Annex to Module 3
Technical Options

NAMAs in the refrigeration, air conditioning and foam sectors. A technical handbook.

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Registered offices
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Programme Proklima

Dag-Hammarskjöld-Weg 1-5
65760 Eschborn, Germany
Phone: +49 61 96 79 - 1022
Fax: +49 61 96 79 - 80 1022

Email: proklima@giz.de
Internet: www.giz.de/proklima

Responsible
Bernhard Siegele, Proklima Programme Manager, bernhard.siegele@giz.de

Authors
Dr. Daniel Colbourne, Dr. Maria Martin, Igor Croiset, Dietram Oppelt (HEAT GmbH, Glashütten)

Editors
Claudia Becker (HEAT GmbH, Glashütten)

Review
Marion Geiss, Sebastian Wienges, Markus Wypior (GIZ), Barbara Gschrey (Öko-Recherche GmbH)

Production
Sophie Charlotte Diesing, Franziska Frölich (GIZ Proklima)

On behalf of
The German Federal Ministry for the Environment, Nature Conservation, Building and Nuclear Safety

Division K II 4, International Climate Finance, International Climate Initiative

Köthener Straße 2-3
10963 Berlin, Germany
Phone: +49 (0)30 18 305 - 0
Fax: +49 (0)30 18 305 - 4375

Email: kii4@bmub.bund.de
Internt: www.bmub.de

Photos
Titel: Marius Graf - Fotolia.com

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Jeanette Geppert, Frankfurt

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1. Detailed description of technical options in the RAC sectors

1.1 Containment methods

1.1.1 Leak reduction (design/construction)

Basic description: Introducing improvements to system design, manufacturing and assembly methods to minimise the amount of refrigerant leakage. This may involve using different types of jointing methods, types of components, carrying out certain type testing, introducing more thorough tests within the production line and associated equipment, improved training for workers and so on.

Primary functions: To reduce the emissions of *GWP* × *mass of refrigerant* and to reduce energy requirements.

Technical maturity/availability: Generally, a variety of standards are currently available to direct enterprises, expertise is available disparately and most test equipment is available. However, the practices are currently rarely applied.

Applicability: Most effective for factory produced and sealed refrigerating systems. Systems that are entirely assembled on site benefit least from these methods.

Cost/infrastructure implications: For manufacturers who do not already apply these practices, there is a considerable cost for purchase of equipment and reorganisation of production facilities, development of new quality refrigerating systems, etc. For enterprises that assemble systems of site, the additional first cost is less, since expenditure is limited to additional installation time and tooling.

Efficiency: Reduction in refrigerant loss improves system efficiency, especially for critically-charged refrigerating systems. Such a system losing 5% refrigerant per year can increase energy use by around 10%.

1.1.2 Leak reduction (maintenance)

Basic description: Implementing routine maintenance of refrigerating systems, which involve leak checking and immediate repair. This may also include the application of fixed gas detection systems to warn of refrigerant leakage.

Primary functions: To reduce the emissions of GWP × mass of refrigerant and to reduce energy requirements.

Technical maturity/availability: All relevant procedures, equipment and instrumentation are widely available.

Applicability: This can be applied to all refrigerating systems.

Cost implications: For direct maintenance activities, the main cost implications relate to costs for transportation and technician time. Thus, larger refrigerating systems and those with higher leakage tend to be more suitable. Gas detection systems are generally fairly high cost and are therefore also more suitable for larger refrigerating systems.

Efficiency: Reduction in refrigerant loss improves system efficiency, especially for critically-charged systems. Larger systems tend to use receivers so leakage will not affect efficiency.

1.1.3 Charge size reduction

Basic description: Refrigerating systems are designed and constructed in a manner that minimises the quantity of refrigerant used within the system. Approaches may include the use of reduced volume heat exchangers, use of low solubility lubricants and so on. Alternatively, it may involve the transition from a direct to an indirect type system.

Primary functions: To reduce the potential of emissions of GWP × mass of refrigerant.

