Resurseffektiva kyl- och värmepumpssystem

Refrigerants with low GWP and cost and energy efficiency optimization of vapor compression systems

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Energimyndigheten

Foreword

“The whole is greater than the sum of its parts”. This old saying is applicable to many aspects in life, and in our opinion also to vapour compression systems. A refrigeration or heat pump unit generally consists of a number of components that are combined into a cycle. The outcome not only depends on the quality of the components, but also on the way they are combined.

The refrigerant is the key component of the vapour compression system as it dictates the design of all other components. Therefore refrigerant alternatives were investigated and the impact of refrigerant selection on system behavior was addressed. Aspects of cycle layout, component size and system control were systematically assessed with a novel methodology which allows finding the optimum between costs and energy consumption.

We hope that the results of this project are not only beneficial for the refrigeration industry in general, but also for you in particular.

Sincerely,

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Summary

There are two major drivers for technological changes in heat pump systems, namely end user requests and legislation. The end users of heat pump systems have during the recent years gained an increased awareness of global warming; combined with increasing energy prices this has brought their attention to energy efficiency. In the interest of reducing global warming in the European Union new legislation and standards are regulating the use of a number of substances, including refrigerants, and setting limits to the energy use of refrigeration systems and heat pumps.

International agreements already led to regulations regarding the usage of fluorinated greenhouse gases which are expected to be augmented by further restrictions on allowed types and amounts of refrigerants. In this changing environment various technologies known to offer a potential for improving energy efficiency of vapor compression systems become interesting also for residential heat pumps. Some examples are variable speed compressor, special expansion solutions, advanced control algorithms, advanced cycle layouts and alternative refrigerants.

Current report summarizes the project entitled “Refrigerants with low GWP and cost and energy efficiency optimization of vapor compression systems”. This project has two parts with the common goal of contributing to the development of the heat pumps and refrigeration systems of the future, both regarding optimum design, from technical and economical point of view, and regarding the choice of refrigerant. The two parts of the project are each presented in the following:

- the first part of the project aims to provide data, support and prerequisite information of alternative refrigerants with low GWP at the phasing out of HFC refrigerants for existing and new heating / cooling systems.
- the second part of the project is focusing on development of a method to systematically analyze refrigeration and heat pumping tasks to find the Pareto front of cost and energy optimal system solutions.

The study has been done in collaboration between KTH The Royal Institute of Technology, and the company Danfoss A/S. A number of alternative low GWP refrigerants has been identified and analyzed to determine their applicability for the potential future use and compliance with relevant legislative acts. A methodology has been developed for systematically finding cost and energy optimal vapor compression system layouts from a large number of possible solutions. The methodology has been tested, in different contexts providing quantified costs and efficiency with relatively simple simulation models and a smaller number of simulations compared to classical optimization approaches.

The project findings were disseminated in a number of publications and presentations.

Sammanfattning

Två krafter driver den tekniska utvecklingen av värmepumpar, nämligen brukarnas önskemål och lagstiftningen. Brukarna har under de senare åren blivit alltmer medvetna om den globala uppvärmningen; detta i kombination med ökande energipriser har satt fokus på energieffektiviteten. För att minska Europas bidrag till den globala uppvärmningen har EU infört ny lagstiftning och nya standarder som berör användningen av ett antal växthusgaser, inkluderande flera köldmedier, samt sätter gränser för energianvändningen för kylanläggningar och värmepumpar.

Internationella överenskommelser har redan lett till regler för användningen av fluorinerade växthusgaser, och dessa regler kan förväntas stramas åt ytterligare rörande tillåtna köldmedier och tillåtna köldmediemängder. I denna föränderliga miljö blir olika teknologier som kan öka energieffektiviteten för ångkompressionsprocessen alltmer intressanta även för värmepumpar. Exempel på detta är varvtalsstyrning, system för återvinning av arbete vid expansionen, avancerade kontrollalgoritmer, avancerade cykler och alternativa köldmedier.

Föreliggande rapport sammanfattar projektet med titeln ”Köldmedier med låg GWP samt kost- och energioptimering av värmepumpsystem”. Projektet har två delar med det gemensamma målet att bidra till utvecklingen av värmepumpar och kylsystem för framtiden, både vad gäller optimering av designen, från teknisk och ekonomisk synvinkel, och vad gäller val av köldmedium. De två delarna av projektet presenteras i det följande:

- Den första delen av projektet har som mål att tillhandahålla data, stöd och information för alternativa köldmedier med låg GWP i samband med utfasningen av HFC-köldmedierna, både för existerande och för nya anläggningar.
- Den andra delen av projektet fokuserar på utvecklingen av en metod för att systematiskt analysera kyl- och värmepump installationer för att hitta optimala avvägningar mellan kostnad och energieffektivitet (Pareto-front) för sådana system.

Studien har gjorts i samarbete mellan KTH och Danfoss A/S. Ett antal alternativa köldmedier med låg GWP har identifierats och analyserats för att bestämma deras tillämpningsområden vid en framtida användning, liksom hur väl anpassade de är till nuvarande och förväntad lagstiftning. En metod har utvecklats för att systematiskt identifiera utformningen energi/kostnadsoptimerade ångkompressionssystem utifrån ett stort antal möjliga lösningar. Metoden har testats i olika sammanhang där kostnader och energieffektivitet kunnat bestämmas med relativt enkla simuleringsmodeller och med färre simuleringar jämfört med tidigare föreslagna metoder.

Resultaten har redovisats i flera publikationer och muntligen vid flera konferenser.

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1. Introduction

The KTH Royal Institute of Technology, Stockholm, Sweden initiated this project together with the company Danfoss A/S, Nordborg, Denmark within the framework of the ”Industrial PhD program” of the Ministry of Science, Innovation and Higher Education in Denmark and Effsys+. The project has two parts with the common goal of contributing to the development of the heat pumps and refrigeration systems of the future, both regarding optimum design, from technical and economical point of view, and regarding the refrigerant selection.

The technology of vapor compression systems exists since more than a century and for decades was varied only marginally. However, in recent times this picture changed dramatically due to the described end user requests and legislation. At the same time the developing world catches up fast on the long-established technology. Many competitors are entering the market with their products, competing heavily on the price. Hence suddenly traditional companies as Danfoss A/S face a market where the products should at the same time become better and cheaper.

During the last years several radically innovative ideas were pursued within the company for components which should increase system efficiency and thereby secure the company’s competitive advantage. However failures occurred due to wrong assumptions early on in the projects. These failures regarded both the real efficiency improvement potential of the new product as well as the new component’s costs in relation to alternative solutions. It became clear that research efforts had to be become more focused to ensure the future well-being of the Danfoss A/S.

At the same time, the design of the vapour compression system is highly dependent on the refrigerant in the system. Conventional technologies imply the prevailing use of Hydrofluorocarbons (HFCs) as refrigerants. However, the concerns on global warming, supported by a number of legislations, require phase out of these substances due to their high contribution to climate change indicated by high Global Warming Potential (GWP) values. For instance, new European regulation on fluorinated gases requires gradual decrease of the use of HFCs in European Union to the limits that are almost five times lower than current values [1]. In order to reach the targets, alternative refrigerants with lower GWP values are needed.

On this background two PhD projects have been initiated. One PhD project aims to better evaluate new technology ideas in an early development stage. A method is wished for that allows at an early stage to both clearly define the target application and to quantify the potential of the idea as well as the potential of competing solutions in regard to this target application. Another PhD project will focus on different low GWP alternative refrigerants that will become a part of an environmentally friendly refrigeration and heat pump technology of the future.

Thus, the project combines these two parts with the common goal of contributing to the development of the heat pumps and refrigeration systems of the future, both regarding optimum design, from technical and economical point of view, and regarding the choice of environmentally friendly refrigerant.

The first part of the project aims to provide data, support and prerequisite information of alternative refrigerants with low GWP at the phasing out of HFC refrigerants for existing and new heating / cooling systems. The focus is given to the new refrigerant thermal properties, requirements for safety of components and energy efficiency. The main objective is to disseminate this knowledge to the Swedish refrigeration and heat pump industry in an accurate, easily understandable and neutral manner. Such knowledge is essential to the heat pump/refrigeration industry for selection of refrigerant in case of phasing out HFC fluids in existing plants and also in design of new plants.

The second part of the project is focusing on development of a method to systematically analyze refrigeration and heat pumping tasks to find the Pareto front of cost and energy optimal system solutions. This being achieved by utilizing the system layout and the individual component efficiency as optimization variables. Focus application is residential heat pumps, emphasizing low refrigerant charge technology.

2. Refrigerants with low GWP

Since the invention of vapour compression refrigeration cycle, the refrigeration industry has undergone through several generations of volatile fluids used as refrigerants (Figure 1). Until 1922 ammonia (NH_3), carbon dioxide (CO_2), sulphur dioxide (SO_2) and water were major working fluids in vapour compression cycles. Out of them ammonia and sulphur dioxide are toxic in small quantities; application of carbon dioxide and water is limited due to their thermal properties. Hydrocarbons (HCs) were also used at that time [2].

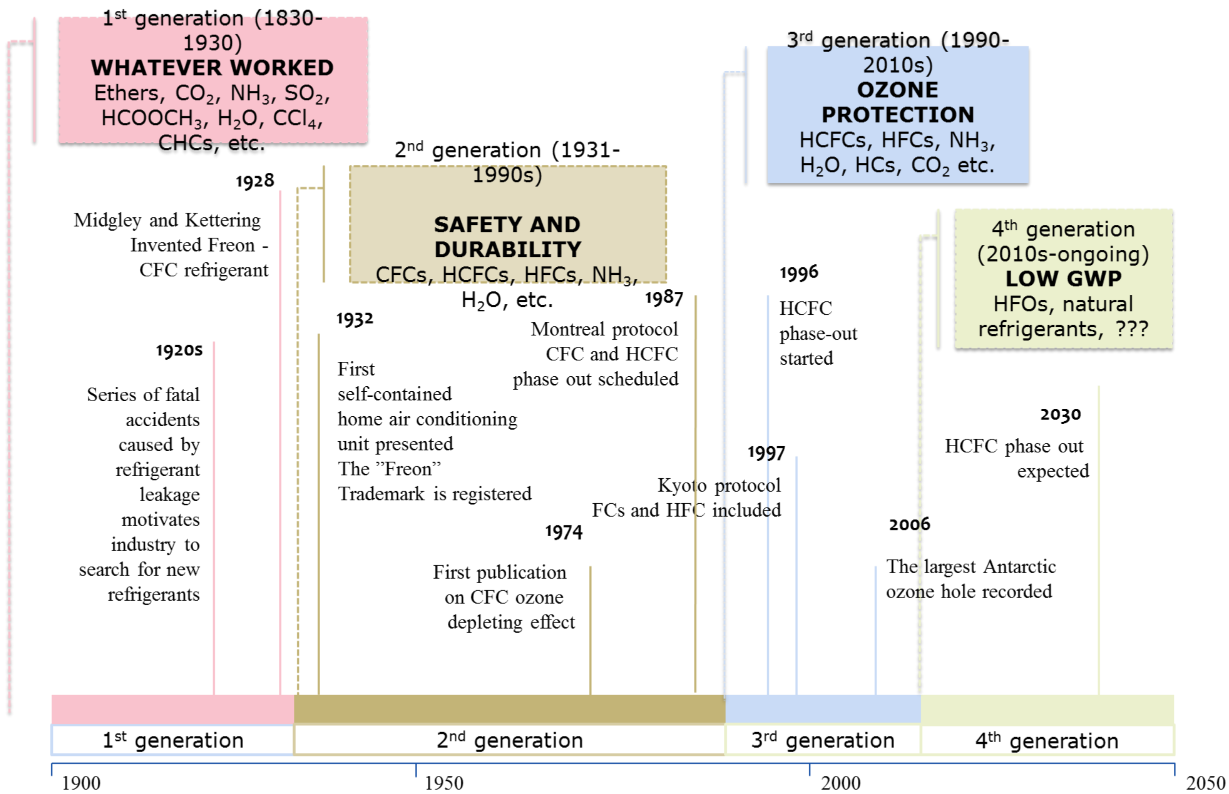

Figure 1 - Refrigerants development timeline

In 1930 at a meeting of the American Chemical Society Thomas Midley presented a new refrigerant to be known as "Freon" [3]. It has been able to provide a solution for refrigeration industry in form of non-flammable refrigerant with no smell and no poisonous effect, hence substituting old toxic refrigerants such as ammonia and sulphur dioxide. This refrigerant has become popular very fast and made the world to believe that the era of chlorofluorocarbons (CFC) has begun [4]. It took almost 50 years to identify the threat to the ozone layer from CFC gases [5]. The work of Molina and Rowland has raised the attention to the effect of CFCs on the environment. This consequently led to the restrictions on CFC release that initiated during the late 1970s and early 1980s [6]. As a result, the Montreal Protocol on Substances That Deplete the

