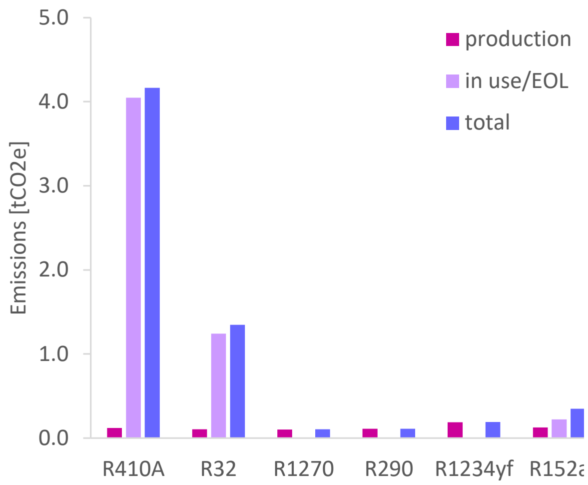


Figure 68: Production, lifetime and total emissions, using 100-year ITH GWPs

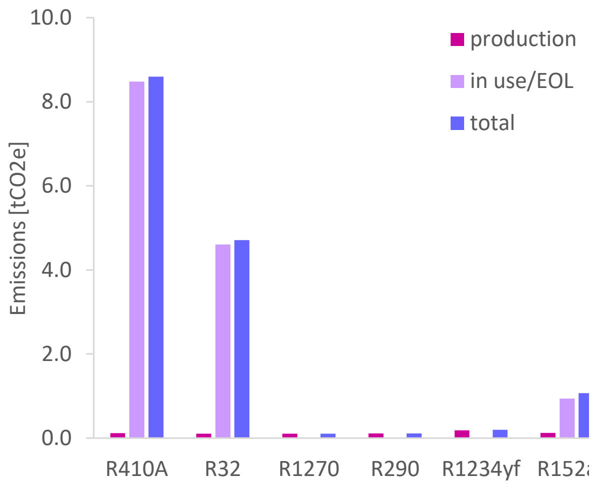


Figure 69: Production, lifetime and total emissions, using 20-year ITH GWPs

Cost-effectiveness are given in Table 15, where results are shown relative to R410A.

Table 15: Cost-effectiveness

	Item	R410A	R32	R1270	R290	R1234yf	R152a
	Emissions reduction (÷ R410A) [tCO2e]	0.00	2.82	4.06	4.06	3.98	3.82

100-year ITH	Additional costs (÷ R410A) [€]	0.0	-16.8	-28.4	-22.6	112.8	-5.6
	Cost-effectiveness (÷ R410A) [€/tCO2]	–	-6.0	-7.0	-5.6	28.4	-1.5
20-year ITH	Emissions reduction (÷ R410A) [tCO2e]	0.00	3.88	8.49	8.49	8.40	7.53
	Additional costs (÷ R410A) [€]	0.0	-16.8	-28.4	-22.6	112.8	-5.6
	Cost-effectiveness (÷ R410A) [€/tCO2]	–	-4.3	-3.3	-2.7	13.4	-0.7

A summary of the results is presented in Figure 70 and Figure 71, which shows from switching:

- From R32 to R410A increases emissions and incurs higher cost so the cost-effectiveness is negative.
- From R410A to R32, R1270 and R290 reduces both cost and emissions, producing a "positive" negative cost-effectiveness.
- From R410A to R1234yf and R152a demands higher cost but yields significant emissions reduction, so cost effectiveness is favourable.
- From R32 to R1270, R290, R1234yf and R152a all lead to both a rise in costs but significantly lower emissions, however, for R152a and particularly R1234yf, the relatively high cost means the cost-effectiveness is less favourable.

By comparison, the price within the European Carbon Trading Scheme is around €30 – 90 per kgCO_2e, indicating that switching to both R1270 or R290 and possibly R152a are viable within this context.

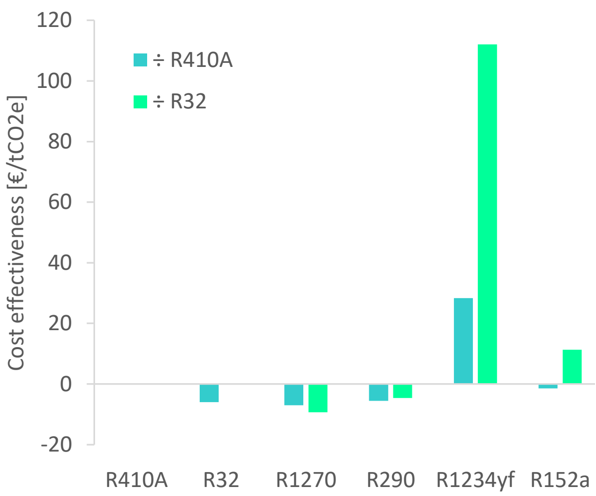


Figure 70: Cost-effectiveness based on 100-year ITH

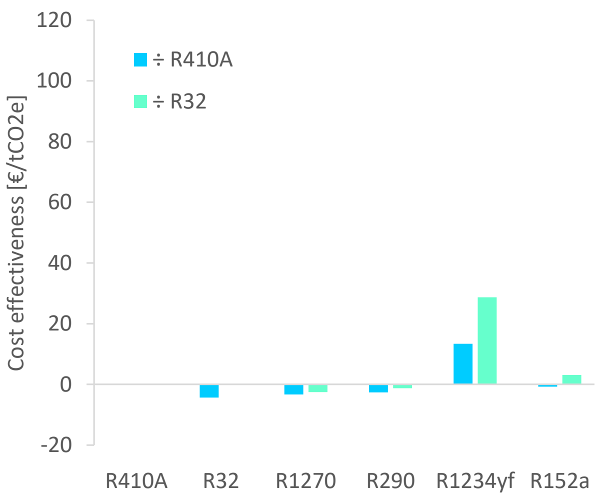


Figure 71: Cost-effectiveness based on 20-year ITH

12 Further considerations

Some additional aspects are considered with respect to the application of alternatives, primarily, noise levels, refrigeration system advances for RACS and development schedules.

12.1 Noise levels

Noise levels emanating from both IDUs and ODUs are reported in the Eurovent data and the Ecodesign regulation requires maximum levels are not exceeded. Noise from the IDU is primarily influences by the fan and airflow and refrigerant flow within the HX, whereas fan and airflow are also relevant to ODU noise, in addition to the compressor.

Figure 72 plots noise levels from units using R410A and R32. Overall, there is no differentiation between the two refrigerant types; R32 units have both the lowest and highest noise levels; this is likely due to the larger number of R32 models within the dataset (about 80% of the total).

It is unlikely that the use of GWP < 150 refrigerants would result in higher noise levels. In fact, smaller pressure differences (condensing – evaporating pressure) tend to support lower compressor and refrigerant flow-related noise, so any change in noise levels would likely be favourable.

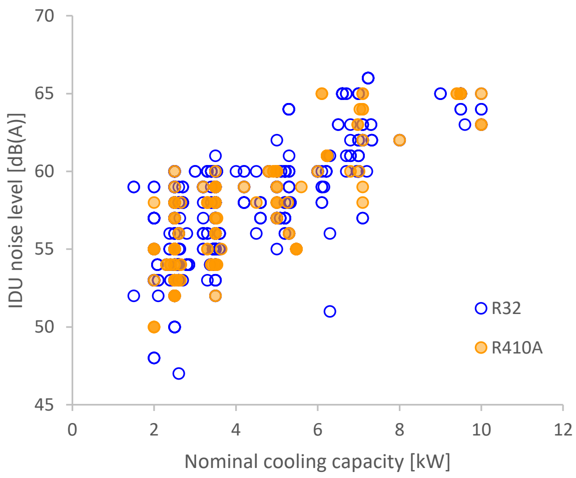


Figure 72: Comparison of IDU noise levels between those using R410A and R32

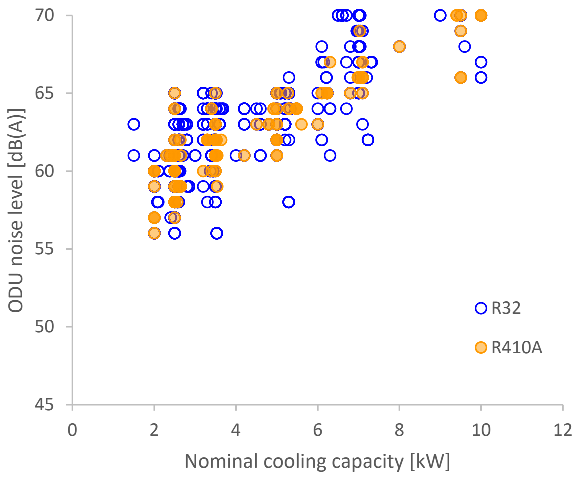


Figure 73: Comparison of ODU noise levels between those using R410A and R32

12.2 Advances in efficiency improvement and charge reduction

It can be expected that over the next decade, manufacturers will aim to achieve a very high seasonal efficiency, say, SEER = 14. Such high SEERs would have to be accompanied with reduced HC charge. Review of the recent literature identifies various studies with consistent objectives, where approaches for reducing charge and simultaneously increasing thermal capacity and/or efficiency are reported. For example:

- Andersson et al. (2022) – present a 3.5 kW split RACS that uses only 143 g of R290.
- Berman et al. (2020) – 15% higher efficiency with SLHX without additional charge.
- Bo and Shen (2020) – 17% higher efficiency with the same charge and nominal capacity through HX and compressor optimisation.
- Chen et al. (2018) – 30% increase in heating capacity and 20% higher efficiency with R290 using vapour injection.
- Fujino et al. (2014) – reports on a novel MCHX evaporator design that resolves the condensate water problem.
- Huang et al. (2018) – computationally and experimentally analysed MCHX evaporator designs for use in reversible RACS.
- Nasution et al. (2019) – 30% improvements in efficiency using a SLHX in an AC with R290.
- Panda et al. (2019) – examine novel MCHX evaporator headers to resolve maldistribution problem for reversible systems.
- Radermacher et al. (2017) – investigated novel HX designs, which showed the leading options could improve performance by more than 15%, lessen material mass by 20% and reduce overall system refrigerant charge by 30 – 40%.
- Ren et al. (2014) – reduce charge by >5% and increase capacity and efficiency by 5% by addition of a special liquid-suction heat exchanger (SLHX).
- Ribeiro and Barbosa (2019) – 10% of R290 charge reduction in ACs by using a novel HX design.
- Satoshi et al. (2012) – special microchannel HX design used effectively in reversible systems (evaporator and condenser), which reduces material mass by a third and quarters the refrigerant quantity, compared to a finned-tube HX.
- Tancabel et al. (2020) – 30% in R290 charge through an alternative HX design.
- Wang et al. (2019) – air conditioner with R290 using various techniques leading to improvement of up to 45% in efficiency.
- Zhou and Gan (2019) – reduce R290 charge by xx% through use of a novel HX design.

In addition, there are various initiatives ongoing to address such topics on a broader scale. For example, the LC150 project is working towards developing HPs for domestic use with very small R290 charge amounts, considering a variety of different technologies.[6]

Ongoing developments associated with charge reduction and efficiency improvements will surely enable greater flexibility in the future.

12.3 Development schedules

An important consideration in this whole discussion are development schedules. Revised designs of RACS for alternative refrigerant can be realised relatively quickly (a year or two) but compressor design and optimisation and refinement iterations can take longer, as well as scaling-up extended production. It is likely to require more than two or three years for most producers to achieve steady output of a range of models.