Technical maturity/availability: There are a variety of technologies currently available for achieving significant reductions in charge sizes, although research and development in terms of fine-tuning and improving components and techniques is continually underway.

Applicability: These techniques can be applied to almost any type of refrigerating systems that does not already employ them.

Cost implications: Cost implications can vary depending upon the type of refrigerating system, charge reduction approach and the refrigerant involved. For example, advanced heat exchangers may have a higher cost. Although the refrigerant is high cost, the reduction in charge can offset the cost of the technology.

Efficiency: Generally, efficiency levels can be maintained or exceeded. However, refrigerating systems become more sensitive to leakage so a loss of a given amount of charge would result in higher energy consumption.

1.1.4 Recovery and recycling

Basic description: This involves the use of recovery machines when removing the refrigerant from refrigerating systems during repair/servicing activities or prior to disposal of a system. The use of recovery equipment must be coupled with training of technicians and adoption of an infrastructure that enables recycling, reuse and/or destruction of the recovered refrigerant.

Primary functions: To reduce the emissions of GWP × mass of refrigerant.

Technical maturity/availability: Generally, all equipment necessary for refrigerant recovery and recycling is widely available. However, suitable destruction facilities are absent in many regions.

Applicability: This can be applied to refrigerants from any type of refrigerating system.

Cost implications: Capital expenditure is necessary for purchase of recovery machines, cylinders and storage facilities as well as recycling machines. Costs are also required to provide technician training. In addition, if destruction facilities are not available, considerable investment is required to set up such facilities or to arrange for shipment of refrigerant to a region which does have them.

Efficiency: There is no impact on system efficiency.

1.2 Refrigerant options

1.2.1 Substitution of HCFC or HFC refrigerants with R-600a

Basic description: HCFC or HFC refrigerants within a refrigerating system are substituted with R-600a, for use in new systems. Due to differences in thermodynamic and transport properties, the substitution is normally accompanied with changes in compressor and sometimes heat exchanger design, as well as modifications to electrical components in order to meet safety requirements.

Primary functions: To avoid the use and emissions of refrigerants with higher GWP.

Technical maturity/availability: R-600a is used in domestic refrigeration appliances and small commercial appliances, worldwide. Due to the large-scale application, it is widely available.

Applicability: Preferentially applied to refrigerating systems with a smaller refrigerating capacity and where existing safety standards and legislation on the use of flammable substances permit.

Cost implications: Possible additional costs due to changes due to modifications to electrical components in order to meet safety requirements.

Efficiency: Minor improvements in refrigerating system efficiency can be achieved if the refrigerating system is redesigned appropriately.

1.2.2 Substitution of HCFC or HFC refrigerants with HC-290 / HC-1270

Basic description: HCFC or HFC refrigerants within a refrigerating system are substituted with HC-290 or HC-1270, for use in new refrigerating systems. Due to differences in thermodynamic and transport properties, the substitution may be accompanied with changes in compressor and heat exchanger design, as well as modifications to electrical components in order to meet safety requirements.

Primary functions: To avoid the use and emissions of refrigerants with higher GWP.

Technical maturity/availability: HC-290 and HC-1270 are used in commercial refrigeration and air conditioning systems worldwide. Due to the large-scale application, HC-290 is widely available, although HC-1270 is less widely available.

Applicability: Preferentially applied to refrigerating systems with a medium and larger refrigerating capacity and where existing safety standards and legislation on the use of flammable substances permit.

Cost implications: Possible additional costs due to changes due to modifications to electrical components in order to meet safety requirements.

Efficiency: Potentially moderate improvements in refrigerating system efficiency can be achieved if the system is redesigned appropriately.

1.2.3 Substitution of HCFC or HFC refrigerants with R-717

Basic description: HCFC or HFC refrigerants within a refrigerating system are substituted with R-717, for use in new systems. Due to differences in thermodynamic and transport properties and chemical compatibility issues, the substitution is normally accompanied with changes in compressor, heat exchanger, pipework and ancillary components.