Ozone Layer has been adopted in order to protect the ozone layer by phasing out the production of numerous substances believed to be responsible for ozone depletion. According to the Montreal protocol regulations, including the London and Copenhagen Amendments, CFCs were forced to be phased-out by 2010, followed by the phase out of hydrochlorofluorocarbons (HCFCs).

New refrigerants development has taken place in order to replace CFCs and HCFCs in many applications. The transition from these substances to mainly different HFCs or their blends took place. However the substitution of such refrigerants with HFCs is not completely solving the environmental problems. Widely used HFCs have quite significant GWP and hence lead to global warming.

As of today, the air-conditioning and refrigeration systems are significant contributors of greenhouse gases (GHG) in atmosphere. It is estimated that they are responsible for approximately 10% of total worldwide CO_2 eq.(uivalent) emissions released [7]. Within this 10%, the share of HFC emissions in total fluorinated gas emission amount is increasing and is expected to further increase, if no actions will be taken (Figure 2).

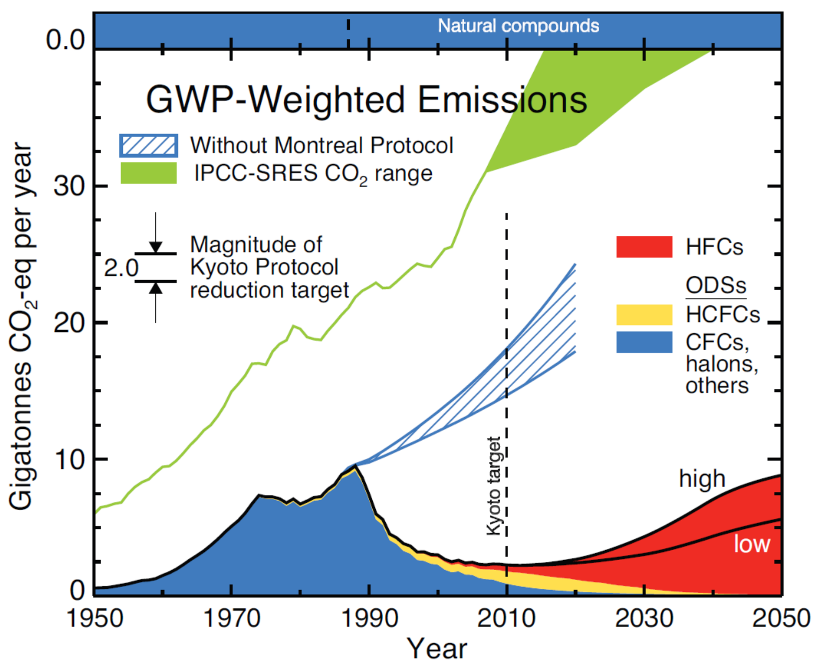

Figure 2 - Global GWP-weighted emissions of refrigerants [8]

As it is seen from the Figure 2, the replacement of CFC and HCFC substances with HFCs has brought feasible environmental benefits, but attention to the increased concentrations of high GWP HFCs should be given. The replacement of high GWP refrigerants with the low GWP alternative ones will allow mitigating the global GHG increase and thus contributing to global warming mitigation.

2.1 Specific goals

The first part of the project aims to provide data, support and prerequisite information of alternative refrigerants with low GWP at the phasing out of HFC refrigerants for existing and new heating / cooling systems. The focus is given to the new refrigerant thermal properties, requirements for safety of components and energy efficiency.

The addressed aspects of this part include the mapping of potential new refrigerants in new and existing refrigeration/ heat pumps systems; identification of conditions for the phasing out of HFC refrigerants and assessment of new refrigerants in term of energy efficiency; investigation of the thermal properties and safety of new low-GWP refrigerants as well as the identification and consequence analysis of phasing out of HFC refrigerants and the introduction of new refrigerants on system performance and price

The main objective is to disseminate this knowledge to the Swedish refrigeration and heat pump industry in an accurate, easily understandable and neutral manner. Such knowledge is essential to the heat pump/refrigeration industry for selection of refrigerant in case of phasing out HFC fluids in existing plants and also in design of new plants.

2.2 Methodology

The important element of the first part of the project is to ensure the continuous information collection in the area of alternative refrigerants development. Given the dynamics of the selected research area, literature review has been one of the methods regularly used in the study. Information from the scientific journals, conference proceedings and other relevant sources of information served a basis for a consequent qualitative and quantitative analyses held in the project.

Literature review was focused on a number of key areas that are important for understanding the feasibility of some substances to potentially become alternative refrigerant. The focus areas include:

- refrigerant thermodynamic and transport properties (e.g. vapor pressure, density and heat capacity, thermal conductivity, viscosity);
- refrigeration cycle characteristics at different combinations of suction and condencing temperatures (e.g theoretic cooling and heating capacities, influence of superheating / subcooling on theoretical coefficient of performance, hot gas temperature at compressor exit during the isentropic compression);
- practical information from new refrigerant use (e.g. material stability and compatibility, oil solubility, leakage tendency, practical energy performance measurements;

- safety aspects (e.g. flammability characteristics, toxicity of decomposition products);
- environmental performance (e.g. impact on the local and global environment during different lifetime stages);
- cost aspects, including refrigerant cost and the potential change of the cost of the system adapted for the use of the alternative refrigerant.

Quantitative analysis consisted of a few case studies, where a number of alternative low GWP refrigerants were studied to determine their influence on total lifetime emissions of a heat pump system. For this analysis the vapor compression refrigeration cycle has been modelled as a part of the heating system it is integrated into; and the results were used in a mathematical model to provide the quantitative data.

The obtained quantitative data has been further analyzed using qualitative approach in order to determine the potential of applicability of a refrigerant for the future sustainable refrigeration and heat pump systems.

2.3 Alternative refrigerants with low GWP

The focus of the first part of the project is given to the refrigerants with low GWP. Thus, the definition of the low GWP refrigerant should be given prior in the beginning of the project. While the term “low GWP” is widely used nowadays, there is no definitive agreement on its definition in the open literature. United Nations Environment Programme progress report [9] discussed this issue and proposed a set of definitions to cover a range of refrigerant with GWP from as low as “ultra-low” up to “ultra-high” GWP ones. Our analysis of the available data [10] results in the conclusion that every refrigerant with GWP of 150 or less is considered as low GWP one for the sake of the current project. However, exceptions are given to some refrigerants that have higher GWP values but are capable of significant environmental benefits when being used instead of conventional high GWP ones.

Given the definition, alternative low GWP refrigerants could be selected from the list of natural refrigerants, synthetic or their mixture.

Natural refrigerants

All currently used natural refrigerants are low GWP ones. Hydrocarbons, Ammonia and CO_2 are widely used today in different refrigeration applications. Due to their low effect on climate change their use will be continued in the future. Other natural refrigerants, as for instance water, air or nitrogen, are possible to be used as well, but their use is greatly limited to specific applications.

Hydrocarbons (HC) as refrigerants are advantageous as non-toxic and low cost. Due to their flammability, HCs are tend to be used in small quantities with charge normally less than 50 g and, thus, in small scale refrigeration units up to about 1 kW refrigeration capacity: small- and medium-sized refrigeration, air conditioning and heat pump systems [2] [11]. For instance, over 85% of domestic refrigerator production in China is based on R600a which is totally dominating refrigerant in many countries. Globally, hydrocarbons are used in around 36% of the domestic refrigerators and freezers, and this number is estimated to rise up to 75% by 2020 [12].

The flammability risks with these refrigerants must be taken seriously and should be reduced by designing systems with minimum charge, leak detection and etc. Considering these safety measures it is possible to make systems with efficiencies equal to, or even higher than, those of R-22 and R-134a systems [2].

Ammonia (R-717, chemical formula NH_3) has been known as a refrigerant for many years and is widely used now in large industrial and food processing applications with high cooling demand. Ammonia is very favourable from the environmental point of view as have zero ODP and no GWP. According to thermodynamic qualities, R-717 is good alternative to R-22 and R-502 as it is readily available, inexpensive and has favourable thermodynamic qualities comparable with other refrigerants. Having high heat transfer coefficient and high value of specific heat of vaporization, ammonia allows designing systems with small refrigerant charge [13].

One of the main difficulties with ammonia as a refrigerant is its high activity towards copper and copper alloys. Hence, the system should be designed in the way to avoid refrigerant's contact with copper.

Ammonia is not miscible with most types of oils and thus intensive development of the oil soluble in ammonia undergoes. Progress, recently achieved in this field which includes development of soluble oil and employment of plate heat exchanger, can enlarge fields of application for ammonia as a refrigerant [11] [13]. Reduction of filling volume of ammonia into the systems was achieved as well [11]. It is expected to see more applications for ammonia in thermal storage systems, district cooling systems, process cooling and air conditioning and others [14].

Carbon dioxide is a natural refrigerant, environmentally friendly with zero ozone depletion potential (ODP) and low GWP and was widely used before even CFCs and HCFCs were introduced. Among the attractive properties of CO_2 are its incombustibility, availability and low cost, which is 100…120 times lower than R-134a [13].

The main problem with CO_2 as a refrigerant is its thermo-physical properties. It has high critical pressure with low critical temperature and low cycle efficiency. In the applications where the condenser is cooled with ambient air the working pressures could be as high as 75 bar and different component design is thus required to sustain high pressure in the system. System performance at high temperatures tends to decrease also what lead to higher energy consumption of such systems in hot climates compared to R22 analogues. Hence, the application of CO_2 is mainly in cold climates and as a low temperature at cascade systems, where the working pressures could be designed to be reasonably low [14].

Synthetic refrigerants

HFC are the most used category of refrigerants to date. Most of them have very high GWP values of thousands of that of CO_2. There are few, however, that have low GWP values of less than 150. R152a and R161 are examples of such.

R-152a has been used for many years as a component in blends, but, due to its high flammability, not as a single substance refrigerant till now. Given the low GWP of 138, refrigerant R152a has been recently investigated in several applications.