[6] https://www.ise.fraunhofer.de/en/press-media/press-releases/2020/consortium-develops-compact-refrigeration-circuit-for-heat-pumps-using-propane.html

13 Concluding remarks

Estimated charge amounts of hypothetical R290 RACS, also accounting for over-sizing where exact sized models are not available, are compared with charge limits of IEC 60335-2-40: 2022. The comparison is shown in Figure 74 and again in Figure 75, but assuming RACS require an additional 20 m interconnecting piping. Since most data-points are encompassed by the charge limit lines, this indicates – from the perspective of the safety standard – application is broadly feasible. With the additional interconnecting piping, there is some overshoot for RACS above 9 kW. However, this can be addressed through selection of R1270 instead of R290, or more likely, further developments on charge minimisation.

Of course, with Class A2L and A2 refrigerants, R1234yf and R152a, application within the constraints of the standard is straight-forwards.

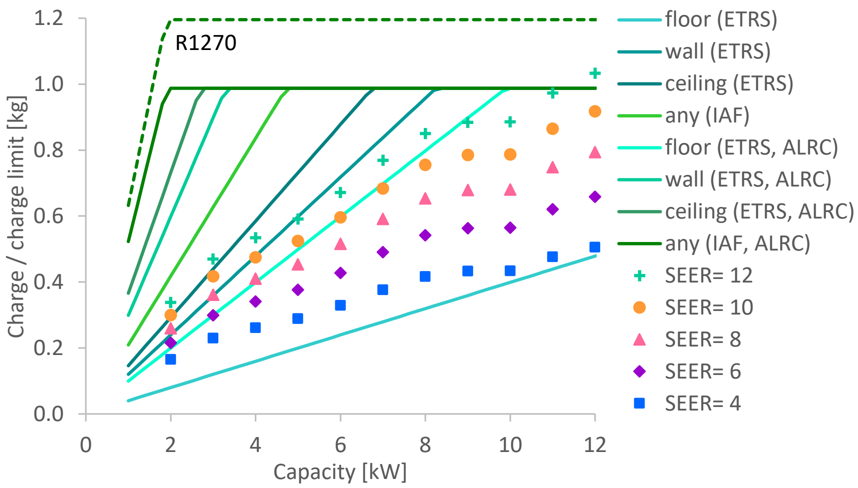


Figure 74: R290 hypothetical system charge amounts (markers) compared to charge limits from IEC 60335-2-40 for cooling applications. R1270 limits as dashed lines. Charge amounts adjusted upwards to account for over-sizing.

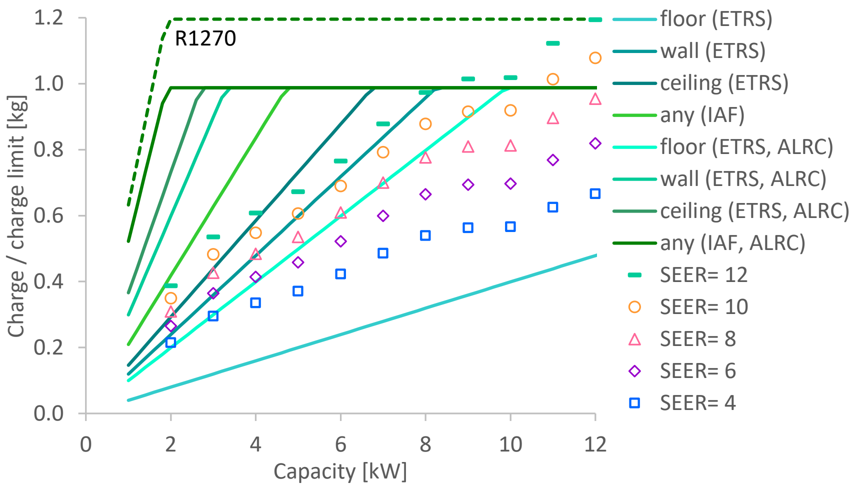


Figure 75: R290 hypothetical system charge amounts with +20 m interconnecting piping (markers) compared to charge limits from IEC 60335-2-40 for cooling applications. R1270 limits as dashed lines. Charge amounts adjusted upwards to account for over-sizing.

Considering the cost implications of adopting R1270 or R290, they are also viable:

- A switch from R410A to R290 is likely to be cost-neutral.
- A switch from R32 to R290 would likely incur a small incremental material cost (<€10).
- A switch from R410A to R1270 is likely to result in a cost benefit.
- A switch from R32 to R1270 would likely incur a negligible incremental material cost (<€5).

In all cases, the variation would be less than 1% of the RACS retail price. These also neglect the lifetime costs associated with re-charging or toping-up of systems, which if accounted for, would yield further cost advantages for R290 and R1270 RACS.

Overall, considering the greenhouse gas emissions associated with various alternatives, all of those with GWP < 150 offer significant benefits, relative to R410A and R32. R1270 and R290 are most attractive due to the smaller material mass, lower manufacturing emissions and smaller charge amount.

Near-future develops are likely to amplify the cost and emissions benefits associated with R1270 and R290 RACS.

The database, simulations and other sources from which the information was gathered is extensive, and the treatment and analysis was thorough and approached with different methodologies. Furthermore, where there is uncertainty associated with any inputs, pessimistic assumptions were used. Thus, the results and conclusions are considered to have a high level of confidence.

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Annex A Discussion of cost implications associated with safety measures[7]

The means to achieve the various mitigation measures can be highly varied across different types of systems, applications, etc. below is a brief description of some general principles for mitigation measures in RACHP.

Mitigation measures are generally offered by RACHP sector safety standards, although corresponding measures are equally sought from standards and guidelines of other industry sectors which also handle such substances. The means to achieve the various mitigation measures can be highly varied across different types of systems, applications, etc. Thus, there are too many variations to address in detail here.

Refrigerant quantity limits

For flammable refrigerants, the possibility of a leak being ignited by an uncontrolled potential source of ignition within the wider area needs to be minimised. This is achieved by limiting the quantity of refrigerant that can leak out such that potentially flammable mixture will not form beyond the RACHP equipment itself. For higher toxicity refrigerants, the possibility of a leak forming a toxic concentration in spaces where occupants may be present must be minimised and is done so by limiting the quantity of refrigerant that can leak out such that potentially toxic mixture will not form beyond the RACHP equipment itself. Thus, refrigerant quantities may be limited according to an "allowable charge limit" (ACL), that is based on the size of the space that the system is located within, installation characteristics of the system and auxiliary equipment and the flammability and/or toxicity characteristics of the refrigerant. Further, there may be an "upper charge limit" (UCL) which is a capped quantity that overrules the ACL.

Materials: Essentially, implementation of the quantity limit does not necessarily demand additional hardware. However, where a manufacturer or installer wishes to use a certain refrigerant in a situation with restrictive quantity limits further design tasks may be required such as charge minimisation (see below), limited releasable charge techniques (see below) and/or multiple refrigerant circuits.

Costs: Whilst there are no direct costs associated with refrigerant quantity limits, practically, any costs involved are associated with the R&D activities to minimise charge (see below) or applying limited releasable charge techniques (see below), as and when required. Splitting the system into two or more circuits can result in a significant cost increase, up to 1.5 times the cost of the original system.

[7] Draft material also provided to UNEP TEAP EETF report, May 2022

Refrigerant charge minimisation

In order to comply with refrigerant quantity limits, or indeed to lower the risk associated with a given system, charge minimisation may be exercised. Historically, little consideration was given to the reduction of refrigerant charge and indeed, often oversized refrigerant reservoirs were applied to prolong the duration that a leaky system would operate for without the need of a service or "topping-up" of the refrigerant. Nowadays, systems may be designed with numerous features, such as avoidance of liquid receivers (or if necessary to handle alternate operating modes, reduced to a necessary volume), smaller heat exchanger tubes (as associated total internal volume), smaller diameter interconnecting tubing and compressors with reduced internal volumes and lubricant charge. It should be noted, though, that within the constraints of current technologies, there is likely a limit of how far charge reduction can go, whilst maintaining a certain efficiency level of a system.

Materials: Generally, charge reduction corresponds to a less system materials, whilst individual component's function essentially remains unchanged. In some cases, construction materials may change, for example, when switching from a finned (aluminium) tube (copper) to micro-channel heat exchanger (all aluminium).

Costs: Charge minimisation typically has a negative cost impact (cost saving) through reduced refrigerant costs, both at manufacture and in-use, but also reduced construction material costs by means of smaller or lighter components. Additional costs are largely associated with R&D resources involved with sourcing and trialling alternate components.

Limited releasable charge

Ordinarily, it is assumed that the leaked amount of refrigerant equals the charged amount. However, there are passive and active ways to reduce the released refrigerant, whereby overall risk can be reduced and refrigerant quantity limits can be more easily satisfied, as described in section 0.

Materials: For PLRC, no additional hardware is required, only to quantify the releasable charge. This may be done by calculation or test or a combination of both. For ALRC, additional components may be needed. For a system with a reciprocating compressor and liquid line solenoid valve, or a rotary compressor with a reversing valve and electronic expansion valve, or similar arrangements, no additional hardware is necessary. Otherwise, additional solenoid valve(s) may have to be fitted.

Costs: For PLRC, the costs are solely associated with the resources necessary to quantify the releasable charge. The same applies to ALRC and possibly an additional solenoid valve(s), the cost of which is dictated by the tube diameter and may range from a few Euros upwards.

Extract ventilation

Deemed not applicable.

Integral airflow

Typically for flammable refrigerants, IAF can be used to mix a leak with the surrounding air to ensure that the concentration remains below the lower flammability limit (LFL). It is not intended to exhaust the mixture from the space, only dilute it, as described in section 0.

Materials: Airflow would usually be achieved with a fan that is part of the system, a condenser and/or evaporator fan, provided the airflow rate and discharge velocity are high enough to disperse a leak. Depending upon the assumed leakage rate, most condenser and/or evaporator fans usually supply sufficient airflow. In the event that this is not the case, either a larger fan/motor assembly or an additional fan may be needed to satisfy the criterion.

Costs: Ordinarily, no further costs are involved, except for the resources to check the effectiveness of the existing airflow. Otherwise, additional costs may be a small incremental cost for a larger fan/motor.

Warning alarms

Deemed not applicable.

Leak detection

A leak detection system is often required as part of the arrangement involving ALRC and IAF, as detailed in section 0. The type of leak detection may employ gas detection, ultrasonic sensors, system operating parameters (pressure, temperature, etc.) or other means such as liquid level sensing, liquid flow fractions, etc. Once the detection system identifies a leak indicator, a signal is sent to initiate the applicable measure.

Materials: A leak detection system involves one or more sensors and a signal processor and controller. There are a wide variety of different sensors and often more than one may be needed.

Costs: Costs can vary extensively. Gas sensors can be catalytic or metal oxide type, ranging from a few dollars upwards, to infra-red or laser gas detection, which can cost in excess of $1000; generally, reliability and precision is reflected in the cost. However, if the use of gas detection proliferates throughout the RACHP sector, there is no reason why more reliable and precise technologies cannot drastically reduce in cost. Ultrasonic sensors are significantly more reliable and are extremely low cost (<€1), although several sensors may be needed, depending upon the equipment they are applied to. Sensor for measuring system parameters include pressure transducers and thermocouples. Whilst the latter have a negligible cost (and may be used anyway) pressure transducer can be in the order of tens of dollars and upwards, again depending upon the refrigerant and component size and similarly for liquid level sensors. Signal processing and control units usually have negligible cost and can nevertheless be integrated into existing electronics of the RACHP equipment.

No ignition sources

It is necessary to minimise the possibility of igniting leaked flammable refrigerant within the RACHP equipment and this is achieved through ensuring against the presence of potential sources of ignition. These may be electrical arcs from switching components, excessively hot surfaces from heaters or naked flames. There are numerous ways and means of achieving avoidance of ignition sources, such as high ventilation rates or repositioning of electrical components so flammable concentrations are avoided at such locations, using sealed enclosed to prevent ingress of flammable concentrations, limiting size of gaps within enclosures so flames cannot propagate outwards to the larger mixture and ensuring electrical current and voltage is below certain values such that sparks have insufficient energy to ignite a flammable mixture. Additional aspects are usually necessary, such as suitably robust housing materials and good quality parts, to guarantee protection against ignition for the lifetime of the equipment.