Primary functions: To avoid the use and emissions of refrigerants with higher GWP.

Technical maturity/availability: R-717 is used in industrial refrigerating systems worldwide. Due to the large-scale application, it is widely available.

Applicability: Preferentially applied to refrigerating systems with a larger refrigerating capacity in non-domestic, non-commercial situations, where existing safety standards and legislation permit.

Cost implications: Additional costs are due to changes in construction materials, safety systems and alternative electrical components in order to meet safety requirements.

Efficiency: Generally notable improvements in system efficiency can be achieved if the system is redesigned appropriately.

1.2.4 Substitution of HCFC or HFC refrigerants with R-744

Basic description: HCFC or HFC refrigerants within a system are substituted with R-744, for use in new refrigerating systems. Due to differences in thermodynamic and transport properties, the substitution is normally accompanied with differences in the basic refrigeration cycle and subsequent changes in compressor, heat exchanger, pipework and ancillary components.

Primary functions: To avoid the use and emissions of refrigerants with higher GWP.

Technical maturity/availability: R-744 is used in commercial and industrial refrigerating appliances and systems worldwide. Due to the large-scale application, it is widely available.

Applicability: Preferentially applied to refrigerating systems in non-tropical climates due to degradation in system efficiency (or increase in system cost) with ambient temperatures above +35° C.

Cost implications: Typically higher costs due to changes due to modifications to refrigerating system components in order to meet pressure safety and minimum efficiency (at high ambient temperature) requirements.

Efficiency: Improvements in system efficiency at lower ambient temperatures and poorer efficiency at higher ambient temperatures.

1.2.5 Unsaturated-HFCs (HFC-12324yf, HFC-1234ze, HFC-1243zf)

Basic description: HCFC or HFC refrigerants within a given system are substituted with unsaturated-HFCs. Due to differences in thermodynamic and transport properties, the substitution may be accompanied with changes in compressor and sometimes heat exchanger design, as well as modifications to electrical components in order to meet safety requirements.

Primary functions: To avoid the use and emissions of refrigerants with higher GWP.

Technical maturity/availability: Unsaturated-HFCs are recently developed substances and are set to be used in automotive air conditioning systems, worldwide. Currently they are not commercially available but are expected to be produced on a commercial scale.

Applicability: Preferentially applied to systems with a small to medium refrigerating capacity and larger self-contained packaged systems (e.g. chillers) and where safety standards and legislation on the use of flammable substances permit.

Cost implications: Possible additional costs due to changes resulting from modifications to system components and electrical components in order to meet safety requirements, whilst the cost of the substances is expected to be greater than that of existing refrigerants by a factor of about ten.

Efficiency: System efficiency is theoretically not greater than with current refrigerants if the system is redesigned appropriately.

1.2.6 HFC / unsaturated-HFC blends

Basic description: HCFC or HFC refrigerants within a given system are substituted with HFC/unsaturated-HFC blends. It is likely that these blends will be formulated to closely match existing refrigerants' thermodynamic properties, so substitution may be on a "drop-in" basis.

Primary functions: To avoid the use and emissions of refrigerants with higher GWP.

Technical maturity/availability: HFC/unsaturated-HFC blends are largely not finalised yet and are thus not commercially available. However, it is likely that their characteristics will not differ significantly from existing refrigerants so they should be easily applicable. Eventually they are likely to be widely available.

Applicability: Anticipated to be applied to any system from small to large refrigerating capacity.

Cost implications: Possible additional costs due to changes resulting from modifications to system components, whilst the cost of the substances is expected to be greater than existing refrigerants by a factor of about five to ten.

Efficiency: System efficiency is theoretically unlikely to be greater than with current refrigerants if the system is redesigned appropriately.