Although R152a is flammable refrigerant, it can be still used if proper safety measures are taken in the design of an equipment. One option is to use R152a as a primary refrigerant of refrigeration systems with secondary loop.

R161 (Fluroethane) is an low GWP refrigerant with favourable environmental properties: zero ODP and low GWP of 4 [15]. Its thermo physical properties are similar to R22 and very close to that of R290.

R161 is considered as an alternative to R22 in room air conditioning application, where it has similar or better system performance [16]. However, it is very flammable as well and this is an important drawback to overcome.

R32 is another favourable HFC refrigerant with rather low GWP. Its development as pure refrigerant is limited with concerns of its high flammability. However, due to its favourable thermophysical properties a number of refrigerants blends are developed with R-32 as one of the components.

Hydrofluoroolefins (HFOs) have been recently rediscovered for potential use in various refrigeration systems. HFOs are generally HFCs, however often referred as HFOs in order to underline their specific properties.

Brown et al. [17], in their study on new, low GWP refrigerants, have brought to the discussion a topic of applicability of a number of fluorinated propene isomers as alternative refrigerants with good environmental properties. In their article the nomenclature rules for propene isomers are presented. They highlights, that propene isomers have different properties. For example, all the isomers with bases 1252 and 1261 are flammable and should not be considered as viable refrigerant option. Out of other 19 possible fluorinated isomers with the bases 1225, 1234 and 1243 Brown et al.

select eight for thermodynamic properties analysis. Figure 3 summarises his work for R-1225ye(E), R-1225ye(Z), R-1225zc, R-1234ye(E), R-1234yf, R-1234ze(E), R-1234ze(Z), R-1243zf and compare values with R134a on P-h diagram.

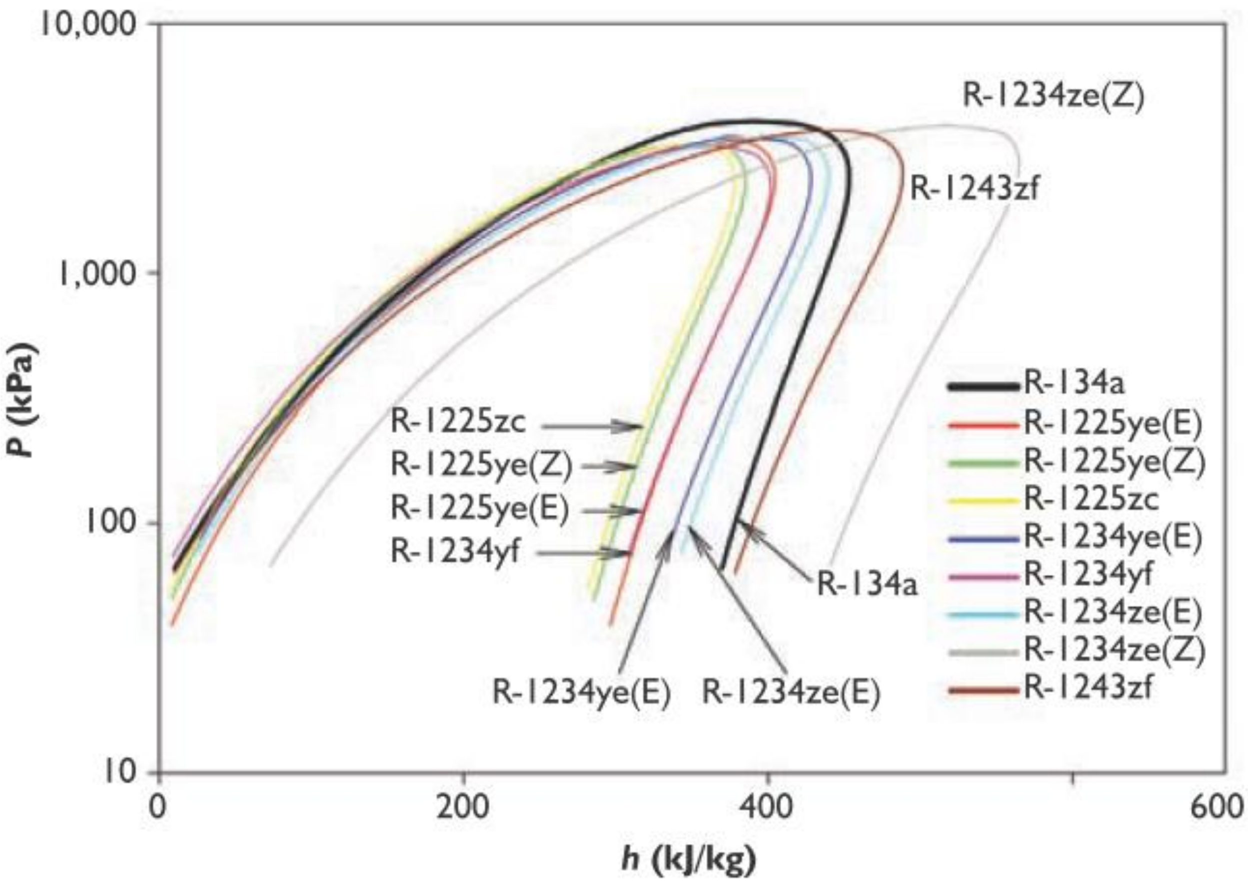

Figure 3 - Pressure vs. enthalpy for eight fluorinated propene isomers [17]

In few years from this publication a number of HFOs has become commercially available or got close to the commercialization. R1234yf has become the most viable option to substitute R134a in MAC systems, although its COP and volumetric cooling capacity is generally a bit lower than R134a. The next closest considered alternatives are the R1234zf and R1234ze(E), however only the latter is close to commercialization. For high temperature heat pumping applications R1234ze(Z) is appropriate replacement to R114 as have nearly identical COP and volumetric heating capacity of just 4.7% lower than the R114 value [17].Both molecules have very low GWP of less than 1 [15].

Refrigerant mixtures

Refrigerant mixtures are set to become suitable alternatives to the existing halogenated refrigerants as, by blending different components with various properties, it is possible to adjust properties to the desirable values. There are three categories of refrigerant mixtures: azeotropes, near azeotropes and zeotropes. All three categories differ with the range of temperature glide they have. Mohanraj summarized a number of experimental studies discussing the suitability of refrigerant mixtures to replace the halogenated refrigerants. The study groups all the mixtures in terms of their composition: HC mixtures, HFC mixtures, HFC/HC mixtures, HCFC mixtures, R744 mixtures and ammonia mixtures [18].

For instance, Honeywell – one of the leading global chemical manufacturers - considers HFOs as good components for refrigeration blends which "balance the attributes of higher capacity and low global warming potential while maintaining the efficiency of present systems without significant increases in system cost" [19]. There are two main HFOs which are considered for such mixtures: R1234yf and R1234ze(E).

Several researches have been performed in order to take advantage of the properties and to increase COP of the refrigerant cycle based on HFOs at various refrigeration applications. It seems to be possible to overcome the drawbacks of the HFOs by mixing it with other refrigerants with larger latent heat values and preferably small GWP value. Table 1 lists some of the refrigerant mixtures that are under consideration.

Table 1 - List of low-GWP refrigerant blends, their composition and respective GWP value

Refrigerant	Supplier	Composition	GWP_{100}
AC5	Mexichem	R-32/R-152a/R-1234ze(E) (12/5/83)	92
AC5X	Mexichem	R-32/R-134a/R-1234ze(E) (7/40/53)	622
ARM-30a	Arkema	R-32/R-1234yf (29/71)	199
ARM-31a	Arkema	R-32/R-134a/R-1234yf (28/21/51)	491
ARM-32a	Arkema	R-32/R-125//R-134a/R-1234yf (25/30/25/20)	1577
ARM-41a	Arkema	R-32/R-134a/R-1234yf (6/63/31)	861
ARM-42a	Arkema	R-134a/R-152a/R-1234yf (7/11/82)	117
ARM-70a	Arkema	R-32/R-134a/R-1234yf (50/10/40)	482
D2Y-60	Daikin	R-32/R-1234yf (40/60)	272
D2Y-65	Daikin	R-32/R-1234yf (35/65)	239
D-4Y	Daikin	R-134a/R-1234yf (40/60)	574
D52Y	Daikin	R-32/R-125/R-1234yf (15/25/60)	979
DR-33	DuPont	R-32/R-125/R-134a/R-1234yf (24/25/26/25)	1410

Refrigerant	Supplier	Composition	GWP_{100}
DR-5	DuPont	R-32/R-1234yf (72.5/27.5)	490
DR-7	DuPont	R-32/R-1234yf (36/64)	246
HPR1D	Mexichem	R-32/R-744/R-1234ze(E) (60/6/34)	407
L-20	Honeywell	R-32/R-152a/R-1234ze(E) (45/20/35)	331
L-40	Honeywell	R-32/R-152a/R-1234yf/R-1234ze(E) (40/10/20/30)	285
L-41a	Honeywell	R-32/R-1234yf/R-1234ze(E) (73/15/12)	943
L-41b	Honeywell	R-32/R-1234ze(E) (73/27)	494
LTR4X	Mexichem	R-32/R-125/R-134a/R-1234ze(E) (28/25/16/31)	1577
LTR6A	Mexichem	R-32/R-744/R-1234ze(E) (30/7/63)	206
N-13a	Honeywell	R-134a/R-1234yf/R-1234ze(E) (42/18/40)	604
N-13b	Honeywell	R-134a/R-1234ze(E) (42/58)	604
N-20	Honeywell	R-32/R-125/R-134a/R-1234yf/R-1234ze(E) (12.5/12.5/31.5 /13.5/30)	975
N-40a	Honeywell	R-32/R-125/R-134a/R-1234yf/R-1234ze(E) (25/25/21/9/20)	1346
N-40b	Honeywell	R-32/R-125/R-134a/R-1234yf (25/25/20/30)	1331
OpteonTM XP10	DuPont	R-134a/R-1234yf (44/56)	631

As one can see from the Table 1, many refrigerant suppliers try to make use of good thermodynamic properties of R32, by mixing it with other refrigerants and thus mitigating their flammability. It is also worth to mention that few of the proposed refrigerant blends have low GWP values. Additional information regarding the applicability of refrigerants mixtures in future refrigeration and heat pump systems can be found in [20], [21].

2.4 Case study on environmentally friendly low GWP refrigerant selection

A few studies were performed in selecting low GWP refrigerant for environmentally friendly heating system based on 30 kW design heating capacity air/water heat pump. The primary use of such system is to retrofit existing multi-family houses and commercial buildings with new sustainable system. The aims of the studies were to undergo the process of the most environmentally friendly refrigerant selection for a given application.

Four refrigerant candidates with GWP of not greater than 150 were considered. The GWP limit, together with other selection criteria (thermophysiscal properties, safety and etc.), has narrowed the refrigerant selection down to four refrigerant options: two hydrocarbons (R290, R1270) and two hydrofluorocarbons (R152a, R1234yf). The refrigerant R410A was taken into account in the analysis as a reference refrigerant.

Both R290 (propane) and R1270 (propene) are natural refrigerants. They are characterized with very good thermo-physical properties and low GWP. They are also of low cost and widely available on the market. R152a and R1234yf are synthetic refrigerants. R152a possess higher specific heating and cooling capacities, compared to that of R1234yf, and also has the highest value of GWP among all the preselected refrigerants. R1234yf is the most expensive refrigerant for the moment due to the limited supply. Compared to R1234yf, R152a is very similar with regard to volumetric cooling capacity and pressure levels, while cycle performance of R152a is more favorable. Pressure levels of preselected hydrocarbons are among the highest, but still below the reference values of R410A.

