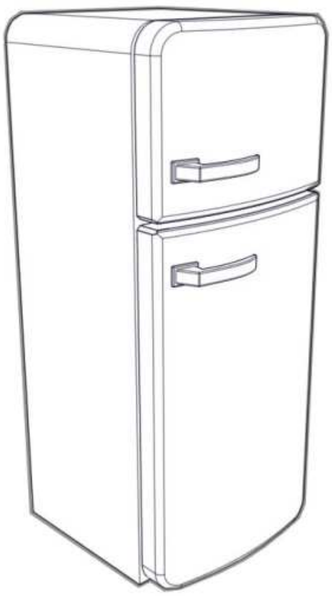
European Commission

Technology Roadmap in preparatory/review study on

Commission Regulation (EC) No. 643/2009 with regard to **ecodesign requirements for household refrigeration appliances**

and

Commission Delegated Regulation (EU) No. 1060/2010 with regard to **energy labelling of household refrigeration appliances**



FINAL ROADMAP REPORT

Prepared by

VHK and ARMINES
in collaboration with Viegand & Maagøe and Wuppertal Institute
contract co-ordination VITO

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Energy

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Acronyms, units and symbols

Acronyms

a	year (annum)
***(*)	3/4 star freezer. Stars relate to Tc (-6, -12, -18 °C= *, **, ****) and for a 3-star with specific freezing capacity 4 star ***(*)
A+, A++, A+++	current energy label class denominations
AC/DC	Alternating/Direct Current
AHAM	US Association of Home Appliance Manufacturers
ANSI	American National Standards Institute
AP	Acidification, kt SO2 equivalent
ARMINES	Mines ParisTech, Energy and Process Department, FR (author)
ASHRAE	American Society of Heating, Refrigerating and Air-Conditioning Engineers
avg.	average
BAT	Best Available Technology
BAU, BaU	Business-as-Usual (baseline without measures)
BC	Base case (average for a category)
BEP	Break-Even Point (not to confuse with bep, best efficiency point, in reports and regulations for other Ecodesign products)
BI	Built-In
BNAT	Best Not Yet Available Technology
BOM	Bill-of-Materials
Cat.	category
CECED	European Committee of Domestic Equipment Manufacturers
CECOMAF	Eurovent Certification scheme
CFC-12	dichlorodifluoromethane (Freon-12, refrigerant with high ODP, now banned)
CIRCA	Communication and Information Resource Centre
CLC, Cenelec	European Committee for Electro-technical Standardization
COP	Coefficient of Performance
C_5H_{10}	cyclopentane, blowing agent for PUR foam
DG	Directorate-General (of the EC)
DoC	Document of Conformity
DoE	US Department of Energy
EC	European Commission
EEI	Energy Efficiency Index
EIA	Ecodesign Impact Accounting (Study for the EC, 2014)
EN	European Norm
EoL	End-of-Life
EU	European Union
FAO	Food and Agricultural Organisation (of the United Nations, UN)
FF	Frost-Free
GHG	Greenhouse Gases
GWP	Global Warming Potential, in Mt CO_2 equivalent
haz.	hazardous
HM	Heavy Metals
ICSMS	Information and Communication System on Market Surveillance

IEC	International Electro-technical Committee
ISO	International Standardisation Organisation
JIS	Japanese Industrial Standard
JRC	Joint Research Centre (of the EC)
LBP	Low Back Pressure
LCC	Life Cycle Costs, in euros
LLCC	(design option with) Least Life Cycle Costs
MEErP	Methodology for Ecodesign of Energy-related products
MEPS	Minimum Efficiency Performance Standard
msp	manufacturer selling price
NF, FF	No Frost, Frost-Free, auto-defrost, not 'static'
NGO	non-governmental organization
ODP	Ozone Depletion Potential
PAH	Polycyclic Aromatic Hydrocarbons
PM	Particulate Matter (fine dust)
POP	Persistent Organic Pollutants
PS	polystyrene (inner-liner, packaging)
PUR	poly-urethane (foam)
PWF	Present Worth Factor
R/RF/W/Fu/Fc	Category denomination proposed by CECED: Refrigerator, Refrigerator Freezer, Wine storage, Freezer upright, Freezer chest. With suffix 'b' it relates to built-in appliances.
R600a	iso-butane (no ODP, very low GWP refrigerant)
RAPEX	EU Rapid Alert System
Re/genT	Refrigeration expert, NL (consultant for CECED)
REACH	Registration, Evaluation, Authorisation and Restriction of Chemicals (Regulation)
RoHS	Restriction of Hazardous Substances (directive)
SME	Small and Medium-sized Enterprise
SPB	Simple Payback period, in years
TC	Technical Committee (in ISO, CEN, etc.)
TR	Technical Report
TRA	Technology Readiness Assessment
TRL	Technology Readiness Level
VAT	Value Added Tax
VHK	Van Holsteijn en Kemna, NL (author)
VIP	Vacuum Insulation Panel
VITO	Vlaams Instituut voor Technologisch Onderzoek, BE (contract-manager)
VM	Viegand Maagøe, DK (review)
VOC	Volatile Organic Compounds
WEEE	Waste of electrical and electronic equipment (directive)
WG	Working Group (of a TC)
WI	Wuppertal Institute, DE (review)
yr	year