1.3 Refrigerants and Systems

1.3.1 Low-GWP + liquid secondary (centralised)

Basic description: A conventional distributed direct expansion system using HCFC or HFC refrigerants within a refrigerating system is replaced with an indirect refrigerating system, utilising an existing low-GWP refrigerant. The central compression system is used to cool a single-phase (liquid) heat transfer fluid which is circulated to heat exchangers distributed throughout the application. Due to differences in the use of fluids and distribution mechanisms, the substitution is accompanied with changes in pipework and primary refrigeration system components.

Primary functions: To eliminate the use of high-GWP refrigerants, improve the tightness of the refrigerant circuit to reduce emissions and to enable the use of flammable and/or higher toxicity refrigerants outside of the sales area.

Technical maturity/availability: Liquid secondary systems are used fairly widely in northern Europe for supermarket systems and worldwide for air conditioning systems.

Applicability: Preferentially applied to medium to large capacity air conditioning systems and medium temperature supermarket systems.

Cost implications: Cost may be higher, equal or lower depending upon the baseline refrigerating system used for comparison, although differences are less with larger capacity applications.

Efficiency: Relative efficiencies are variable; they may be higher, equal or lower depending upon the baseline system used for comparison, the temperature level and the design approach used, although typically better with higher application temperatures.

1.3.2 Low-GWP + liquid secondary (discrete)

Basic description: A conventional distributed direct expansion system using HCFC or HFC refrigerants within a condensing unit (combined with a single or dual remotely located evaporator) system is replaced with an indirect refrigerating system, utilising an existing low-GWP refrigerant. A central compression system is used to cool a single-phase (liquid) heat transfer fluid which is circulated to one or two heat exchangers within the application. Due to differences in the use of fluids and distribution mechanisms, the substitution is accompanied with changes in pipework and primary refrigeration system components.

Primary functions: To eliminate the use of high-GWP refrigerants, improve the tightness of the refrigerant circuit to reduce emissions and to enable the use of flammable and/or higher toxicity refrigerants outside of the sales area.

Technical maturity/availability: Liquid secondary systems are used fairly widely in larger centralised systems but seldom for smaller capacity systems.

Applicability: Can in principle be applied to any single or dual application system.

Cost implications: Cost will be higher, although it is sensitive to capacity and depending upon the baseline refrigerating system used for comparison.

Efficiency: Relative efficiencies are likely to be lower, depending upon the baseline system used for comparison and also on the temperature level (air conditioning, chilled produce or frozen produce) and the design approach used.

1.3.3 Low-GWP + phase-change fluid (PCF) evaporating secondary

Basic description: A conventional distributed direct expansion system using HCFC or HFC refrigerants within a refrigerating system is replaced with an indirect system, utilising a low-GWP refrigerant. The central compression system is used to cool a PCF (involving an evaporating/condensing vapour, typically CO_2) which is circulated to heat exchangers distributed throughout the application. Due to differences in the use of fluids and distribution mechanisms, the substitution is accompanied with changes in pipework and primary refrigeration system components.

Primary functions: To enable the avoidance of higher-GWP refrigerants, where toxicity and/or flammability characteristics limit the use of low-GWP refrigerants in certain types of location.

Technical maturity/availability: PCF evaporating secondary systems have moderate application in food processing and air conditioning systems and a widespread use in supermarket systems.

Applicability: Preferentially applied to medium to large capacity systems.

Cost implications: Cost may be higher, equal or lower depending upon the baseline refrigerating system used for comparison, although differences are less with larger capacity applications.

Efficiency: Relative efficiencies are variable; they may be higher, equal or lower depending upon the baseline system used for comparison, the temperature level and the design approach used, although typically better with higher application temperatures.

1.3.4 Low-GWP + cascade

Basic description: A conventional distributed direct expansion refrigerating system using HCFC or HFC refrigerants within a system is replaced with a cascade type system, utilising an appropriately chosen low-GWP refrigerant for the high-temperature stage and an appropriately chosen low-GWP refrigerant for the medium- and low-temperature stages. The high-stage refrigerant is typically a flammable (hydrocarbon) or higher toxicity (R-717) refrigerant, which can be contained outside or in a special machinery room, whilst the medium- and low-stage refrigerant may be R-744.