Life-cycle climate performance (LCCP) analysis has been selected as a method to quantify the amount of GHG emissions that occur due to the heat pump based heating system operation throughout their entire lifetime. This method is the most versatile method as it accounts for all direct and indirect emissions during the entire lifetime. The calculation can be performed according to the Equation 1.

$$LCCP = \text{total lifetime direct emissions} + \text{total lifetime indirect emissions} = (GWP \cdot L \cdot n) + (Ea \cdot \beta \cdot n) + I + D \quad (1)$$

where,

GWP – global warming potential of refrigerant;

L – annual leakage rate in the system, kg;

n – life of the system, years;

Ea – annual energy consumption, kWh·year^{-1};

β – carbon dioxide emission factor (kg CO_2-eq. emissions per kWh);

I – other indirect emissions (materials and refrigerant chemical consumption and transport, recycling), kg CO_2-eq.;

D – other direct emissions (manufacturing, transportation and end-of life leakage), kg CO_2-eq.

Direct emissions occurs regularly (due to refrigerant leaks from the heat pump) and irregularly (during servicing operations, refrigerant transportation, in case of accidents and etc.). The amount of direct emissions is expressed in amounts of CO_2-eq. emissions, which equals to the product of GWP value of chemical and its corresponding emitted mass. As indirect emissions originate from the energy production process, their amount is a function of total amount of energy consumed and CO_2-eq. emissions associated with producing of a unit of this energy.

The system performance has been modeled for every refrigerant in the analysis, and, coupled with other input parameters, a total LCCP value for a heat pump system has been calculated (Figure 4).

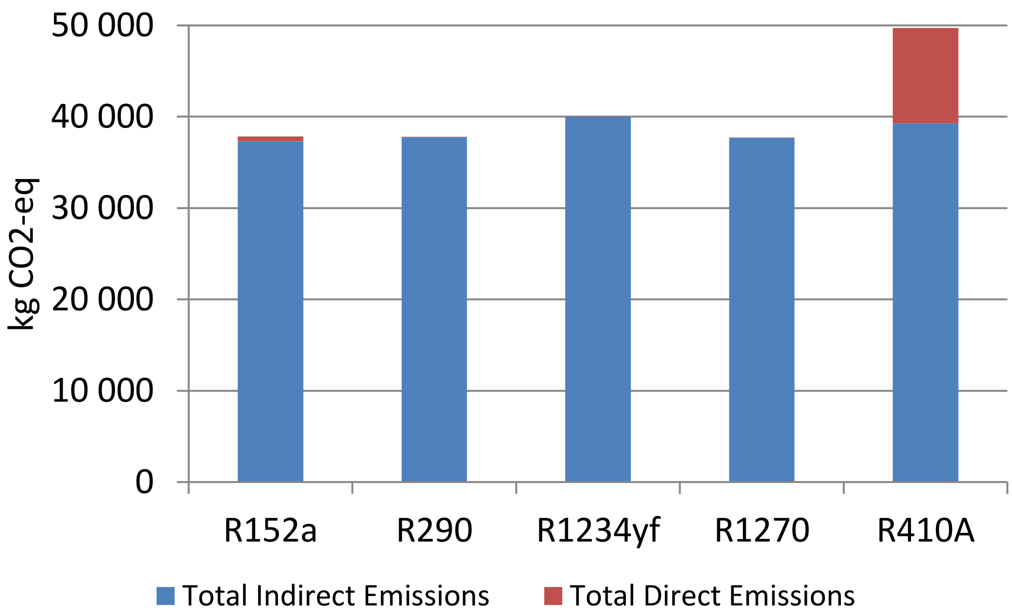

Figure 4 - Total lifetime CO_2-equivalent emissions associated with heat pump operation, all refrigerants

As it seen from the plot on the Figure 4, R152a has the lowest life cycle climate impact over the four compared low GWP refrigerants, whereas R1234yf – the highest. The indirect contribution of R410A refrigerant is close to the values of the other refrigerants, but due to its significantly higher GWP value, it has much worse LCCP.

Among the low GWP refrigerants, R1234yf has the highest lifetime emissions, whereas R152a, R290 and R1270 are almost equal, with hydrocarbons showing the best environmental performance. The difference between R290, R1270 and R152a is negligibly small and, from the environmental point of view, R290, R1270 and R152a could be considered as equally good. Thus, the selection of low GWP refrigerant for heat pump in the modelled system should be made considering other selection criteria, as it is reported in [22].

The analysis, presented above, implies a number of assumptions of the input data. For instance, carbon intensity of the electricity generated was assumed to be 165 g CO_2-eq./kWh, which is the mean value for the electricity distributed through the UCTE

European grid. Other assumptions include annual leakage rate of 3% of refrigerant charge, 4 litres refrigerant charge, 70% reclaim loss at the end of life of heat pump, 15 years lifetime.

This data, as for instance annual leakage rate or carbon intensity of consumed electricity generation, is difficult to get with high degree of accuracy. For this reason, a sensitivity of the modelled results was tested against the different quality of the input data. All the above-mentioned assumptions are combined under the baseline scenario in sensitivity analysis.

The function of LCCP analysis is to identify the refrigerant, which will lead to lowest lifetime CO_2-eq. emissions. One way to compare LCCP analysis results of different refrigerants is to compare the LCCP value of each refrigerant to the average of all four refrigerant candidates. A diagram on the Figure 5 presents the LCCP analysis results for the "Baseline" scenario, that implies the assumption values presented before [22].

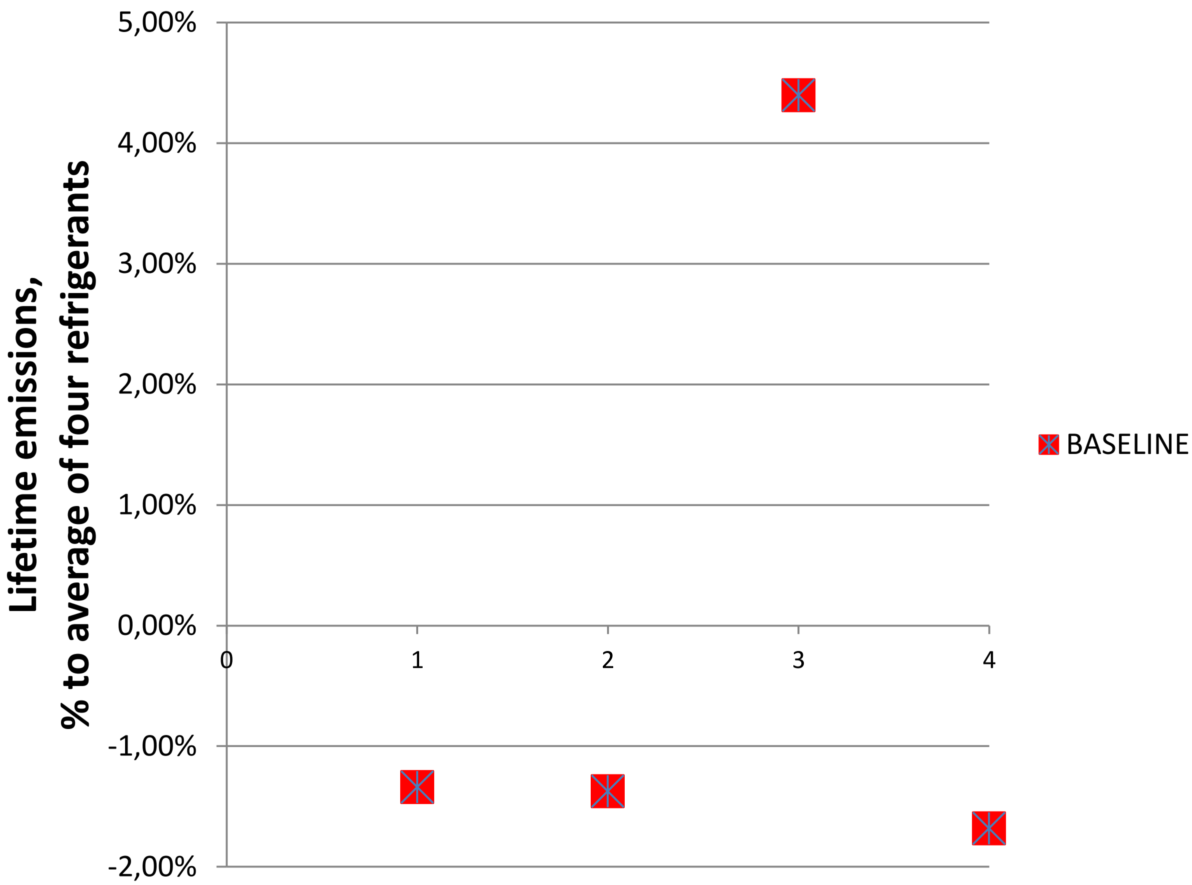

Figure 5 - "Baseline" scenario relative LCCP results (where 1 stands for R152a, 2 – R290, 3 – R1234yf, 4 – R1270)

Of our interest is to compare how the results are sensible to the made assumptions. For instance, annual leakage rate can be greater than 3% of refrigerant charge annually. Figure 6 compares LCCP results for “Baseline” scenario with “5% annual leakage” and “10% annual leakage” scenarios. The difference between both scenarios is in the annual leakage rate assumed: 3%, 5% and 10% respectively.

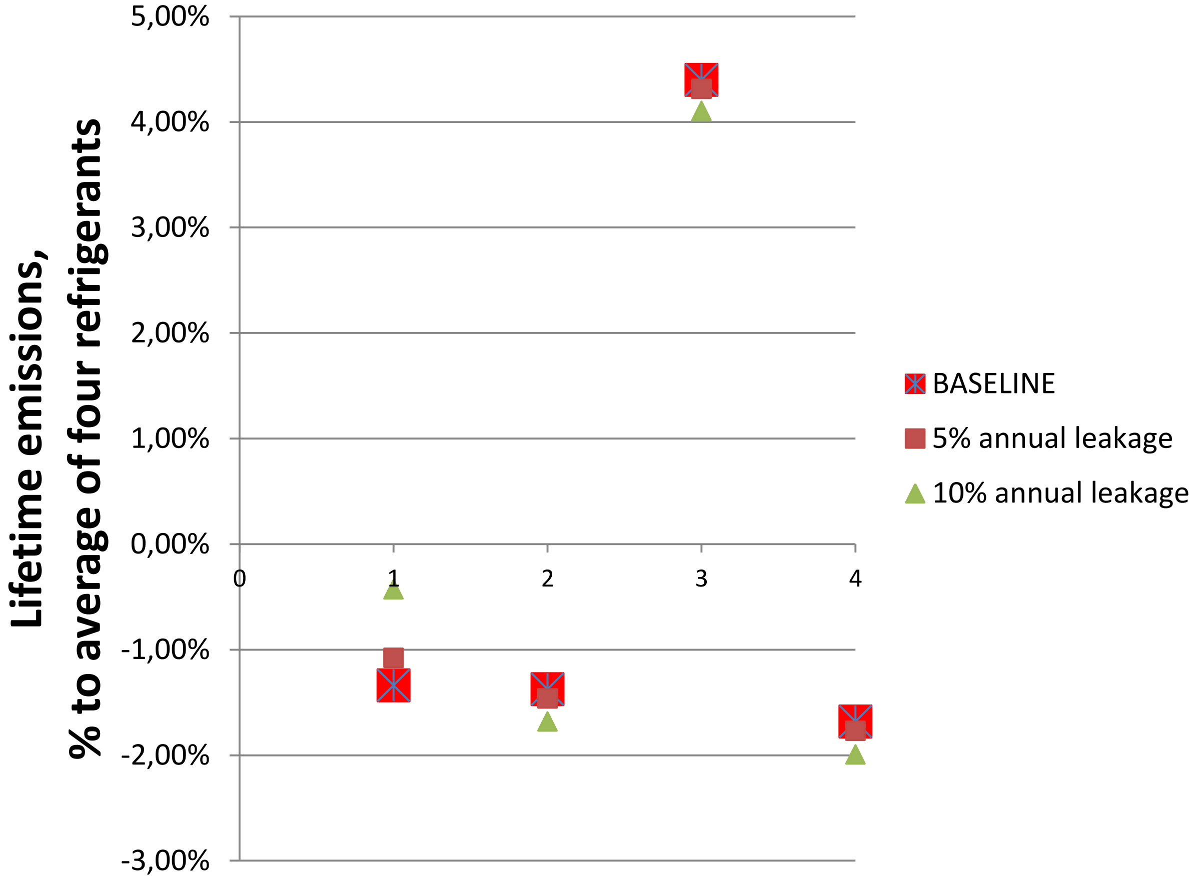

Figure 6 - “Baseline” scenario relative LCCP results compared to “5% annual leakage” and “10% annual leakage” scenarios (where 1 stands for R152a, 2 – R290, 3 – R1234yf, 4 – R1270)