Materials: Given the wide variety of options for avoiding ignition sources there are a similarly extensive number of material implications. Usually, there will be additional plastic enclosures or dividing plates, depending upon the type and size of equipment and refrigerants involved. Most component manufacturers now offer products (compressors, valves, etc.) that are approved for use with flammable refrigerants, against the applicable safety standards.

Costs: Similarly, additional costs can range from negligible to thousands of dollars (e.g., for large industrial installations), although in most cases, economically effective approaches have been found.

Increased system tightness

By introducing appropriate design and construction measures to the refrigerating system, the likelihood of leakage and the possibility of larger leak holes can be reduced. Various safety standards and guidelines include such measures and are referred to as “enhanced tightness refrigeration systems” (ETRS); see section 0. Requirements may include better system components and fittings, avoidance of constructional circumstances likely to lead to leakage, more rigorous testing and leak checking and quality control programmes.

Materials: System components and fittings that have been tested and approved to the applicable standards.

Costs: Whilst some tested and approved components and fitting will be higher cost than basic ones, as more and more manufacturers adopt the regime, additional costs should become negligible. More rigorous leak testing requires additional equipment and procedures for production lines and quality control programmes demand additional resources of workers. However, provided the output of a production facility is large enough, additional costs become negligible (per unit produced). Furthermore, regardless of whether the refrigerant is conventional or a more hazardous alternative refrigerant, reduced leakage has significant advantages in terms of better system reliability, lower lifetime service costs and consequent reputational benefits.

Based on the requirements of IEC 60335-2-40 clause 22.125, Table 16 summarises the cost implications for RACS. Assuming a reasonable annual production, 100,000 units per year, the incremental cost for complying with ETRS would be no more than €1 per unit.

Table 16: Cost implication associated with elements of ETRS

Requirement	Cost implication
a) compressors, pressure relief devices and pressure vessels of the refrigerating system shall be located in locations other than the occupied space,	None (condensing unit must be outside)
b) refrigerant distribution assemblies shall meet all applicable requirements of this standard,	None (not applicable to single splits)
c) refrigerating systems shall use only permanent joints indoors except for site-made joints directly connecting the indoor unit to the refrigerant piping, or factory-made mechanical joints in compliance with ISO 14903,	None (all indoor joints must be brazed)

Requirement	Cost implication
d) refrigerant containing parts in indoor units shall be protected from damage in the event of catastrophic failure of moving parts, e.g., fans, belts,	None (demonstrated that IDU fan cannot damage HX or piping)
e) refrigerant containing pipes in the occupied space in question are installed in such a way that they are protected against accidental damage	Negligible (low level piping must be sheathed)
f) the refrigerating system of each indoor unit shall be tightness tested at the factory with detection equipment with a capability of 3 grams per year of refrigerant or less under a pressure of at least 0,25 times the maximum allowable pressure. No leak shall be detected,	Negligible (leak test production equipment – usual cost approx. €250,000, but assuming production of 100,000 units over 5 years, cost would be about €0.5 per unit)
g) vibrations exceeding 0,30 G RMS, when measured with a low pass filter at 200 Hz, are not allowed in the refrigerant containing parts in the occupied space under normal operation.	Negligible (type test for each model)
h) indoor heat exchangers shall be protected from damage in the event of freezing, as demonstrated by a test.	Negligible (type test for each model)
i) the maximum speed of the indoor fan, in normal operation, shall be less than 90 % of the maximum allowable fan speed as specified by the manufacturer of the fan wheel. If the manufacturer does not specify a maximum allowable fan speed, then the fan wheel shall be tested.	Negligible (type test for each model)

Instructions/marking

Information about safe practices needs to be relayed to workers (such as technicians) and to users. Additional information may relate to the hazardous characteristics of the refrigerant. This additional information usually involves instructions in manuals and marking or signage on the equipment. Examples include details about safe handling of the refrigerant during servicing of the equipment and “flammable refrigerant” warning triangles.

Materials: Additional pages in a manuals and adhesive stickers.

Costs: Material costs are negligible, the main cost implication being that associated with sourcing and drafting the relevant information.

Annex B Derivation of RACS prices

The internet was trawled for the retail price of RACS from the Eurovent database. Prices for some models could only be found on internet sites of certain countries; all models could not be sourced from any one country. Prices for models found only in countries outside the Euro-zone were converted to Euros using the exchange rate on 23rd – 28th April 2022. Where prices were listed as inclusive of VAT, they were reduced according to that country's VAT rate. Prices listed as exclusive of VAT were used as-is. In some cases, prices were not quoted with reference of VAT and thus were assumed to be exclusive of VAT. Crucially, many internet sites listed products with "RRP" (recommended retail price) but listed them with a discount price, representing between 10 – 50% discount. In some countries, legislation states that such discounts must be genuine (i.e., such a product must be retailed at the RRP for a certain proportion of the year), whilst in others no such rules apply. Given the uncertainty arising from these practices, a price corresponding to the arithmetic mean of the RRP and discounted price were used. About 35 models were sold in Roubles, but these were negated due to the unrepresentative exchange rate at the time.

Annex C Evaporator characteristic data

Evaporator characteristic data are presented in Figure 77 to Figure 106. The evaporator selection is based on the following:

- All selections within ±0.2 kW and ±0.2 K of capacity and ETD of target balance point.
- Eliminate selections with pressure drop greater than 1.5 K
- For R290 and R1270, selection with smallest operating refrigerant charge
- For other refrigerant, selection with lowest component cost
- Interpolate between number of rows as necessary

Selections and associated parameters are listed in Table 9.

A common legend for the data is in Figure 107.

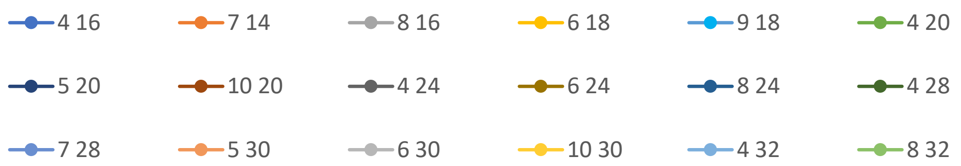
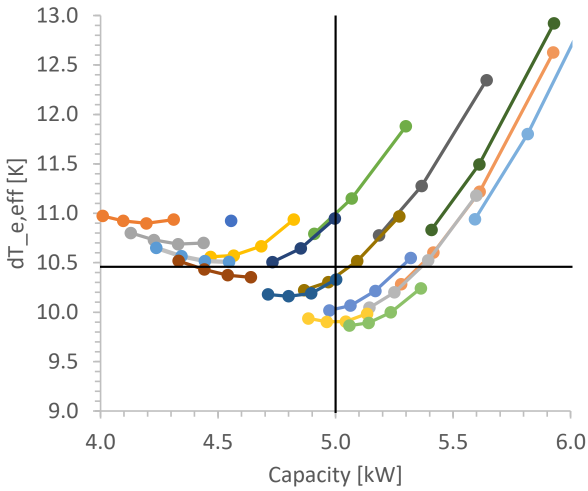


Figure 76: Common legend for evaporator characteristic data graphs; first value is the number of circuits, second value is the number of rows