Units

P-,T-,G-, M-,k-, d-, c-, m-, μ-, n-	Peta-, Tera-, Giga-, Mega-, kilo-, deci-, centi-, milli-, micro-, nano- : parameter prefixes to indicate 10^15, 10^12, 10^9, 10^6, 10^3, 10^-1, 10^-2, 10^-3, 10^-6
CO2, CO_2	Carbon dioxide (reference for GWP)
J	Joule, SI-unit of energy
g	gramme, SI-unit of weight
h	hour, unit of time (3600 s)
Hg	Mercury equivalent (reference for HM emissions to water)
i-Teq	reference for emissions of POP
K	(degree) Kelvin
kW	kilo Watt, 10^3 W
L, ltr	litres (volume in m³)
m	meter, SI-unit of length
m^2	square meter, unit of surface
m^3	meter cube, unit of volume
Mt	MegaTonne (10^6 metric tonnes, 10^9 kg)
Ni	Nickel (reference for emissions of HM to air and PAHs)
PO4, PO_4	Phosphate (reference for Eutrophication)
s	second, SI-unit of time
t	metric tonne
TWh	Tera Watt hour 10^{12} Wh
W	Watt, SI-unit of power (1 W= 1 J/s)
Wh	Watt-hour, unit of energy (1 Wh=3600 J)

Symbol	**Parameter**
A	'Auto-defrost' compensation factor
A	Refrigerator envelope surface (m²), usually with suffix
a	Air passage height below unit (m)
A_{cd}	Condenser area (m²)
AE, AEC, E	Annual Energy consumption, in kwh/a
B	Built-in compensation factor
b	Height & depth compressor area (m)
c	Suffix for compartment-specific parameters
C	Combi-factor
COP	COP value with actual Tev and Tcd
COP_{cyc}	Avg. Cop actual tev and tcd & cycling loss
COP_{nom}	Nominal compressor COP at -23.3/54.4 °C, sub-cooling 32.2 °C
Cycling loss	Part load losses (in % COP)
D	Multidoor compensation factor
d	Depth (m)
E_{16}	Daily energy consumption, in kwh/d, at 16 °C ambient test
E_{32}	Daily energy consumption, in kwh/d, at 32 °C ambient test

E_{aux}	Electricity CPU and possible fan (kwhel/a)
E_{daily}	Daily (24h) energy consumption E_{daily}, in Wh
$E_{loss\ tot}$	Annual heat energy loss (kwh_{th}/a)
eq	Suffix, means 'equivalent' for compartment
$F,\ f$	Regional weighting factor between E_{16} and E_{32}, implicitly determines average ambient temperature
h	Height (m)
k	Heat conductivity (W/mk)
k	Heat conductivity, in W/mk
L_{dr}	Length of door perimeter
$Load\ factor$	Ratio of heat load to cool power
M, N	Correction parameters for equivalent volume
P	Power, in W
Pc	Cool power (W)
P_{door}	Door heat loss $L_{dr}*U_{door}$ (W)
P_{loss_tot}	Total heat power loss $P_{trans} + P_{door}$ (W)
P_{nom}	Nominal compressor cooling power (W)
P_{trans}	Transmission heat loss (W)
q	Specific electricity consumption, in kwh/litre net volume
R^2	R-square, measure for confidence level of a regression
r_c	Compartment temperature correction (for Veq)
$SAE, SAEC$	Standard Energy consumption, in kwh/a
T	Temperature
t	Parameter: wall thickness ; unit: metric tonne (1000 kg)
t	Average wall thickness (m)
T_a	Ambient temperature (°C)
T_a	Ambient temperature (during tests)
T_c	Compartment temperature (°C)
T_{cd}	Condenser temperature (°C)
T_{cold}	Evaporator temperature inside the compartment (°C)
T_{ev}	Evaporator temperature (°C)
T_{ref}, T_c	Reference or 'design' air temperature of the compartment
U_{door}	Heat transfer coefficient door gasket (W/mk)
U_{wall}	Heat transfer coefficient wall (W/m²K)
V	Volume
V	Refrigerated volume (m³ or litre)
Veq	Equivalent volume
$Vgros$	Gross inner volume, including technical spaces e.g. For evaporator, lighting, etc.
$Vnet$	Net inner volume, excluding technical spaces e.g. For evaporator, lighting, etc.

w	Width (m)
ΔE_{df}	Defrost and recovery energy, in Wh
$\Delta E_{processing}$	Load processing energy (not used in the EU)
ΔT_{cd}	Condenser temperature difference K
ΔT_{cold} , ΔT_{ev}	Temperature difference between the evaporator and the average air in the compartment
Δt_{df}	Defrost frequency/interval, in h, rounded to the 1st decimal
ΔT_{ev}	Evaporator temperature difference (K) [r/f]
ΔT_{hot} , ΔT_{cd}	Temperature difference between the ambient air temperature and the condenser
η	Efficiency

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Executive summary

This is the final report of the technological roadmap requested by the European Commission in the frame of the preparatory review study of the existing Ecodesign and Energy Label regulations for household refrigeration appliances. The study started in January 2015 and ended in January 2016 (final report, 1st version).