Primary functions: To enable the avoidance of higher-GWP refrigerants, where toxicity and/or flammability characteristics limit the use of low-GWP refrigerants in certain types of location, whilst exploiting the most favourable characteristics of certain low-GWP refrigerants.

Technical maturity/availability: Cascade refrigerating systems have moderate application in food processing and air conditioning systems and a widespread use in supermarket systems.

Applicability: Preferentially applied to medium to large capacity systems.

Cost implications: Cost may be higher, equal or lower depending upon the baseline refrigerating system used for comparison, although differences are less with larger capacity applications.

Efficiency: Relative efficiencies are variable; they may be higher, equal or lower depending upon the baseline refrigerating system used for comparison, the temperature level and the design approach used, although typically better with higher application temperatures.

1.3.5 Distributed water-cooled

Basic description: A conventional distributed direct expansion refrigerating system using HCFC or HFC refrigerants within a system is replaced with a combined indirect type system with small discrete refrigerating systems, utilising a low-GWP refrigerant. The central chiller is used to cool a single-phase (liquid) heat transfer fluid which is circulated to water-cooled condensers. They are rejecting heat from small refrigerating systems positioned within display cabinets or on top of/besides cold rooms or small air handling units distributed throughout the application. Due to differences in the use of fluids and distribution mechanisms, the substitution is accompanied with changes in pipework and primary refrigeration system components.

Primary functions: To enable the avoidance of higher-GWP refrigerants, where toxicity and/or flammability characteristics limit the use of low-GWP refrigerants in certain types of location.

Technical maturity/availability: Such systems are used in northern Europe for supermarket systems and are under development in other parts of the world for air conditioning.

Applicability: Preferentially applied to medium to large capacity air conditioning systems and supermarket systems.

Cost implications: Cost may be higher, equal or lower depending upon the baseline refrigerating system used for comparison, although differences are less with larger capacity applications.

Efficiency: Relative efficiencies are variable; they may be higher, equal or lower depending upon the baseline system used for comparison, the temperature level and the design approach used, although typically better with higher application temperatures.

1.3.6 District cooling

Basic description: Conventional direct expansion refrigerating systems using HCFC or HFC refrigerants are replaced with localised secondary cooling coils within the application, which are fed from a remotely located large-scale chiller. The large chiller provides chilled water to a very large number of localised cooling coils, normally distributed across a number of buildings. Any primary refrigerant can be applied.

Primary functions: To enable the avoidance of refrigerating systems that use higher-GWP refrigerants or to reduce the overall mass of higher-GWP refrigerant per kW of cooling.

Technical maturity/availability: District cooling is currently used within a number of countries, both in hot and cooler climates. There are a number of companies that provide equipment and services.

Applicability: Such refrigerating systems are applicable in any location where there is a fairly high population density.

Cost implications: A direct cost comparison is not particularly simple since the technology requires the purchase and installation of one single very large refrigerating system instead of individual purchases of thousands of small refrigerating systems. However, theoretically the overall cost per kW of cooling should be lower.

Efficiency: Provided that the chosen chiller is of high efficiency and the distribution system is well designed, the efficiency should be greater than the combination of discrete refrigerating systems.

2. Outlook on new technologies

Refrigerants: HFC-161 is not currently applied commercially, but is undergoing testing and trials in certain refrigerating systems. HFC-152a is not currently used commercially as a pure substance, but as a component for some other (higher-GWP) HFC mixtures. Therefore, it should be possible to source the pure product. For both refrigerants, there might be additional costs, but potentially also moderate improvements in refrigerating system efficiency.

Refrigerant producers are currently working on the development of new refrigerant mixtures involving unsaturated HFCs (R1234yf, R1243zf, etc) with HFCs (such as R152a, R32, etc) and it is likely that most of the major producers will be formally announcing such mixtures over the next five years. However, it is unlikely that any of the mixtures will have a GWP of less than 300 and most will have a high price.