Absolute values of LCCP results are much higher for “10% annual leakage” scenario, compared to “5% annual leakage” and “Baseline” scenarios. However, respective values do not affect the LCCP results in terms of ranging the refrigerants (see Figure 6), where R1234yf is still the refrigerant with highest lifetime emissions amount, and propane and propene showing lowest lifetime CO_2-eq. emissions.

A number of different scenarios were investigated in similar analysis. Carbon intensity of the consumed electricity generation and loss of the refrigerant at the end of life are shown to influence the LCCP results the most. Thus the quality of these data requires higher attention.

This data has been refined in another case study, where effect of climate conditions on life cycle climate performance have been studied [23]. The system performance of the above described system has been studied in three European locations that are listed in the standard EN 14825 [24]. These three locations are selected in order to represent main European climates with warmer (Athens, 3590 heating hours), average (Strasbourg, 4910 h) and colder climates (Helsinki, 6446 h).

For an air/water heat pump based heating system the temperatures of both evaporator and condenser have to adjust following the ambient temperature. Hence, the system performance is dependent on the ambient temperature. The modelled heating COP values at every potential ambient temperature are presented on the Figure 7. The amount of the hours the respective temperature occurs during the heating period, is presented on the Figure 7 as well.

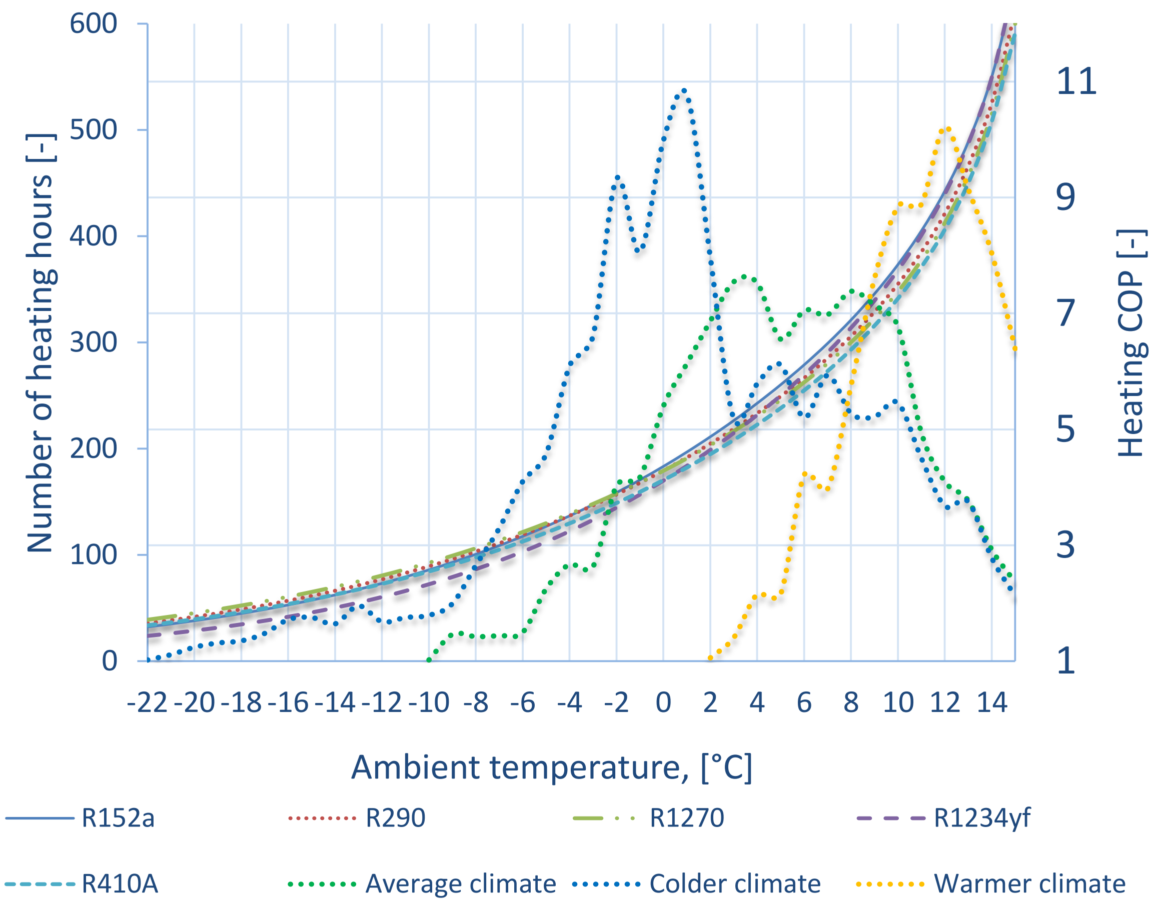

Figure 7 - Heating COP of a heat pump at different ambient conditions; number of heating hours that occur at colder, average and warmer European climates

While at low and at high ambient temperatures some refrigerants clearly outperform others, in the middle range of temperatures some refrigerants outperform others at a certain ambient temperatures. For example, R152a outperforms hydrocarbon at ambient temperature of around -3 °C and higher (Figure 8), while at temperatures below -3 °C both propane and propene have better COP than R152a. Thus, the total energy consumption of the system based on these refrigerants will be dependent on prevailing ambient temperatures during the heating season.

Given the above discussed assumptions, as presented in [22]. and refining carbon intensity of electricity supplied to heat pump to represent that of the ENTSO-E electricity grid (462.1 g CO_2-eq per kWh), the total lifecycle climate impact for each of the three above mentioned climates can be calculated (Figure 9, Figure 10 and Figure 11).

The results reveal that for low GWP refrigerants, indirect emissions are dominant in total lifetime emissions amount and thus system performance is of vital importance in order to minimize LCCP. Each of the analysed low GWP refrigerants has lower life cycle climate emissions, compared to the baseline refrigerant R410A. Among the low GWP refrigerants, the lifetime emissions value is for a large extent dependent on heat pump performance, which varies with ambient conditions for every refrigerant. However, the emissions decrease obtained by use of low GWP refrigerant is unproportional to their corresponding GWP value decrease.

Different refrigerants show different best lifetime environmental performance at various locations, thus this should be taken into consideration when attempting to extend a judgment of an environmental performance by LCCP or TEWI analysis at a single location for a locations where the climate conditions differ.

LCCP analysis is relevant for a given location and for a given system. Considering that the repetitive calculations can be required for every system at each location and with every potential refrigerant, there is a need for a simpler environmental metric that can facilitate the refrigerant selection process, but still deliver good level of system’s environmental impact estimation. For this reason comparative analysis of different environmental metrics has been made, as presented in [25]. The result of the analysis indicates that TEWI is the most appropriate environmental metric to use for a selection of an environmentally friendly low GWP refrigerant. TEWI is better than GWP as accounts for both direct and indirect emissions from the refrigeration system operation. It also has advantage in comparison to LCCP due to its lower amount of data input.

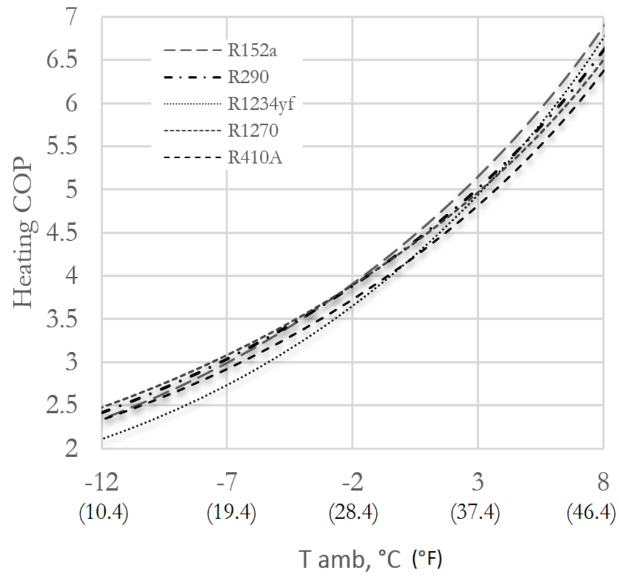

Figure 8 - Modeled heating COP of the heat pump over a range of ambient temperatures

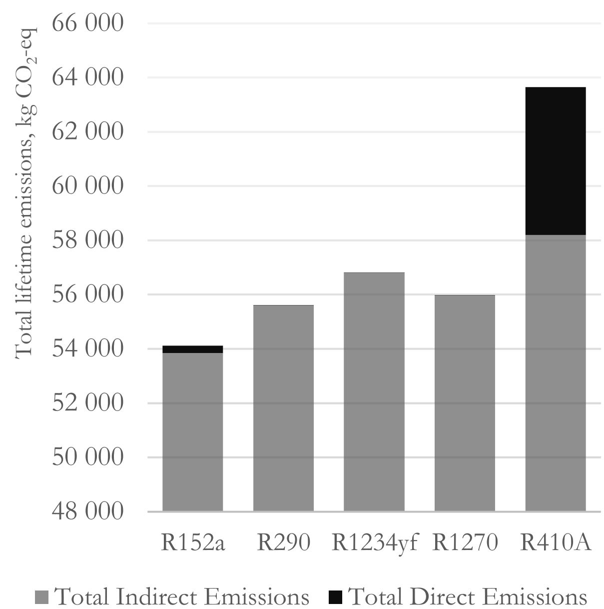

Figure 9 - Total lifetime CO_2-equivalent emissions associated with heat pump operation, warmer climate example (Athens)