Balance point



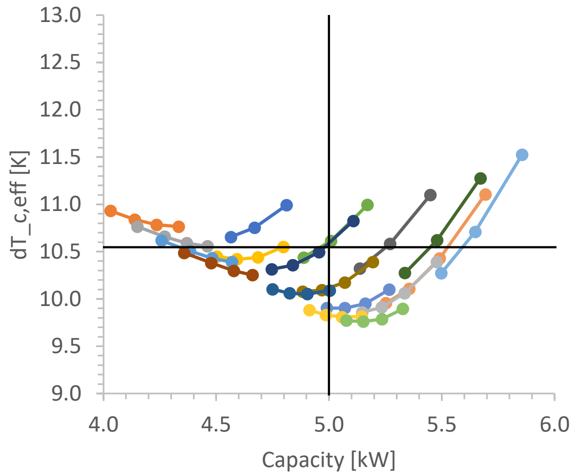


Figure 77: Selection balance point for R410A evaporator

Figure 78: Selection balance point for R32 evaporator

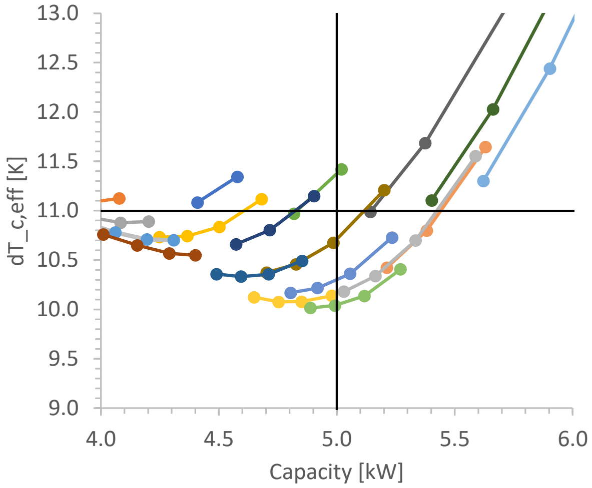


Figure 79: Selection balance point for R1270 evaporator

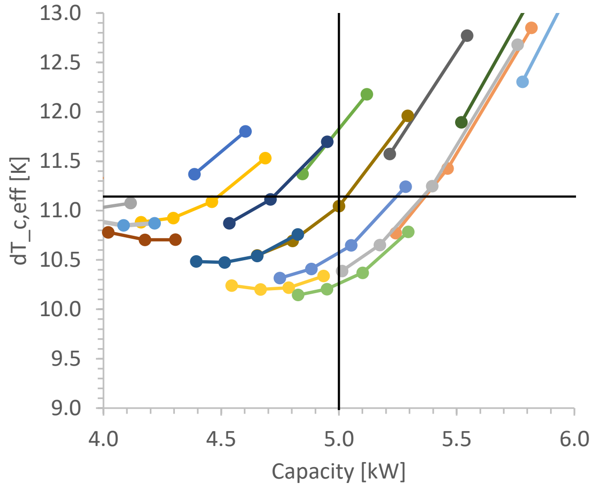


Figure 80: Selection balance point for R290 evaporator

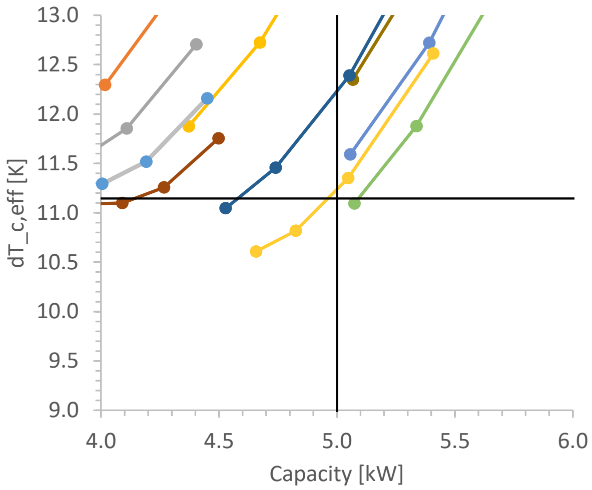


Figure 81: Selection balance point for R1234yf evaporator

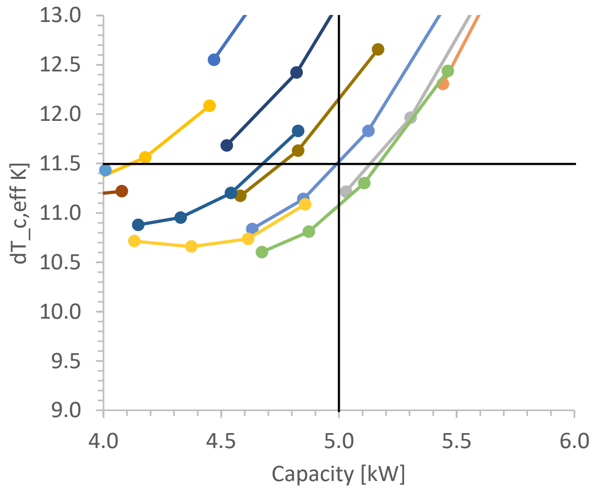


Figure 82: Selection balance point for R152a evaporator

Pressure drop

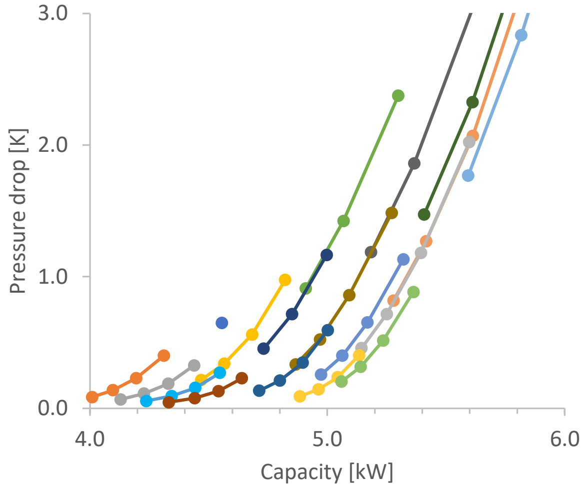


Figure 83: Pressure drop for R410A

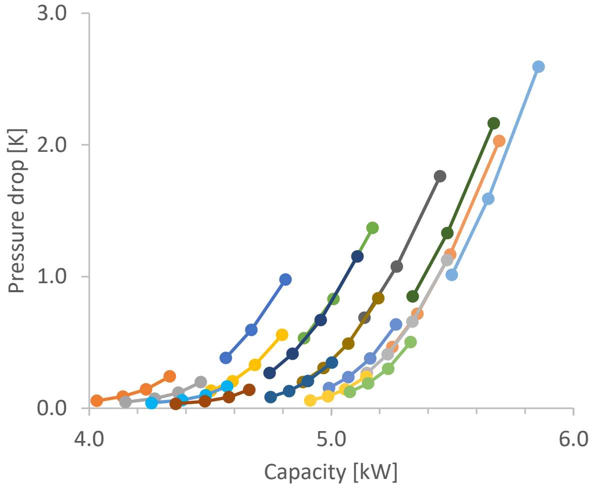


Figure 84: Pressure drop for R32

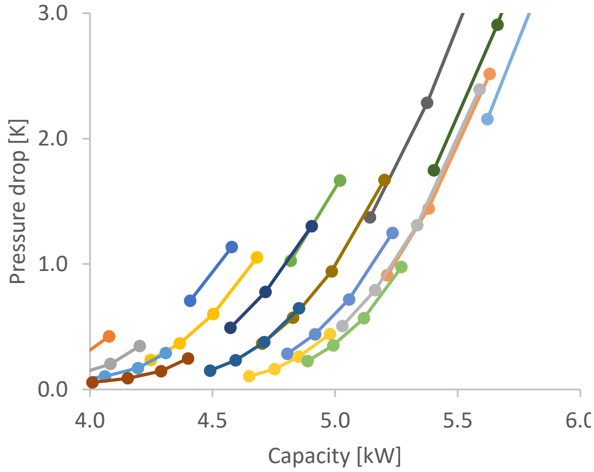


Figure 85: Pressure drop for R1270

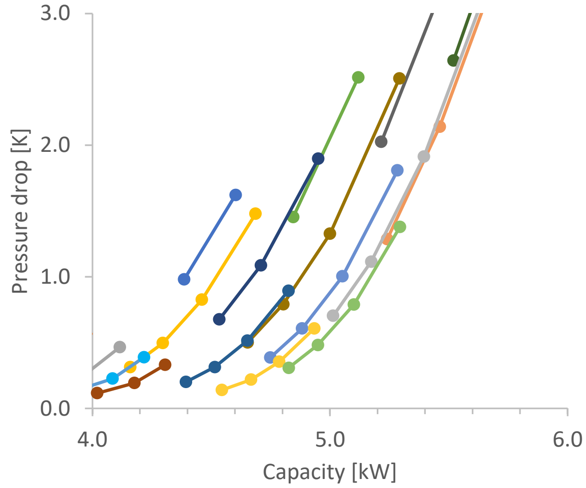


Figure 86: Pressure drop for R290

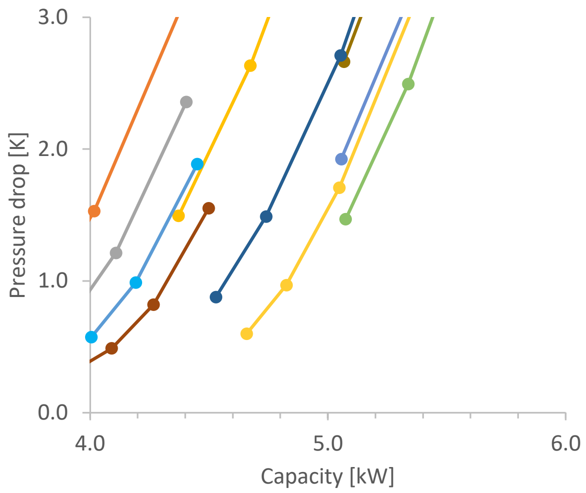


Figure 87: Pressure drop for R1234yf

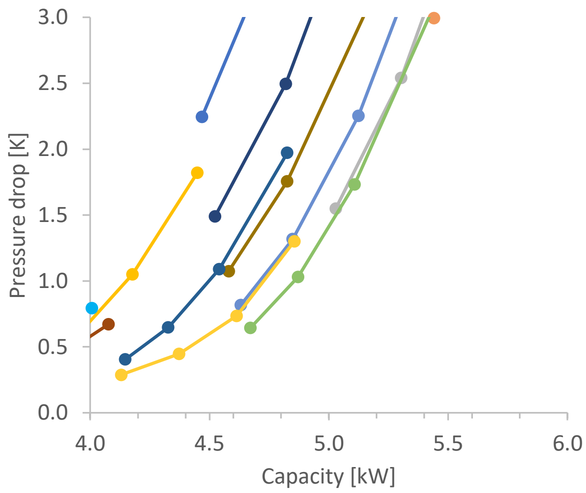


Figure 88: Pressure drop for R152a

Coil volume

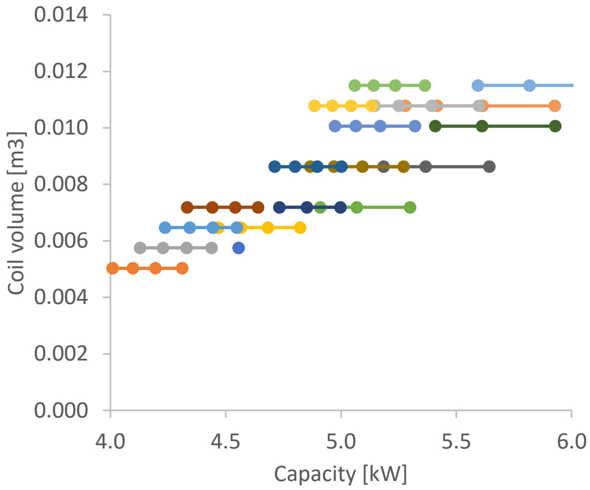


Figure 89: Coil volume for R410A

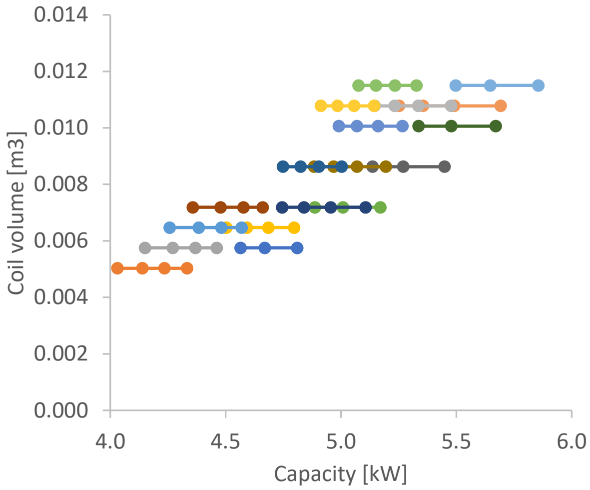


Figure 90: Coil volume for R32

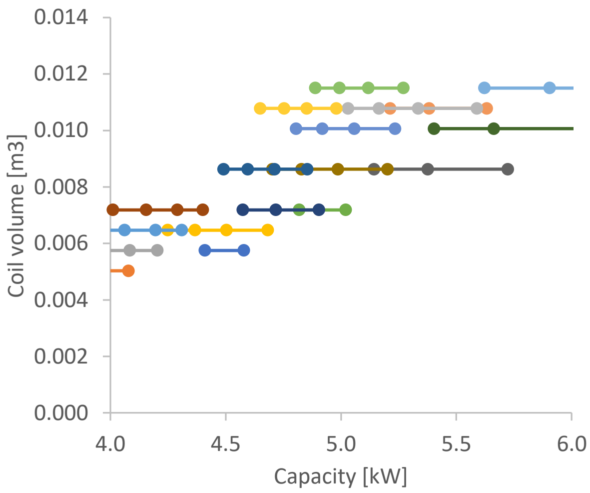


Figure 91: Coil volume for R1270

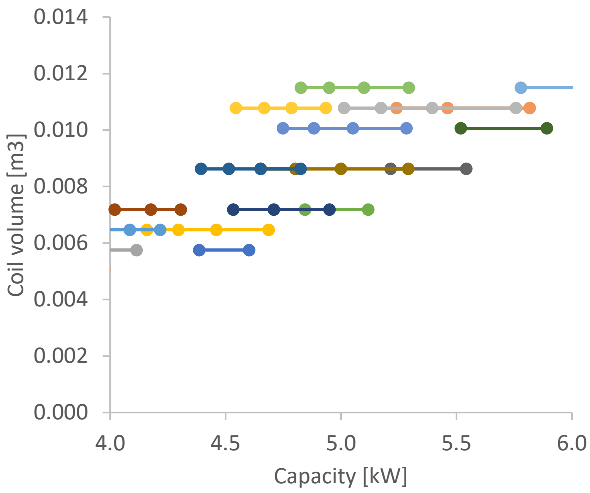


Figure 92: Coil volume for R290

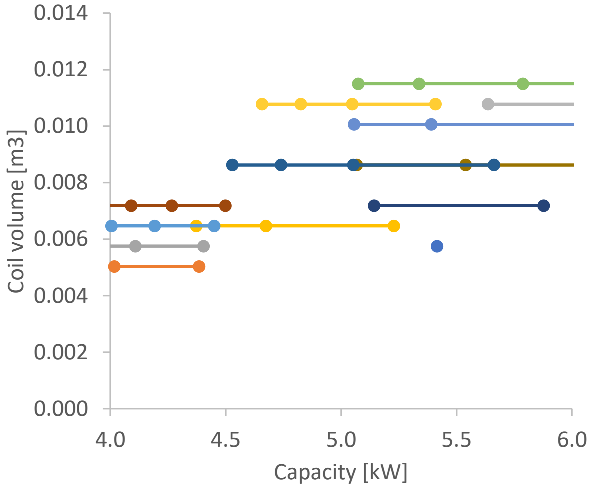


Figure 93: Coil volume for R1234yf