Magnetic systems: A small number of prototype machines have been developed although to date nothing has been commercialised. They are not-in-kind refrigerating systems working on the principle that special materials heat up when subjected to a magnetic field. When they are removed from the magnetic field, they cool down again. Heat transfer fluids are cyclically passed over the material and take up the heat/cold and pass it on. This is a promising technique that can -in theory- be applied widely. The cost is likely to be somewhat greater than conventional compression systems, but efficiency is found to be very high, especially for lower temperature levels. The primary hurdles are related to the selection and availability of the specialist magnetic materials required.

Stirling system: In certain niche applications, these machines are commercially available from a small number of manufacturers. They are a particular type of combined compression/heat exchanger device. In theory, such Sterling type cooling machines can be applied widely. Due to the extent of current developments and level of commercialisation, the cost of Sterling machines is somewhat greater than conventional compression systems. Efficiency is known to be high, especially for lower temperature levels.

Niche technologies: Niche applications might only by favourable under special circumstances. Ejector cycles refrigerating systems belong to this group, which are only in a very small number commercially available. They consist of a heat-driven cycle, where the refrigerant is driven through an ejector. This leads to an energy saving compared to a conventional refrigerating system. The systems have low efficiency, but where waste heat is available, cooling can be provided for free.

Desiccant refrigerating systems are used fairly widely in niche applications with a small number of manufacturers producing a range of equipment. A mass of hydrophilic material is used to remove moisture from an air stream before it is passed to the application. They are generally of interest in regions with high humidity and where they can be integrated into broader cooling (and heating) systems. In isolation, efficiency is higher than conventional compression type refrigerating systems.

3. Market penetration

3.1 Constraints to market penetration

Limitations of each technical option in the RAC sector are due to safety, cost and/or efficiency implications and the amount of effort/resources imposed to integrate that technical option into the subsector. In the foam sector, limitations are mainly caused by standards, the risk of construction fire, insulation value classifications, automotive standards regarding VOCs (volatile organic compounds) or dictated by standardisation of car models. Other limitations are costs and availability of specific blowing agents. It is therefore necessary to consider the use of each relevant technical option for a specific subsector within the context of the various limiting factors.

Safety constraints: The application of refrigerants or specific blowing agents is generally controlled by national regulations, such as those dealing with the use of hazardous substances, buildings or construction industry insulation materials. Generally such regulations are non-specific in terms of how refrigerants can be applied and aim towards "safe use". However, in many countries, safety standards and codes of practices are available, which are more specific in the manner by which refrigerants are applied; also noting that such standards and codes are normally not legally mandatory but are considered as "best practice". Foams must adhere to specific fire resistance classifications. Depending on the location where the foam is used in construction in some cases HCs do not provide the desired classification. This can lead to the use of combinations of different blowing agents to find a mix that provides the desired classification of the foam and blowing agent.

Many of the currently used HFCs have a safety classification of lower-toxicity/no flame propagation (i.e., class "A1"). This means that they can be applied to most situations without consideration of charge quantity limitations and other safety considerations. However, many technical options are flammable or have higher toxicity or both (typically "A2", "A3" and "B2" classifications), which results in limitations of the quantity of refrigerant permitted within different locations. As such, where standards specifically limit certain technical options in particular locations, this can impact on the penetration rate[1].

1 As an example, R-717 (class B2) is not permitted to be used in direct systems, so the maximum penetration for room air conditioners would be 0%, whilst HC-290 (class A3) can be used in direct systems provided the charge size is below a certain quantity. Thus, the penetration would be more than 0% but less than 100% because it would not ordinarily be possible to use HC-290 in systems that require a large charge.

Whilst safety standards may partially or wholly restrict certain technical options from being used in certain locations, it is possible to redesign refrigerating systems in order to ensure the refrigerant is kept within an alternative location or reduce the quantity of refrigerant in a system. However, this may then impose other constraints such
as related to cost and/or efficiency. Alternatively, efforts can be made to modify and extend the inclusivity of standards in such a way that more innovative approaches to design can be made by industry (whilst maintaining the same level of safety).