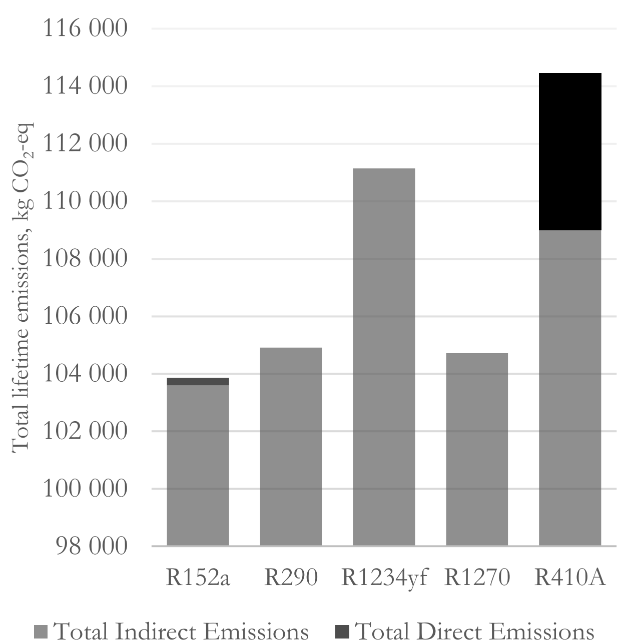

Figure 10 - Total lifetime CO_2-equivalent emissions associated with heat pump operation, average climate example (Strasbourg)

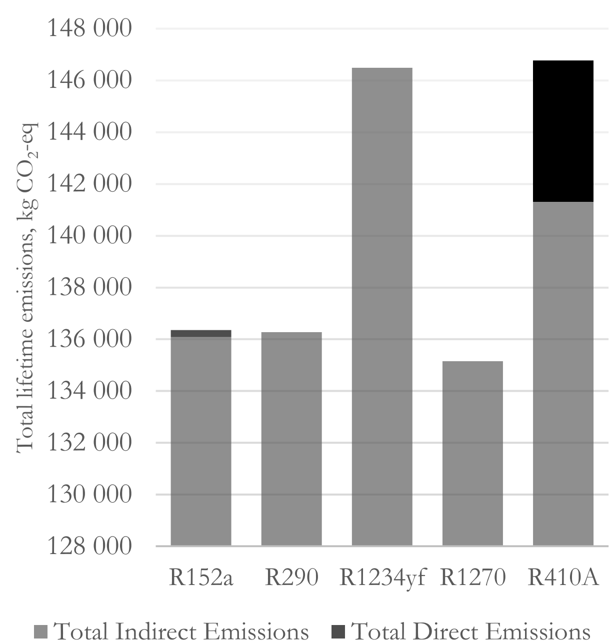

Figure 11 - Total lifetime CO_2-equivalent emissions associated with heat pump operation, colder climate example (Helsinki)

2.5 Goal fulfillment and major learnings

Potential alternative low GWP refrigerants have been mapped. A number of potential alternative low GWP refrigerants have been identified. That includes natural, synthetic refrigerants and their blends. For a number of the applications, the list of the alternatives is narrowed down to a couple of the low GWP refrigerants alternatives (mobile air conditioning systems, domestic refrigeration units). Whereas for other applications, the list of potential alternatives consists of tens of different refrigerants and their blends.

The conditions of HFC refrigerants phase out are dictated by a number of the regulations, including European F-gas Regulation [1] and MAC Directive [26]. For those refrigeration applications, where natural refrigerants cannot be applied due to technical or safety reasons, a number of HFO refrigerants or their blends with HFC substances are considered as potential replacements.

In order to boost the development of new sustainable refrigeration systems it is important to obtain sufficient knowledge of thermodynamic properties for their potential alternative refrigerants. A number of HFOs have their reliable equations of state already published. That allow a greater number of involved parties to participate in the thermodynamic cycle analysis of any refrigeration system of interest. For a number of new alternative refrigerants this data is still to be obtained.

Safety investigations are an important component in the process of identification of alternative low GWP refrigerants. Potential safety threats related to R1234yf use have been identified and are a subject of active discussions between product manufacturers and chemical producers. Flammability in general seems to be a safety aspect to handle for many future refrigeration applications as many new low GWP refrigerants are somewhat flammable.

Environmental safety is another important concern. Low GWP value of alternative refrigerants does not bring respectively low environmental impact from the refrigeration system operation, if compared to systems that use conventional high GWP refrigerants. The model has been built to evaluate total environmental effect originated from a refrigerant use by accounting for the entire amount of GHG emissions associated with the heat pump system operated with several low GWP refrigerants. It was shown, that indirect emissions – emissions of GHG originated from the electricity production used to drive the heat pump – are the greatest contributor to total lifetime GHG emissions. Thus, the selection of the most environmentally friendly low GWP refrigerant is, in many cases, the selection of the most efficient one and more accent on the system energy efficiency should be given in future developments.

The findings of the project were compiled in the internal report draft [27] and continuously disseminated towards the Swedish refrigeration and heat pump industry in timely manner. The topics covered, among others, include the review of potential refrigerant replacements for such applications as mobile air conditioning, heat pumps and other refrigeration needs; questions on stability and compatibility of refrigerant R1234yf; review of different environmental metrics and their use in selection of the most environmentally friendly refrigerant for a specific application; new opportunities of natural refrigerants as low GWP alternatives to HFCs; review of the legislation acts in the area and their effect on refrigeration industry in Sweden, European Union and globally; and other. The internal report draft is a constantly up-to-date document that summarizes all the findings in the field of new alternative low GWP refrigerants and is planned to be used as a source of information for further scientific and popular science publications.

A number of the objectives were, however, not met completely due to the dynamics of the new refrigerant development during the few preceding years. For instance, extensive experimental work results on heat transfer and pressure drop determination for a number low GWP refrigerant, that were close to commercialization, became publicly available during the timeframe of this project. Similar extensive data published on R1234yf stability and compatibility.

Meanwhile, new regulations require Swedish industries to take immediate decisions in terms of selection of refrigerant that will comply with the current requirements that will be in action in the future. Therefore, keeping in mind the main objectives of the project, some partial objectives, where extensive experimental work has been performed by other research groups, were replaced by available information compilation and knowledge dissemination.

3. Cost and energy efficiency of air-water heat pumps

There are two major drivers for technological changes in heat pump systems, namely end user requests and legislation. The end users of heat pump systems have during the recent years gained an increased awareness of global warming; combined with increasing energy prices this has brought their attention to energy efficiency. In the interest of reducing global warming in the European Union new legislation and standards are setting limits to the energy use of refrigeration systems and heat pumps. International agreements already led to regulations regarding the usage of fluorinated greenhouse gases which are expected to be augmented by further restrictions on allowed types and amounts of refrigerants. In this changing environment various technologies known to offer a potential for improving energy efficiency of vapor compression systems become interesting also for residential heat pumps. Some examples are variable speed compressor, special expansion solutions, advanced control algorithms, advanced cycle layouts and alternative refrigerants.

Any structured process of developing a new heat pump or a new heat pump component requires early on comparing many different competing options which must be evaluated regarding several, often opposing, objectives. Not every possible combination of technologies is equally adequate or feasible, nor equally costly or equally complex. Hence finding a 'good' heat pump design states a multi objective optimization problem. The 'best' design does not exist but only solutions which are optimal compromises, graphically represented in the pareto front. But not only is the amount of possibilities nearly infinite, also each change of a single aspect affects all other components in the system.

An overview over the relevant literature [28] shows that a gap exists between comparative studies and optimization studies. Comparative studies generally consider various cycle layouts and refrigerants but quantify a single objective only, typically the efficiency. Optimization studies, especially those considering multiple objectives, mostly assess only a singular detail of the problem, e.g. the design of a component. Filling this gap is obviously not straightforward, since the number of possibilities for refrigerant choice, system layout and component design forms a vast solution space.

Hence typically any attempt to improve the system efficiency requires the allocation of considerable research resources. Thus the costs of an improved system consist not only of the first costs of a more complicated system but also have to cover the investment in research. The risk is high that at the end of a research or development project the gained increase in efficiency is not in a reasonable ratio to the increased costs for the customers. Therefore the main question is: How can the effect of a new technology on system efficiency and cost be quantified and compared with alternative solutions, even though early on in a development project uncertainties both regarding technology details and costs are high, the solution space is vast, and interactions are strong?

3.1 Specific goals

The main goal of this part of the project is to establish an optimization methodology for systematically finding cost and energy optimal vapor compression system layouts from a large number of possible solutions. This screening method should be applicable in the early phase of a development project when the solution space is vast and little information is available about competing options. As a first step towards finding optimal system designs the screening method should safely allow deselecting inferior solutions.

To ensure that the methodology can be applied in various contexts by different groups, the computational effort as well as the effort form implication of the methodology should be as small as possible.

To allow cost and efficiency comparisons for the target application air-water heat pumps appropriate optimality criteria have to be developed. An overview of technical possibilities and challenges should be given. A selection of technologies which are either knew to the market or known from other vapor compression applications should be compared using the screening method.

3.2 Methodology

A methodology is developed which combines methods of simulation, data regression and optimization. Details can be found in various publications [29] [30] [31] [32]. To minimize simulation effort multiple decoupling approaches are employed. First, on the modeling level an object oriented approach is used: Individual components of the heat pump are described as submodels which can be combined to a heat pump cycle. This enables to reuse components for building various cycles and to quickly implement different component descriptions in multiple cycles by changes on the component level only. The exchangeability of submodels is depicted in Figure 12. The reusability of submodels is depicted in Figure 13.

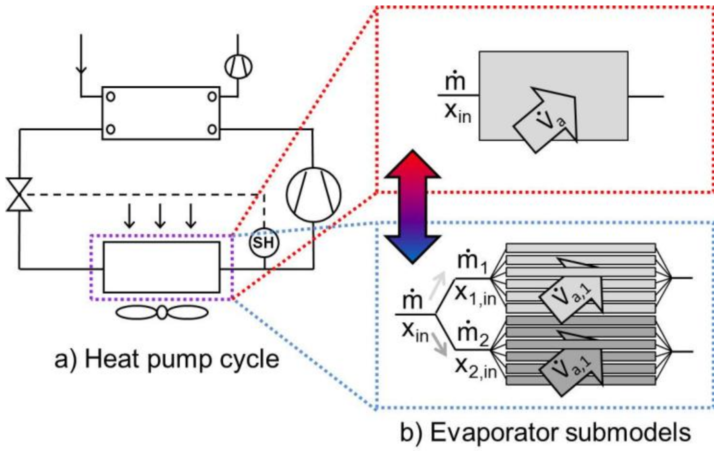

Figure 12 - Exchangeability of submodels.

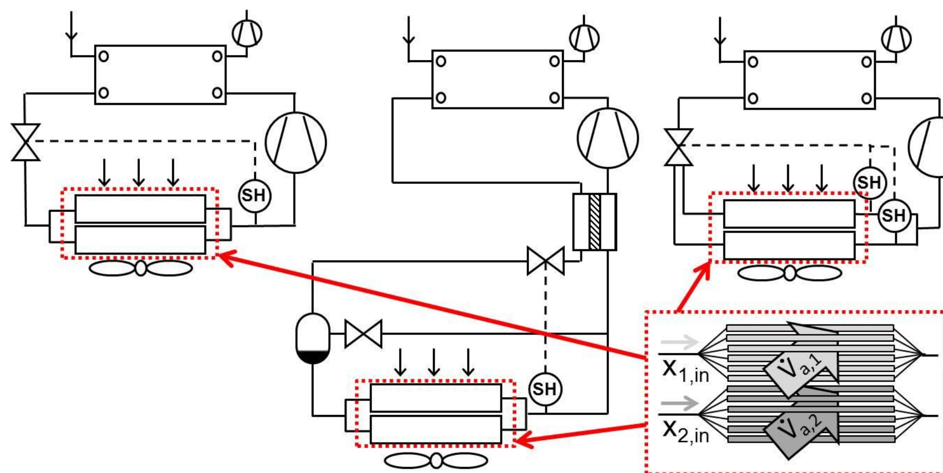

Figure 13 - Reusability of submodels.