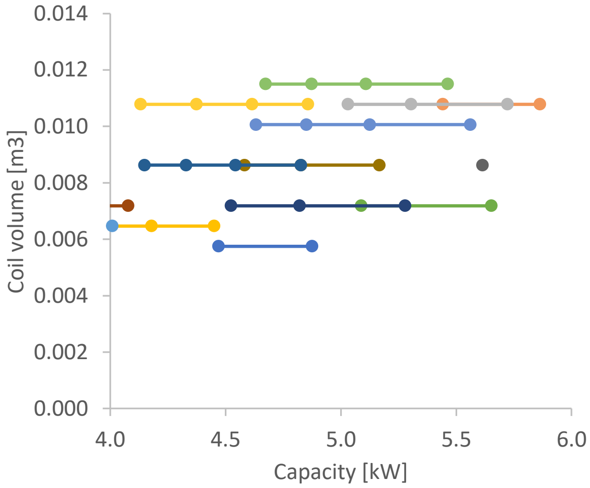


Figure 94: Coil volume for R152a

Refrigerant mass in operation

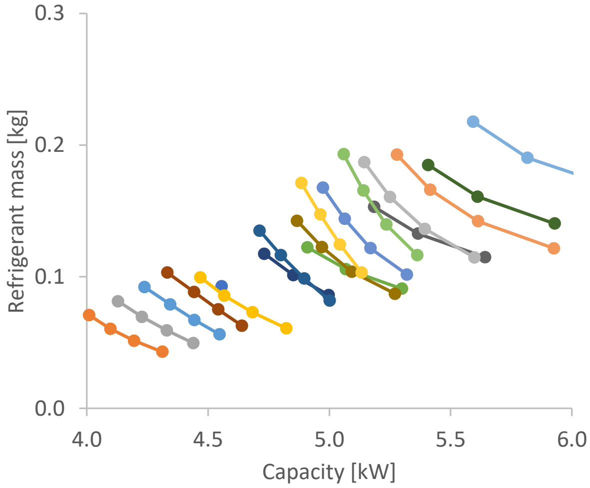


Figure 95: Mass of R410A in operating evaporator

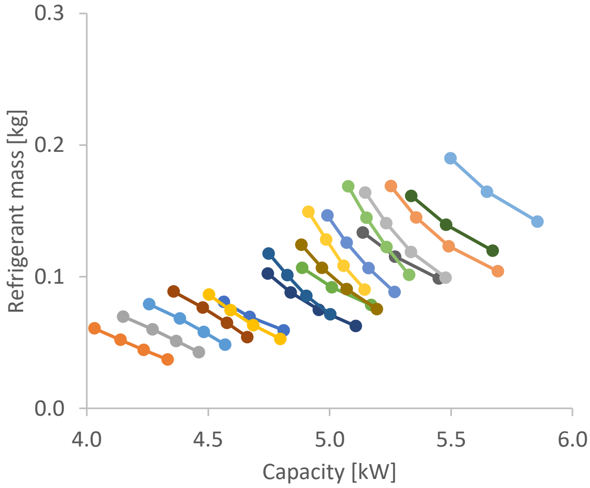


Figure 96: Mass of R32 in operating evaporator

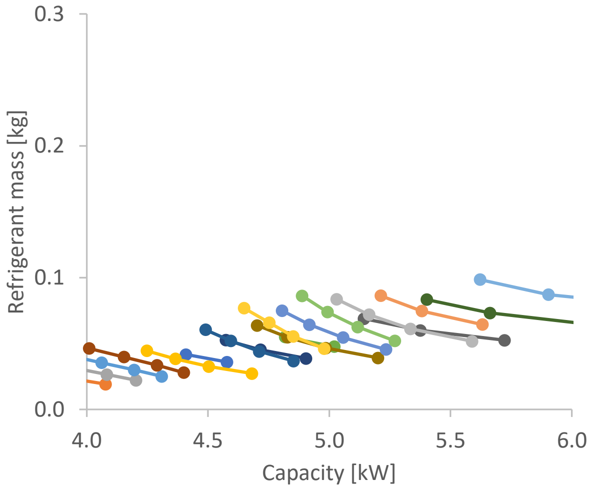


Figure 97: Mass of R1270 in operating evaporator

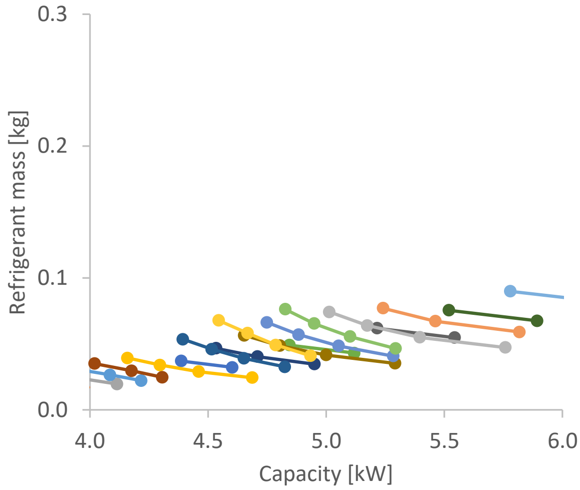


Figure 98: Mass of R290 in operating evaporator

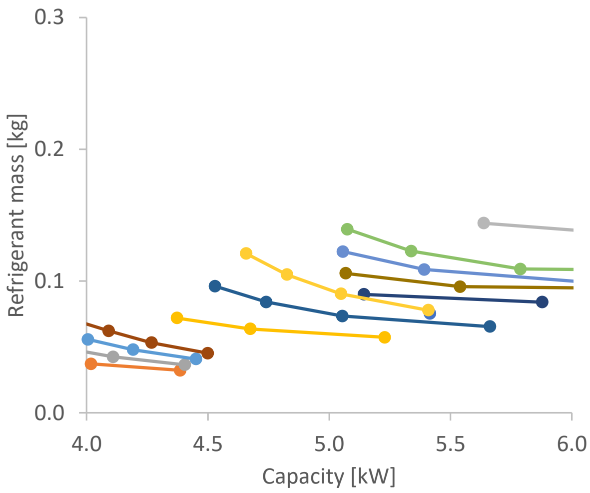


Figure 99: Mass of R1234yf in operating evaporator

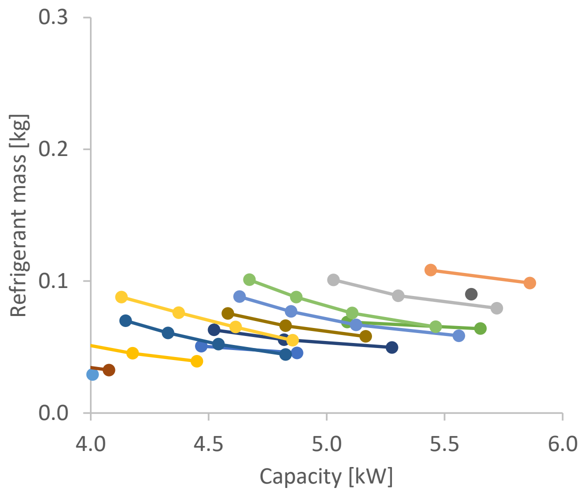


Figure 100: Mass of R152a in operating evaporator

Component material cost

Including copper tubes, aluminium fins and refrigerant during operation.

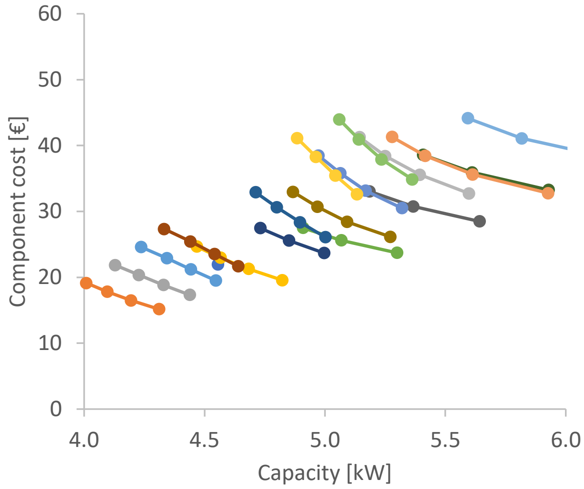


Figure 101: Sum of material costs for R410A

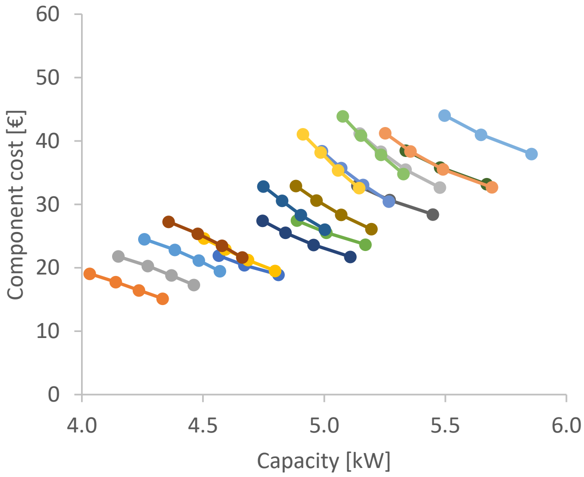


Figure 102: Sum of material costs for R32

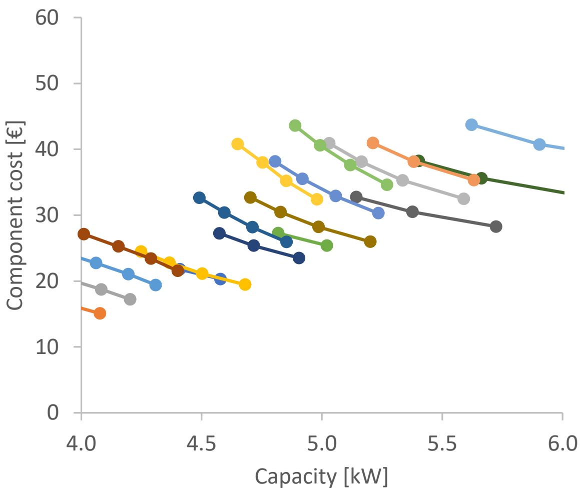


Figure 103: Sum of material costs for R1270

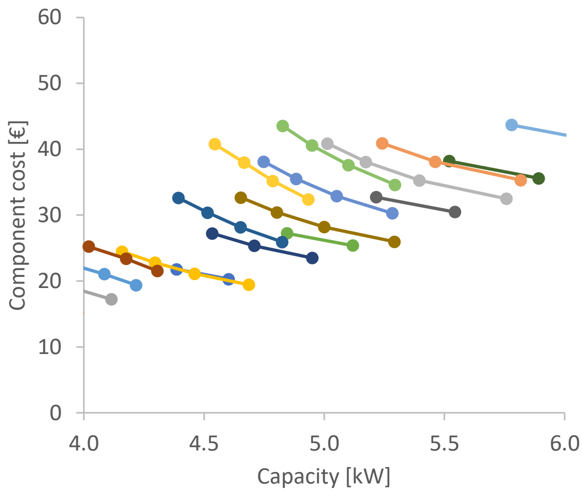


Figure 104: Sum of material costs for R290

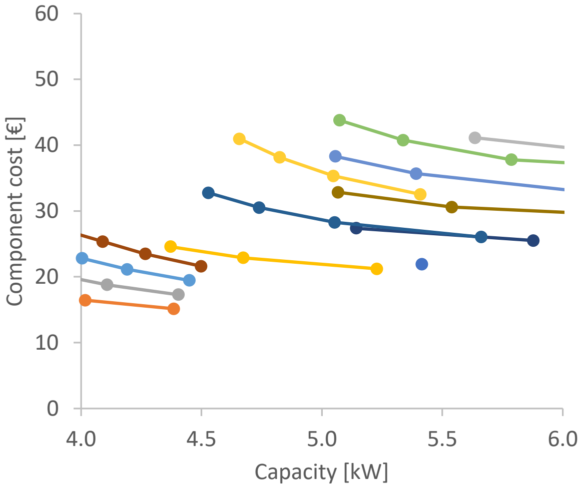


Figure 105: Sum of material costs for R1234yf

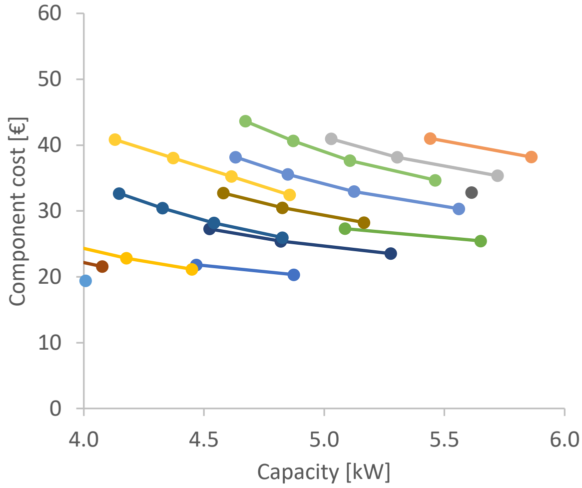


Figure 106: Sum of material costs for R152a

Annex D Condenser characteristic data

Condenser characteristic data are presented in Figure 108 to Figure 137. The condenser selection is based on the following:

- All selections within ±0.2 kW and ±0.2 K of capacity and ETD of target balance point.
- Eliminate selections with pressure drop greater than 1.5 K
- For R290 and R1270, selection with smallest operating refrigerant charge
- For other refrigerant, selection with lowest component cost
- Interpolate between number of rows as necessary

Selections and associated parameters are listed in Table 11.

A common legend for the data is in Figure 107.

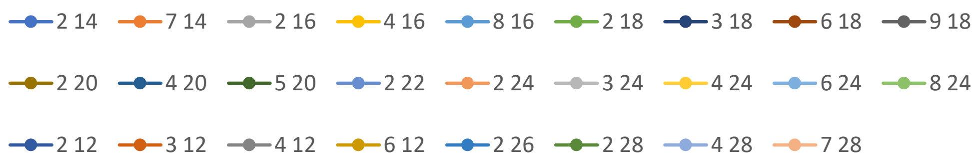
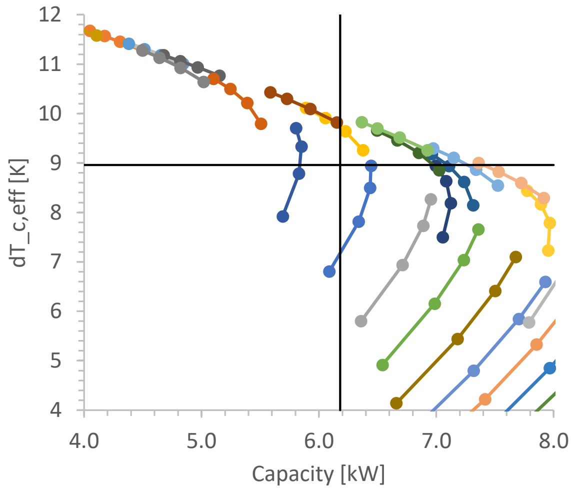


Figure 107: Common legend for condenser characteristic data graphs; first value is the number of circuits, second value is the number of rows

Balance point



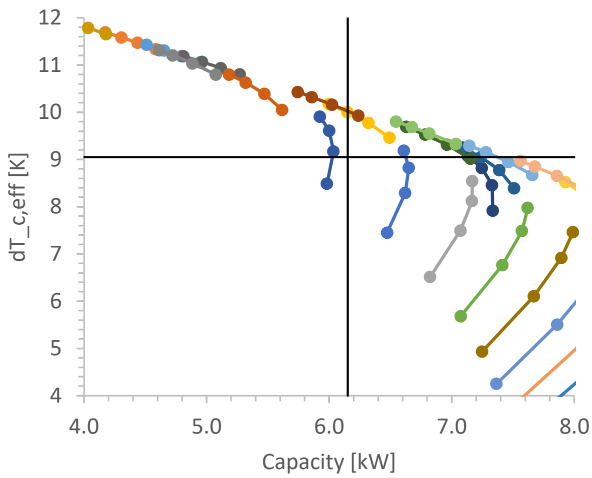
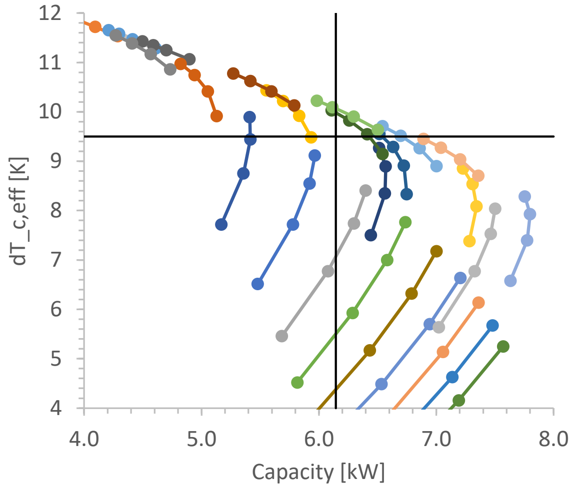


Figure 108: Selection balance point for R410A condenser

Figure 109: Selection balance point for R32 condenser



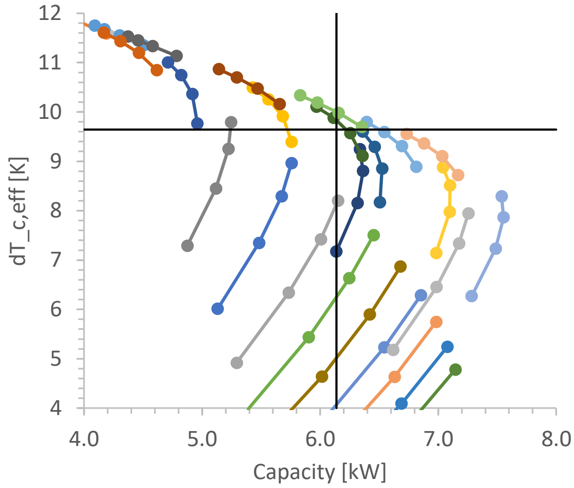
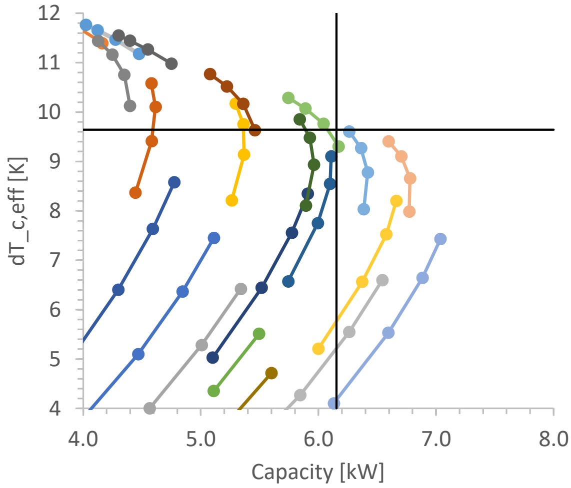