For foam, health issues due to emissions are normally not a constraint for production purposes as factories can take the necessary provisions. They are an issue when these emissions occur during the use of the foams. The location and industry setup could be a constraint when local fire prevention regulations prohibit the use of e.g. flammable blowing agents.

Efficiency constraints: It is a basic principle that any technical option under consideration does not risk offsetting refrigerant-related (for RAC) or insulation-related (for foam) emissions reduction by consuming more energy. Furthermore, this principle is in line with the fact that in many countries, there are – or will be – minimum efficiency standards for specific product types. Therefore technical options can only be considered where systems would achieve at least the same level of efficiency. In general, most of the technical options under consideration in the RAC sector can already provide at least the same level of efficiency as the existing refrigerants. In cases, where technical options have a poorer efficiency than the existing HFC technology when used in comparable refrigerating systems, additional materials and components may be required to bring the efficiency up to the required level, which may incur costs. In the foam sector, most of the technical options do not have the same level of insulation efficiency as the existing blowing agents. Therefore in order to have a neutral conversion the insulation thickness needs to be increased which is an additional cost factor for the technical option. In the particular case of refrigeration foam, insulation specific technologies, like vacuum panels, can be adopted. In some cases technical options may not be able to achieve the required efficiency level (even with optimisation), in which case the penetration rate would be limited.[2]

Cost constraints: In principle, any technically feasible technical option can be used for any application, provided unlimited funds are available to implement it. However, the market may not accept products at considerably higher cost (price) than existing products. The cost implication of using different technical options may be affected by several different parameters, including safety requirements, desired efficiency, system complexity and special materials. Therefore it is important to identify situations where technical options may result in excessively high cost such that the penetration potential of those technical options would be limited.

Availability of materials and components: For RAC, some refrigerating system parts are specific to certain refrigerants (for example, compressors). Whilst it is feasible to use a given refrigerant within a particular type of system, if no suitable components are available, this would affect the (near term) penetration rate of that technical option. Currently, not every refrigerating system could be built with every technical option using dedicated "off the shelf" parts; as a result some technical option systems would need to be improvised, which could lead to higher costs and/or lower efficiency. Similarly, whilst certain refrigerants are available in sufficient quantities, others – such as newly developed unsaturated HFCs – are not yet commercially available at the scale necessary to satisfy widespread use in certain subsectors. As the market availability can be assumed to develop over time, the accurate quantitative assessment of the penetration rates is key condition for the estimation of the HFC reduction potential in the latter periods.

For foam, the effectiveness of a technical option regarding the performance mainly depends on the raw materials and not on the blowing agent. For specific technical options which are currently not widely used in specific regions this can lead to limited penetration rate. The same is valid for the availability of blowing agents and the logistics when these are not available locally. The market availability can be assumed to develop over time, but an accurate quantitative assessment is difficult to assess, as it is strongly dependant on regional factors and production availability.

2 As an example, the technical option transcritical use of R744 (which is more energy efficient than most HFC systems in geographical zones with moderate climate) could be used in air conditioning systems within temperate climates. The penetration could reach 100% there, but in hot climates the ideal cycle efficiency of R744 would still be below the minimum efficiency of such air conditioners and therefore the penetration would be 0%. Thus, the penetration rate would be reduced according to share of moderate and hot climates.

System complexity and design know-how: Systems running on ODS, HFCs and HFC blends are of similar complexity and design. In contrast, design and construction of a refrigeration or air conditioning system running on flammable refrigerants or trans critical R-744 systems require additional knowledge and training. This is the same for the use of flammable blowing agents. Therefore, design engineers and technicians need to acquire additional know-how in order to install technical technology properly.

Industry size and investment costs: For foam, this is another constraint to market penetration. In general, every industry will seek to achieve the lowest production costs and at the same time adhere to the regulations in place. The limitation is the balance between investment costs, return on investment and markets mechanisms. When markets do not enforce a change industry will not willingly change. Also the size of the production facility and the product itself play a role. Industries producing relatively low quantities are from an infrastructural point of view limited with regard to R&D and capacity to convert.