Second, in the context of costs and efficiency evaluation the system performance has to be assessed over a long period of time, namely on an annual level. To reduce the number of simulations, the method described in the standard EN14825 [24] is applied. Heat pump performance is calculated for a small number of ambient conditions as graphically illustrated in Figure 14, annual system performance is calculated by summing up the results according to the occurrence of these conditions in different climate zones.

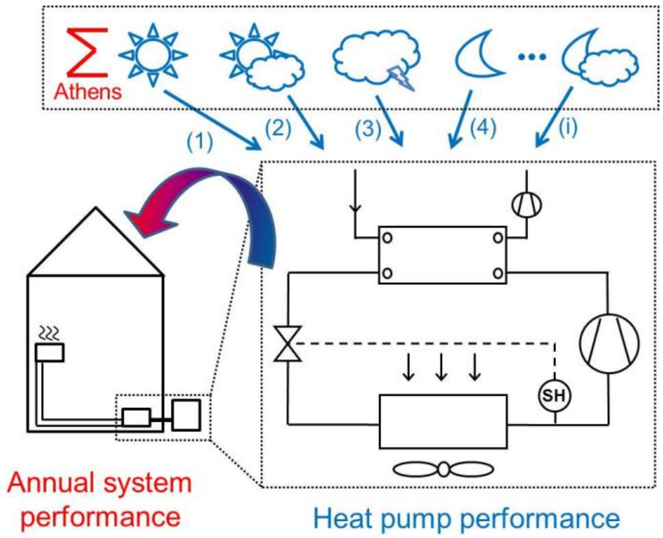

Figure 14 - Annual performance calculation based on combination of a limited number of operating condition simulations.

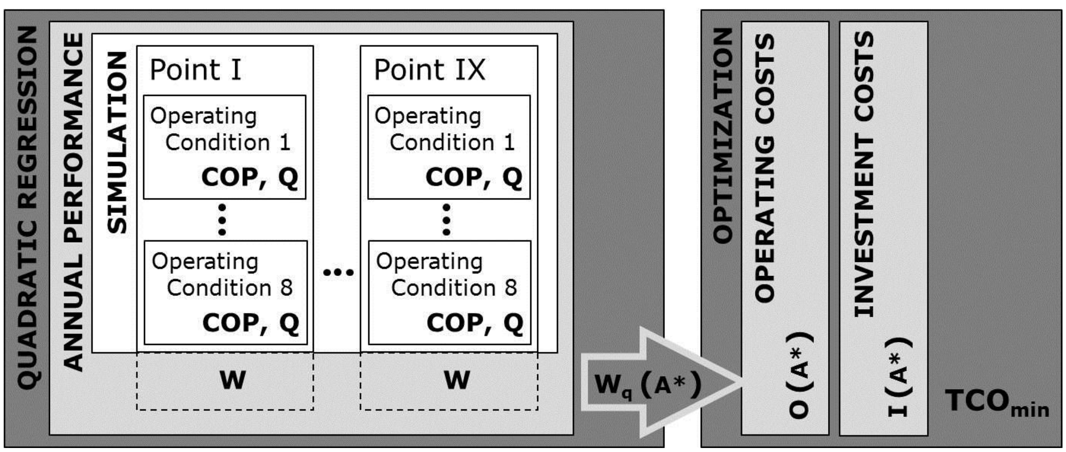

Figure 15 - Decoupling of simulation and optimization.

Third, price information is very volatile, varying with time, location, and with the business partners involved. To enable quick recalculations with new cost information, simulation and optimization parts are separated as shown in Figure 15. The rectangle on the left depicts the simulation part, consisting of simulations at several ”points” which are characterized by variation of component sizes, here exemplarily the heat exchange areas of evaporator and condenser A*. Simulations at each point are performed for varying operating conditions, annual performance is calculated. A quadratic regression is applied to create a function describing this performance for varying component sizes.

This function is combined with economic information like operating and investment costs before an optimization algorithm is applied. For air-water heat pumps an appropriate optimization criterion can be the minimum total cost of ownership (TCO_{min}) of a system seen from the perspective of the end customer, as shown in Fig. 4. Alternatively the perspective of the heat pump manufacturer can be chosen, then the goal is maximizing the seasonal coefficient of performance SCOP [24] while at the same time minimizing investment costs. The latter poses a multiobjective optimization problem, the result is a two-dimensional pareto front.

3.3 Exemplary applications

This methodology is applied in different contexts as presented in several publications which are listed below. A short summary of the content is given.

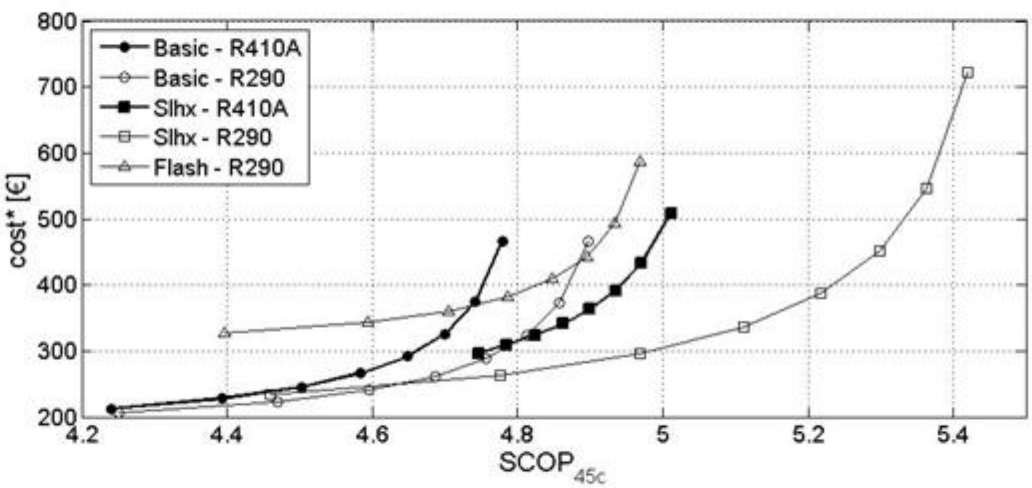

Figure 16 - Pareto fronts of optimal solutions for different cycle layouts and refrigerants.

In [29] the screening method is described and applied to evaluate in an energy efficiency/component cost space the potential of different cycle layouts and refrigerants. The method is applied to air/water heat pumps and exemplary results are presented comparing R410A and R290 in a basic cycle, a cycle with internal heat exchanger (Slhx) and a two stage cycle with flash tank (Flash) as shown in Figure 16. The method is supposed to be used as a screening method to compare competing solutions. As such it fulfills several main goals: Computation time is reduced so that a high number of cycle-refrigerant combinations can be simulated. Assumptions are made such that comparisons are as generic as possible without requiring detailed component information. The separation of component costs and system effects as well as the use of basic correlations for all objectives make the evaluation process transparent. The approach is applicable not only for heat pumps but also for other vapor compression applications.

Adjusting capacity to changing demand by variable speed control is known to offer efficiency improvement over classical on/off control. In [30] the economic viability of both control schemes is assessed with a total cost of ownership analysis for residential air-water heat pumps operating in different climate zones. Component sizes are optimized for both control methods individually. Results show optimal compressor displacement volumes to be smaller for variable speed than for on/off control. The optimal ratio of evaporator to condenser size is smaller for the variable speed system. Variable speed control is shown to be uneconomic for space heating in warmer climate while for average climate cost-effectiveness depends on the economic framework. For colder climate variable speed control is the more profitable choice in all considered cases; savings of up to 5000 EUR compared to on/off control can be achieved within 15 years of operation. The difference in total cost of ownership (TCO) between fixed (fs) and variable (vs) speed control in three different climate zones is depicted in Figure 17 for different economic assumptions.

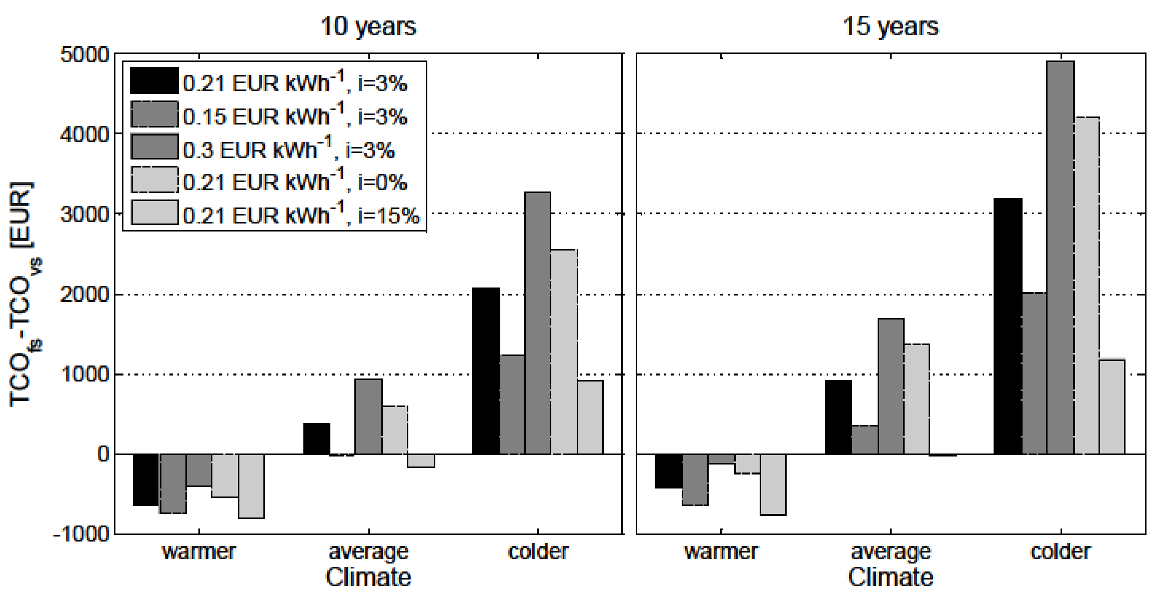

Figure 17 - Savings in total cost of ownership when switching from fixed to variable speed control.

[31] presents an approach to quantify the effect of evaporator maldistribution on operating costs of air-water heat pumps. In the proposed simulation model maldistribution is induced by two parameters describing refrigerant phase and air flow distribution. Annual operating costs are calculated based on heat pump performance at

distinct operating conditions. Results show that percentage increase of operating costs is similar for the three considered climate zones, even though the effect of maldistribution on heat pump performance varies with operating conditions. Differences in terms of absolute cost increase for the climate zones arise mainly due to a varying number of operating hours. Absolute cost increase is considerable in the average and especially colder climate zone and can only partly be reduced by enlarging the evaporator. Relative and absolute annual increase of operating costs induced by maldistribution on the air side (air side distribution parameter f_a) and the refrigerant side (phase distribution parameter f_x) of the evaporator are presented in Figure 18.