Figure 110: Selection balance point for R1270 condenser

Figure 111: Selection balance point for R290 condenser



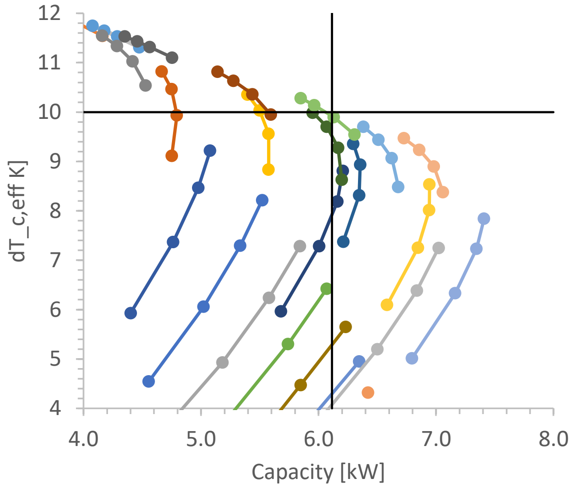


Figure 112: Selection balance point for R1234yf condenser

Figure 113: Selection balance point for R152a condenser

Pressure drop

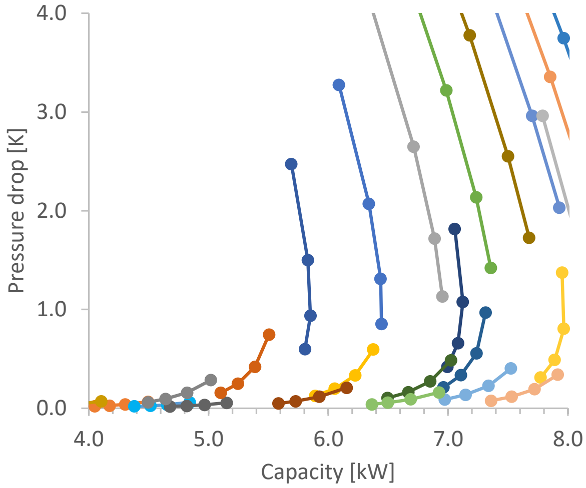


Figure 114: Pressure drop for R410A

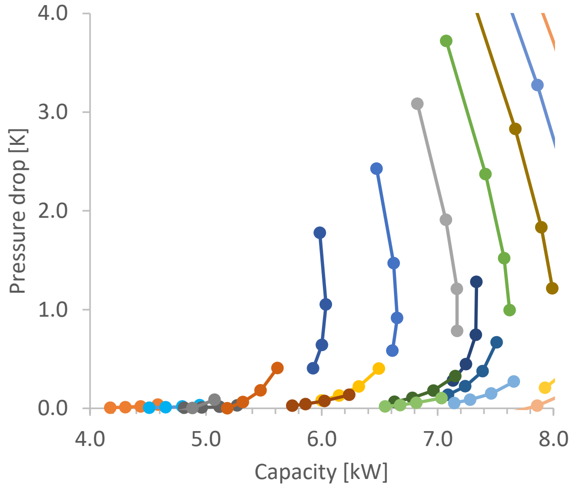


Figure 115: Pressure drop for R32

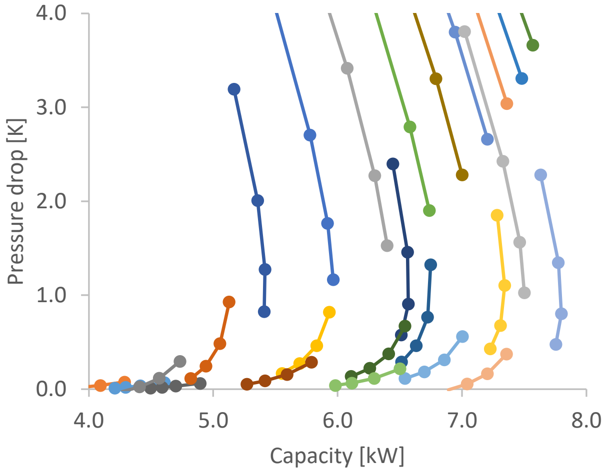


Figure 116: Pressure drop for R1270

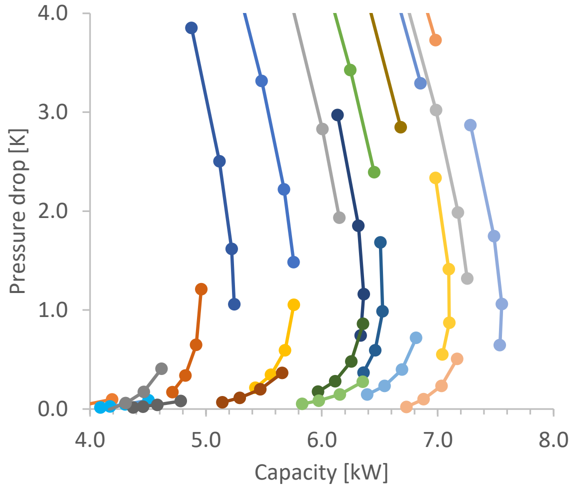


Figure 117: Pressure drop for R290

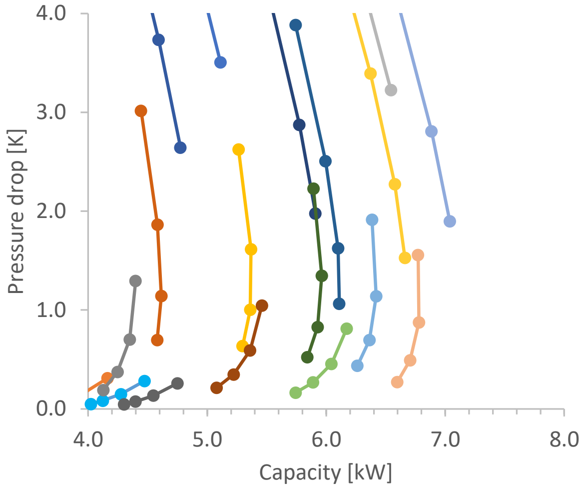


Figure 118: Pressure drop for R1234yf

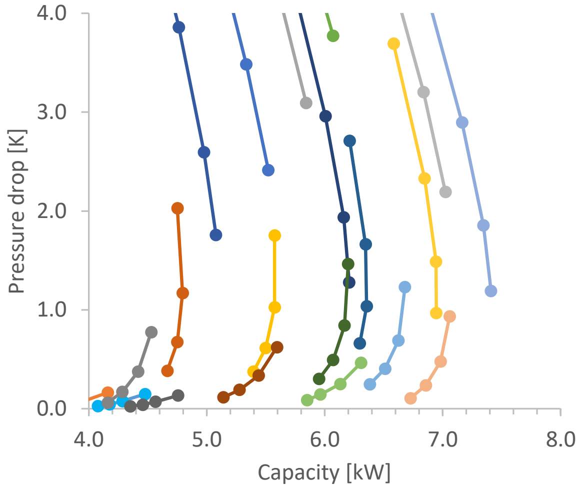


Figure 119: Pressure drop for R152a

Coil volume

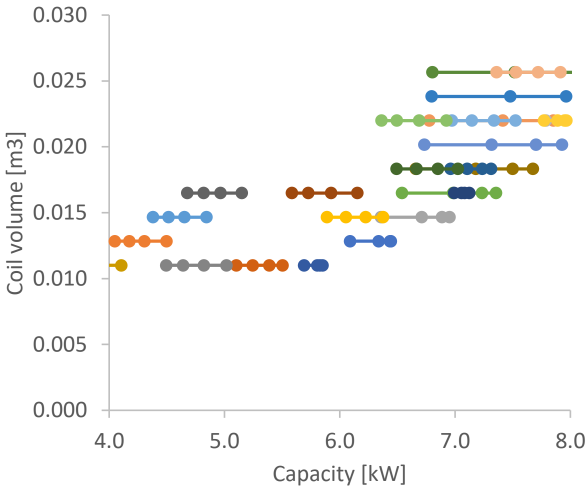


Figure 120: Coil volume for R410A

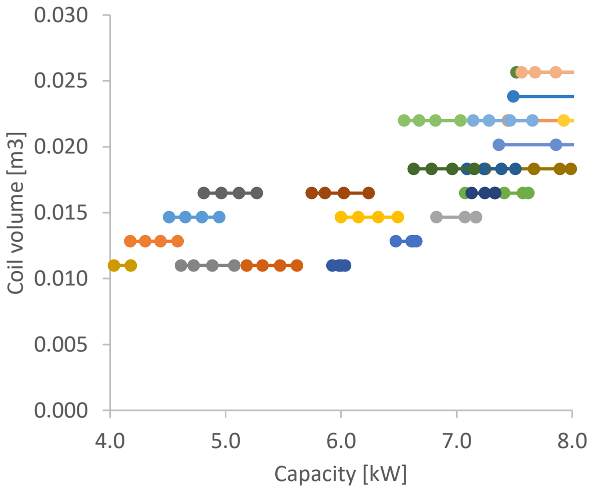


Figure 121: Coil volume for R32

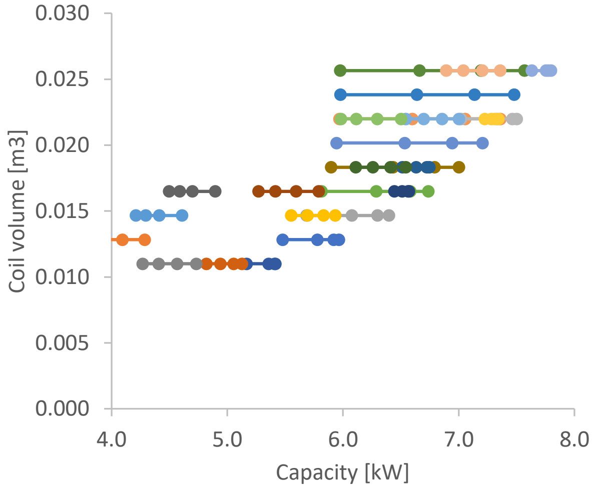


Figure 122: Coil volume for R1270

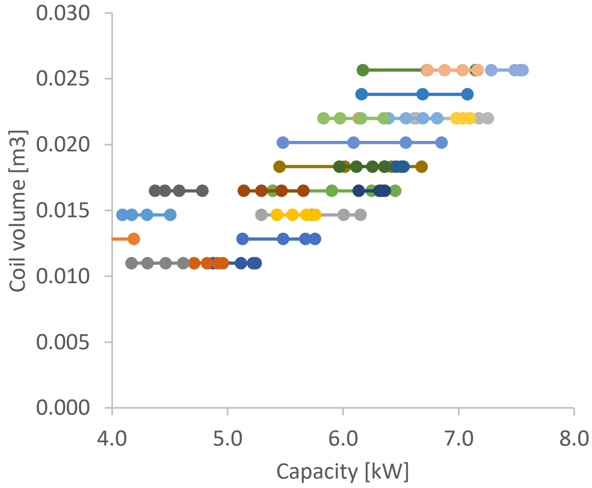


Figure 123: Coil volume for R290

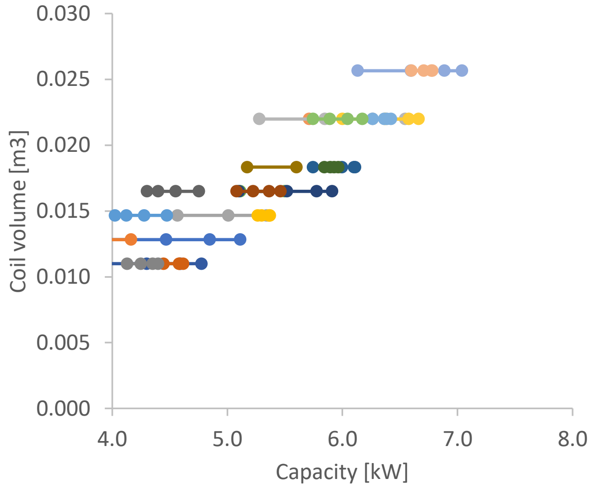


Figure 124: Coil volume for R1234yf

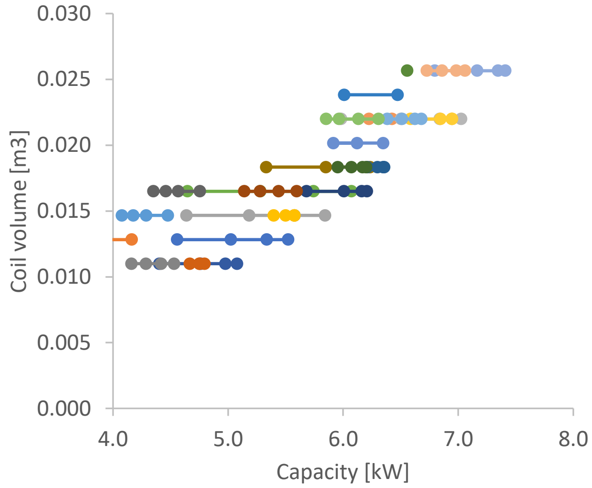


Figure 125: Coil volume for R152a

Refrigerant mass in operation

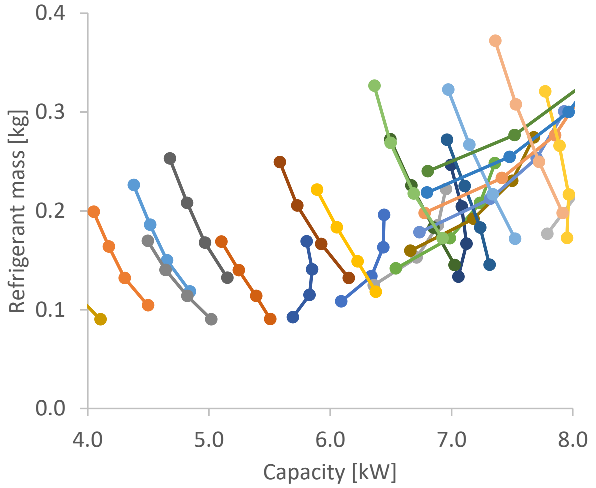


Figure 126: Mass of R410A in operating condenser

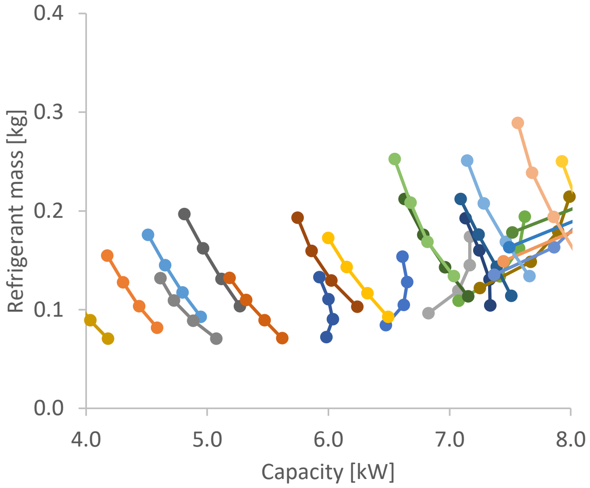


Figure 127: Mass of R32 in operating condenser

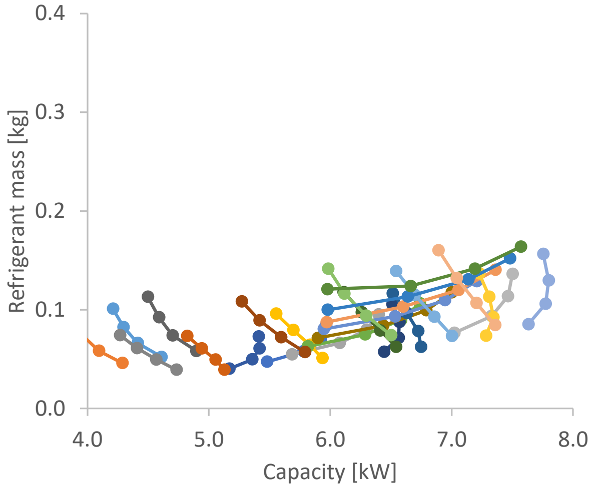


Figure 128: Mass of R1270 in operating condenser

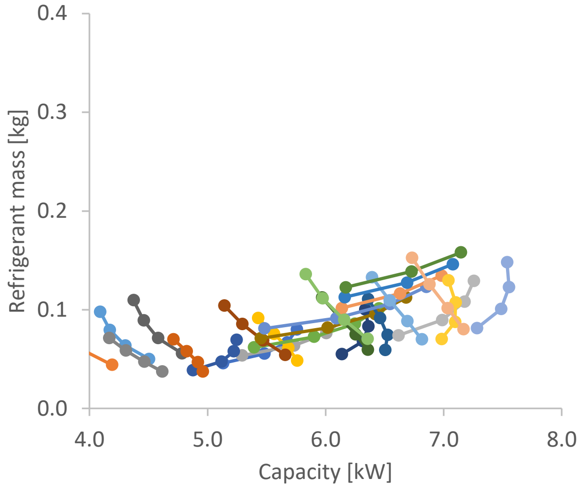


Figure 129: Mass of R290 in operating condenser

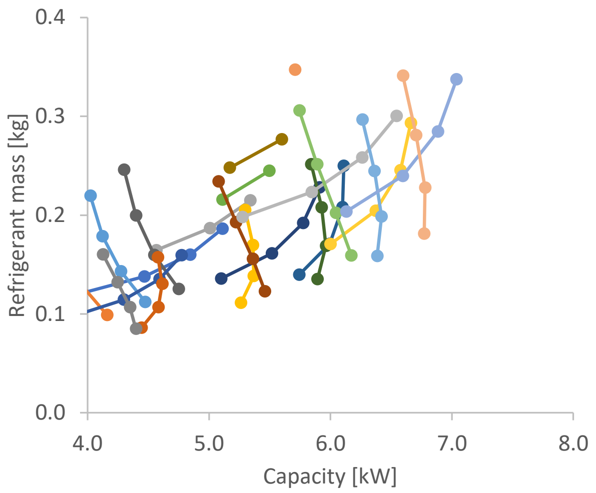


Figure 130: Mass of R1234yf in operating condenser

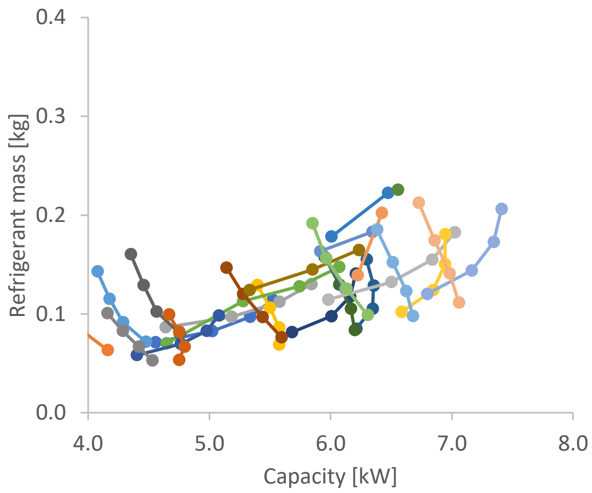


Figure 131: Mass of R152a in operating condenser

Component material cost

Including copper tubes, aluminium fins and refrigerant during operation.