3.2 Determination of penetration rates

In estimating the maximum potential penetration rate, several factors are considered. For each of the constraints considered above in the RAC sector, the proportion (of refrigerant quantity, not necessarily number of refrigerating systems), χ , for each constraint, i , of the subsector that could not accommodate the specific technical option due to each is estimated. These factors are estimated for some nominal year, being a period sufficient to enable the various temporary constraints to be overcome (currently assumed to be about 10 years from the present). This should therefore account for both (i) anticipated technical developments and (ii) market maturity.[3]

For foam, these factors are however mainly external, i.e. less related to the product itself. Therefore the main parameters to consider are applications where the industry size and investment costs are the limiting factors. External factors like standards for particular applications must be in place and suitable for the particular technical option. The availability of suitable raw materials is no issue here as the technical options considered are already widely spread in developing countries. The availability of blowing agents is a problem, especially with regard to the newly developed technical options. Whilst the constraints detailed above are mechanistic, another constraint may be included to account for the "willingness" of the market to adopt a given technical option. Special training for technicians, interpretation of complicated standards and so on might be needed to increase the penetration rate.

The overall maximum penetration rate is then estimated from $1\text{-max}\ \{i \times \chi\}$ i.e., the maximum possible penetration under business-as-usual should be based on the maximum proportion of a subsector unable to accommodate the technical option for any of the given constraints. For each technical option the proportions (χ) are based on expert knowledge of the characteristics of the refrigerating systems and equipment, system design characteristics, requirements of safety standards, technology requirements, etc. and coupling these with characteristics of the refrigerants under consideration.

Whilst the constraints detailed above are mechanistic, another constraint may be included to account for the "willingness" of the market to adopt a given technical option, which may be a function of the additional considerations necessary to suitably apply a particular technical option. These considerations may include having to get special training for technicians, interpretation of complicated standards and so on. Using this approach the maximum penetration rate could be scaled down.

3 For example, where charge size limits are a limiting factor, it can be assumed that research and development efforts over the next 20 years will reduce specific charge sizes (kg/kW) to below today's lowest values, or that system components for certain technical options are widely available such that the product development and small production scale costs have been eliminated from the purchase price.

For each technical option and subsector, a maximum penetration rate is given in the module. Penetration rates for some intermediate period (between the present and the selected nominal year for achieving the penetration rates) are obtained from linear interpolation between then and the current status of penetration of each technical option. It must be noted that there is no generally accepted methodology for the determination of penetration rates, and that the rates are subjective and with uncertainties. Evidently, it is not possible to precisely forecast and quantify the technical development in the coming years. The penetration rates for the numerous individual technical options rely on the best knowledge of experts. The assessment is inter alia a result of detailed literature study, and of intensive discussion with the industries concerned.

3.3 Combination of penetration rates ("penetration mix")

In reality a subsector may comprise a number of different technical options. However, the mix of different technical options cannot necessarily be represented by the maximum penetration values for each technical option since the same constraints that apply to one technical option may apply to another (for example, flammability, etc). Thus, we define the adjusted penetration rates of the technical options as percentages which add up to 100%. Economic technical options are preferentially used, in terms of cost per reduced tonnes of CO_2, considering their maximum technical penetration rates. In case the market is not fully penetrated by the cheapest technical option, the market is successively filled up with further technical options, whereby not exceeding 100%.

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Deutsche Gesellschaft für
Internationale Zusammenarbeit (GIZ) GmbH

Registered offices
Bonn and Eschborn,
Germany

Programme Proklima

Dag-Hammarskjöld-Weg 1-5
65760 Eschborn, Germany
Phone: +49 61 96 79 - 1022
Fax: +49 61 96 79 - 80 1022
Email: proklima@giz.de
Internet: www.giz.de/proklima