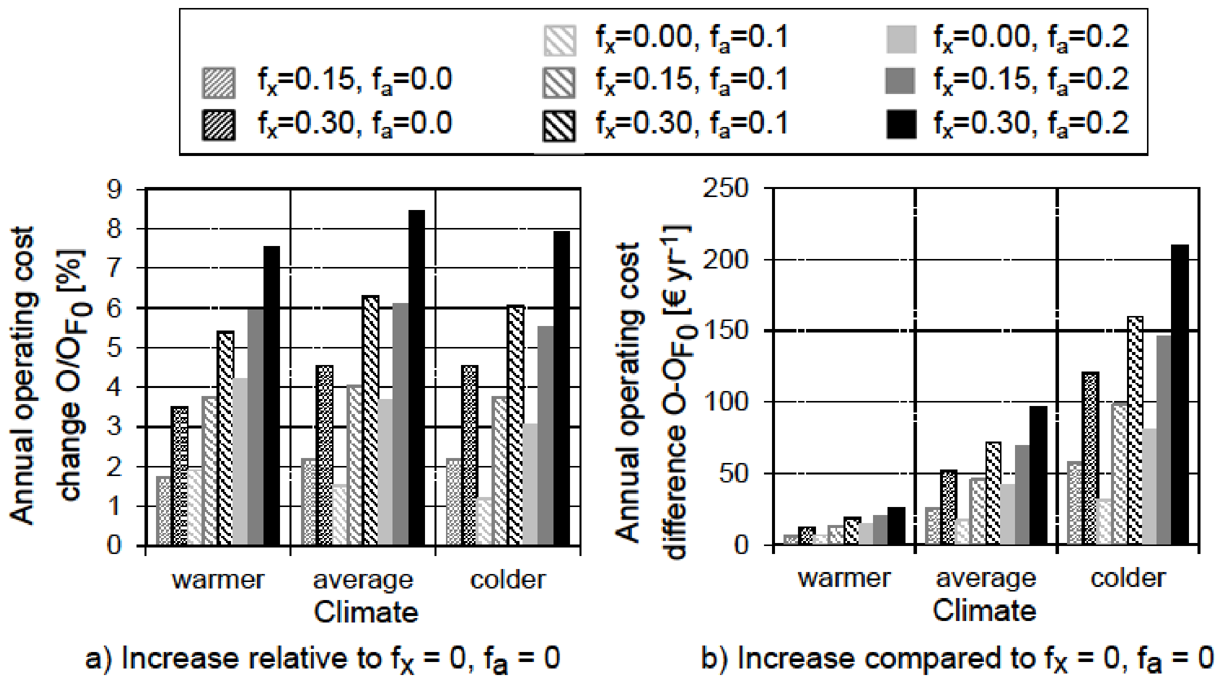

Figure 18 - Increase in annual operating conditions induced by maldistribution in the evaporator.

In [32] a methodology is applied to quantify the effect of evaporator maldistribution on operating costs of air-water heat pumps. The approach is used to investigate the cost-effectiveness of two technologies enabling to counteract maldistribution: a flash gas bypass setup and the individual superheat control in parallel evaporator channels. In the total cost of ownership analysis, different scenarios for climatic conditions, severity of maldistribution, and economic framework are considered. Results show that the flash gas bypass system is cost-effective only in a few conditions, namely severe maldistribution, high electricity prices, and colder climate. Investment in the individual superheat control technology, however, can be quickly amortized in many scenarios. For the warmer climate zone with a small number of operating hours counteracting of maldistribution does not pay off under the used economic assumptions. Savings realized with the individual superheat control within 10 years of operation are presented in Figure 19 for two maldistribution scenarios.

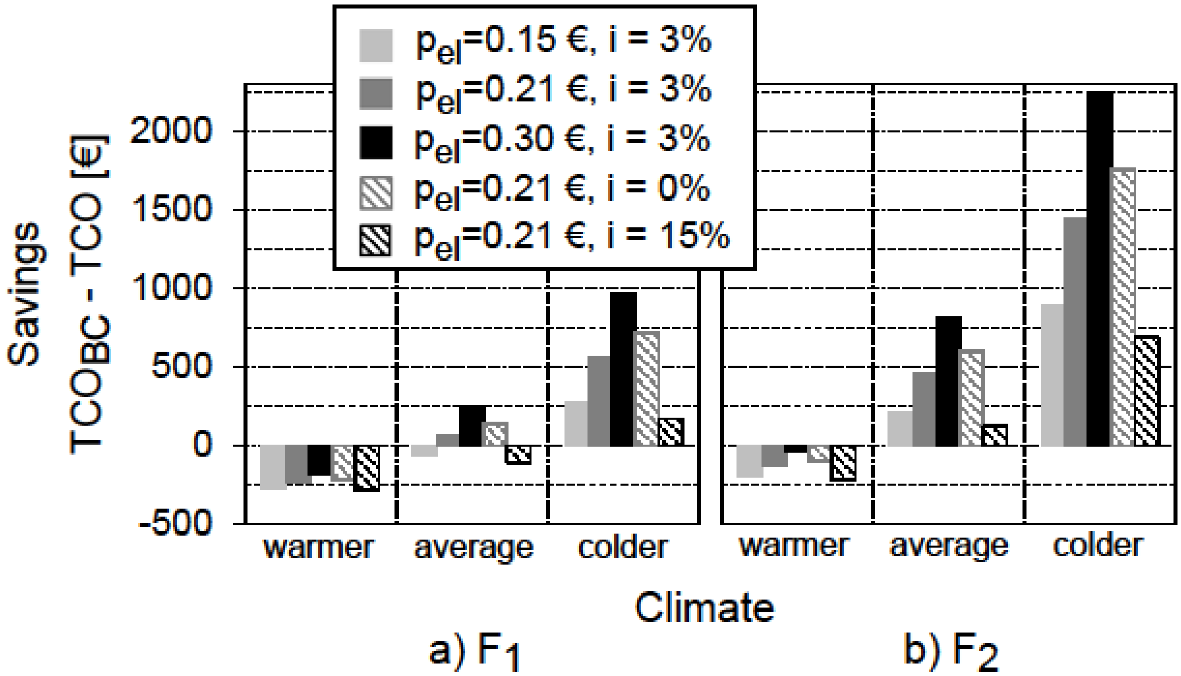

Figure 19 - Savings gained by switching to a new technology to counteract maldistribution after 10 years of operation for two maldistribution scenarios.

3.4 Goal fulfillment and major learnings

A detailed knowledge and understanding of the focus application residential air-water heat pumps has been developed in the early stage of the project. As major challenge the control of the system under strongly varying operating conditions throughout a year has been identified. As this field currently offers the highest potential for improvement the application focus of the project shifted from low charge components towards capacity and superheat control. Additionally too few experimental data of low charge heat pumps were available to establish reliable models of low charge components and their impact on system behavior. Therefore this topic has been assessed to be less apt to develop a methodology for finding cost and energy optimal system layouts.

A methodology has been developed that combines system simulation, performance calculation and cost-efficiency optimization. As the simulation part is the most time consuming step, it is largely decoupled from performance calculations and optimization.

This allows for a given technology to reduce the simulation effort to a small number of simulations for varying operating conditions. Based on these simulations system performance can be calculated for different climate zones. In a final step performance functions are combined with economic information to allow optimization. In the optimization step either the viewpoint of the heat pump manufacturer or the end consumer can be taken, the objective function differs for both cases.

The methodology has been tested in different contexts: Comparisons of refrigerant and cycle setup, comparisons of capacity control schemes and comparisons of different technologies tackling a problem on the component level. In all cases it has been proven possible to quantify costs and efficiency with relatively simple simulation models and a smaller number of simulations compared to classical optimization approaches.

However it became obvious that a further decoupling of system layout, refrigerant and component effects is not possible. All effects are in the same size of order regarding both changes in system efficiency and investment costs. Comparing technologies at wrongly chosen component sizes can largely under- or overestimate the improvement potential of a technology.

To account for the sizes of the main components which dominate both system performance and investment costs, namely the heat exchangers and compressor, a regression method has been implemented. This method allows describing system performance as continuous quadratic function of component sizes. Using statistical methods, namely the design of experiments theory, only a limited number of simulations with varying component sizes are required for regression of a quadratic function. Using this function, technologies can be compared at individually optimized component sizes to reveal a realistic performance improvement potential.

With this methodology it is possible to reduce the simulation effort for comparing a large number of possible solutions while taking into account important component effects. Therefore the approach can be used in an R&D department to evaluate and compare the potential of new technologies for a given application during an early development stage.

4. Knowledge dissemination

Knowledge dissemination has been set to be one of the main objectives of the project. News reports on developments in refrigerant front were regularly presented in an accessible way in the industry media. Great emphasis was given on designing information so that it communicates the news to the industry timely in an accurate, easily understandable and neutral manner.

Knowledge dissemination has been directed to reach versatile audience that is involved in refrigeration industry. It aimed to reach many different categories of specialists, including installers, service technicians, sales persons, politicians and governmental agencies representatives, consultants, researchers, industry representatives, etc.

Several information dissemination channels has been used to disseminate the knowledge gained from the project. Publications in scientific journals and conference presentations reach generally scientific community [30] [29] [31] [32] [33] [22] [23] [25] [34] [35].

General audience, including multidisciplinary research representatives, that involved in the field of refrigeration and heat pump technology, has been constantly updated with the latest findings through different means of communication, that include:

- Active participation and presentation on the relevant events, poster presentations [36] [37] [38] [39]
- Other publications, including the publications in popular science [40] [41] [42]
- Regularly updated news section on the project web page at the KTH web site [43]
- Regular publications in the Kyla+ industry: [20], [44], [45], [46], [47], [48], [49], [50], [21], [51], [52], [53], [54], [55], [56].

The knowledge dissemination has thus reached various specialists and is beneficial to the industry as a whole.

5. Future research

Study on alternative low GWP refrigerants has been a part of current project. During the last few years a number of events have occurred that dictate the further developments in this area, as for instance the new European Union’s Regulation on fluorinated greenhouse gases [1]. The Regulation is facilitating the HFC refrigerants phase out by introducing ambitious phase out schedule for a great share of currently used HFC gases. By this, the refrigeration industry has been given a clear signal towards the further developments, and many involved parties will need to adapt to the requirements of the Regulation.

At the same time, many potential low GWP substances that have been under development during the last few years are very close to the commercialization. For instance, R1234yf is already used in the mobile air conditioning systems in all new car models, first chillers based on R1234ze(E) refrigerant are already in operation. Few promising refrigerants, including R1234ze(Z) and R1336mzz, are developed for high temperature applications and can find their use in residential and industrial heat pump applications.

From the other side, GWP is not a perfect environmental metric to account for the total environmental effect of a refrigeration system. Other environmental metrics can be used to better represent these effects, but the calculation methodology should be further developed and standardized in order to facilitate similar calculations for a wide number of industry representatives.

A methodology was developed for systematically finding cost and energy optimal vapor compression system layouts from a large number of possible solutions. While the sensitivity of results towards economic parameters can be quickly quantified by repeating the last step of the methodology, testing the sensitivity towards model parameters and correlations requires repetition of the first, most time consuming step of simulation. It should be studied whether the repetition of the complete procedure is required or whether sensitivity can be reasonably quantified based on simulations of the previously optimized component sizes. In the latter case the effort for a thorough sensitivity study would be largely reduced.

The studies published so far neglect one major aspect of air-water heat pump performance: the frosting and defrosting of the evaporator under certain operating conditions. The improvement potential of several of the considered technologies can be expected to be bigger than calculated for dry air. A future study should try to consider and quantify this aspect.

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