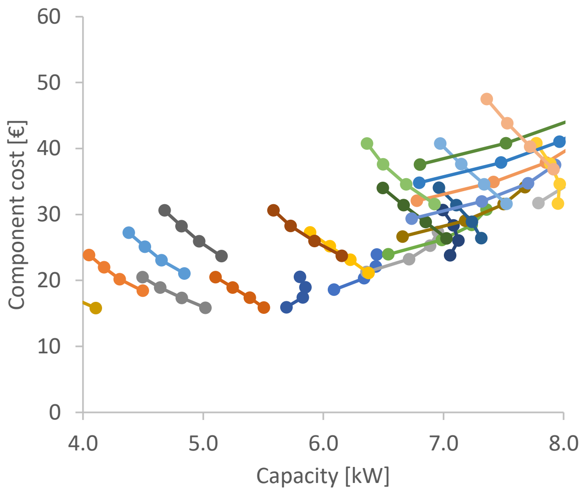


Figure 132: Sum of material costs for R410A

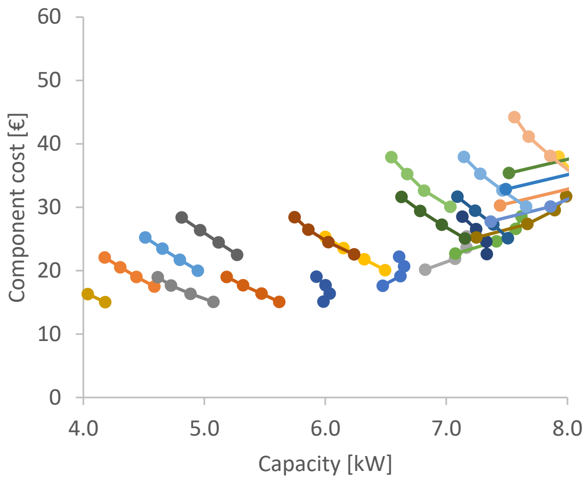


Figure 133: Sum of material costs for R32

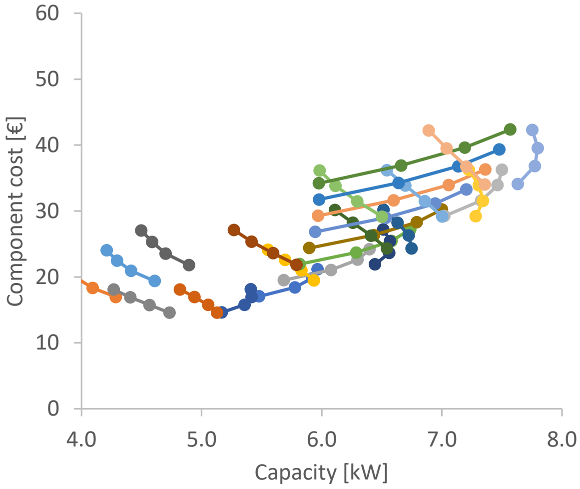


Figure 134: Sum of material costs for R1270

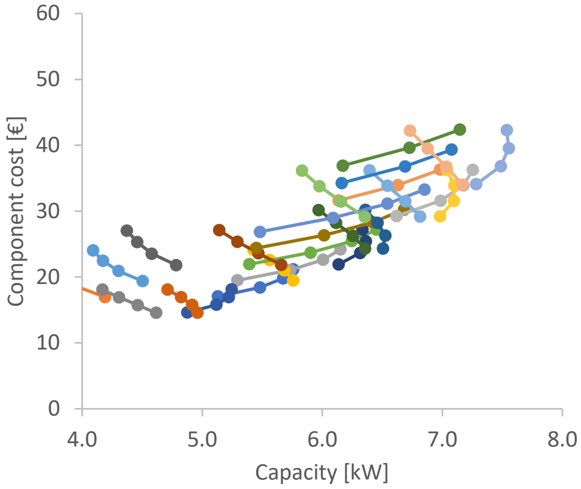


Figure 135: Sum of material costs for R290

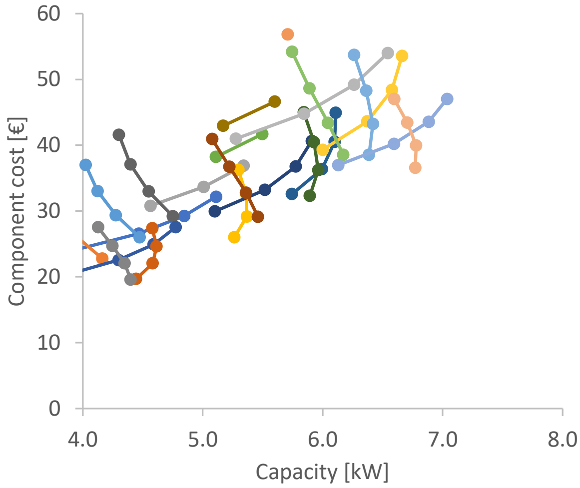


Figure 136: Sum of material costs for R1234yf

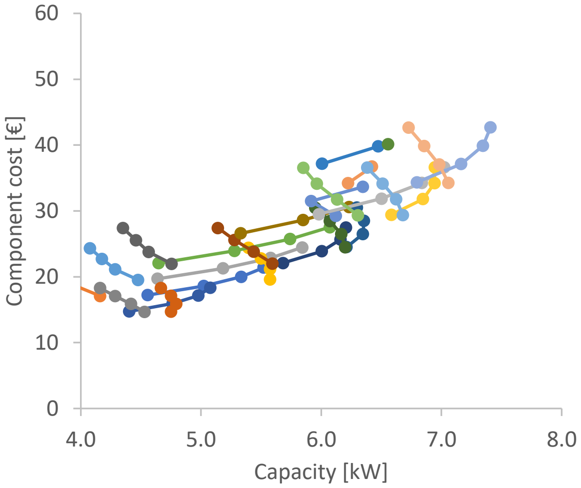


Figure 137: Sum of material costs for R152a

Annex E Data for R290 models

Table 17 includes the basic data for the various R290 models used within the main sections.

Add Thermotar data

Table 17: Basic data for R290 models

Manufacturer	Model	Pdesc kW	SEER	Pdesh kW	SCOP	Lw_idu dB(A)	Lw_odu dB(A)	Charge	V_idu	V_odu	M_idu	M_odu
ElectriQ	eIQ-12WMINV-V3	3.5	6.1	3.6	4.2			0.40	0.044	0.095	10.0	30.0
ElectriQ	eiQ-9WMINV-V3	2.6	6.2	2.6	4.2			0.32	0.039	0.095	8.5	30.0
Godrej	GIC 12TGC5-WUA*	3.5	9.1			42	60	0.31	0.052	0.136	10.0	26.0
Godrej	GIC 18PGC5-W*	5.2	9.4			42	64	0.37	0.068	0.158	11.0	29.0
Godrej	GIC 18TGC3-WUA*	5.1	7.5			42	64	0.37	0.091	0.163	11.5	28.5
Godrej	GIC 24MGP5-WRA*	6.3	9.5			48	54	0.38	0.086	0.201	16.5	30.0
Midea	MSAEBU-09HRFN7-QRD0GW	2.6	6.8	2.4	4.0	54	58	0.32	0.047	0.128	8.0	30.0
Midea	MSAEBU-12HRFN7-QRD0GW	3.5	6.5	2.5	4.0	54	60	0.40	0.047	0.128	8.2	30.0
Midea	MSAECU-18HRFN7-QRD0GW	5.0	6.8	4.3	4.0	57	60	0.49	0.070	0.148	10.8	37.0
Midea	MSAEDU-24HRFN8-QRD0GW	7.3	7.0	5.3	4.0	59	65	0.53	0.088	0.215	14.3	46.0
Chunlan	CS-09/AZ3BPdWb-2	2.6	7.8	2.8		38	50	0.28	0.043	0.106	9.3	30.0
Chunlan	CS-12/AZ3BPdWb-2	3.5	7.3	3.9		39	51	0.36	0.043	0.106	9.3	30.0
Chunlan	CS-09R/AZ3Wb-0	2.6	7.8	2.8		38	50	0.28	0.043	0.106	9.3	30.0
Chunlan	CS-12R/AZ3Wb-0	3.5	7.3	3.9		39	51	0.36	0.043	0.106	9.3	30.0

* Cooling-only models

Imprint

Published by:
Deutsche Gesellschaft für
Internationale Zusammenarbeit (GIZ) GmbH

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Eschborn, 2022