This roadmap intends to give a technology overview of the past, current, best available and non-available technologies in order to allow the Commission to develop a strategy on future effective support under the European research framework program and to foster the development and production of energy efficient technologies within the European Union.

Best available technologies have been identified in the preparatory review study report. Altogether, the application of these technologies to present average products could enable to reach savings ranging from 45 % for freezers up to 70 % for wine coolers. The most important ones are larger insulation thickness (up to 100 mm), the integration of vacuum insulated panels in appliance walls and doors, high efficiency compressors and the use of variable speed drive compressors. Although no development could be identified, the development of more efficient small compressors, below 85 W cooling capacity could have a strong impact on the energy efficiency of refrigerators and refrigerator-freezers.

Best non available technologies have been screened. For each one, the following points are presented: the description of the technology, recent researches and development activities, the Technology Readiness Level, a conclusion on recommended R&D activities.

Regarding insulation technologies, with VIP readily available to the manufacturers, only little energy efficiency gains can be hoped. Still, VIP cannot cover more than 45 to 65 % of the refrigerator cabinet surface and aerogel panels which have 20 % lower thermal conductivity that cyclopentane PU foams could help increase best products efficiency by 10 % maximum, not before 2020 (TRL 5 estimated), if costs remain competitive.

There is a number of vapor compression refrigeration cycle improvement which could occur for combined refrigerator-freezer appliances. However, existing concepts should be proved on representative appliances in representative conditions (new standard for instance). Gains in the order of 10 to 20 % could be feasible, probably not before 2020 however.

Most promising solid state refrigeration technologies appear to be magnetic refrigeration (TRL 3-4) and thermo-elastic refrigeration (TRL 2):

- magnetic refrigeration could help decreasing the energy consumption by at least 15 %. However, its potential development still depends on rare earth metals, which are costly. More optimistic plan this technology to reach the market soon after 2020.
- thermo-elastic refrigeration could lead to even more energy efficient appliance, with close to 25 % gain, while it uses low cost materials. Material reliability for a large number of cycles could lead to reliability issues however. This technology most likely should not be available before 2025-2030 however.

1 Goals

This refrigeration and freezer technological roadmap is part of Ecodesign and Energy Label review on household refrigeration in the European Union.

Building a Technology Roadmap for household refrigeration appliances consists in describing best available and not yet available technologies as well as trends in usage and markets for a time scope. To give a technology overview of the past, current, best available and non-available technologies should allow the Commission to develop a strategy on future effective support under the European research framework program and to foster the development and production of energy efficient technologies within the European Union.

The first part of the Technology Roadmap consists in showing previous technological innovations and current product technologies including products with standard improvement options. Then, the Best Available Technologies (BAT) are analyzed and an outlook of the Best Non Available Technologies (BNAT) is done. Among them, possible technical innovations which could significantly improve energy efficiency are identified and performance and approximate cost relative to today’s baseline equipment is evaluated when feasible.

Thus, this Technology Roadmap includes a basic estimation of the potential of future technologies, including energy efficiency improvements, as well as an indication of potential hindrances to a successful market entry such as research gaps or missing production facilities.

2 TRL methodology and report organisation

The evaluation of technology is now commonly done using the Technology Readiness Levels by both governments / public agencies and private actors. This codified system helps qualifying technology life stage from the idea / concept to the market application and thus main research and development actors to manage technology development, using a common language.

For this report, the H2020 EU research program TRL definitions are used[1]. The definitions are given below:

TRL 1 – basic principles observed

TRL 2 – technology concept formulated

TRL 3 – experimental proof of concept

TRL 4 – technology validated in lab

TRL 5 – technology validated in relevant environment (industrially relevant environment in the case of key enabling technologies)

TRL 6 – technology demonstrated in relevant environment (industrially relevant environment in the case of key enabling technologies)

TRL 7 – system prototype demonstration in operational environment

TRL 8 – system complete and qualified

TRL 9 – actual system proven in operational environment (competitive manufacturing in the case of key enabling technologies; or in space)

The report is organized as follows:
- Presentation of product archetype (Ch 3),
- Discussion of present to BAT technologies (Ch 4),
- Screening of BNAT technologies (Ch 5).

For Best Non Available Technologies, the following points are presented:
- the description of the technology,
- recent researches and development activities,
- the Technology Readiness Level (Appendix A),
- a conclusion on recommended R&D activities.

[1] HORIZON 2020 – WORK PROGRAMME 2014 - 2015, General Annexes, Extract from Part 19, Commission Decision C(2014)4995. G. Technology readiness levels (TRL)

3 Present product archetype

3.1 General working principle

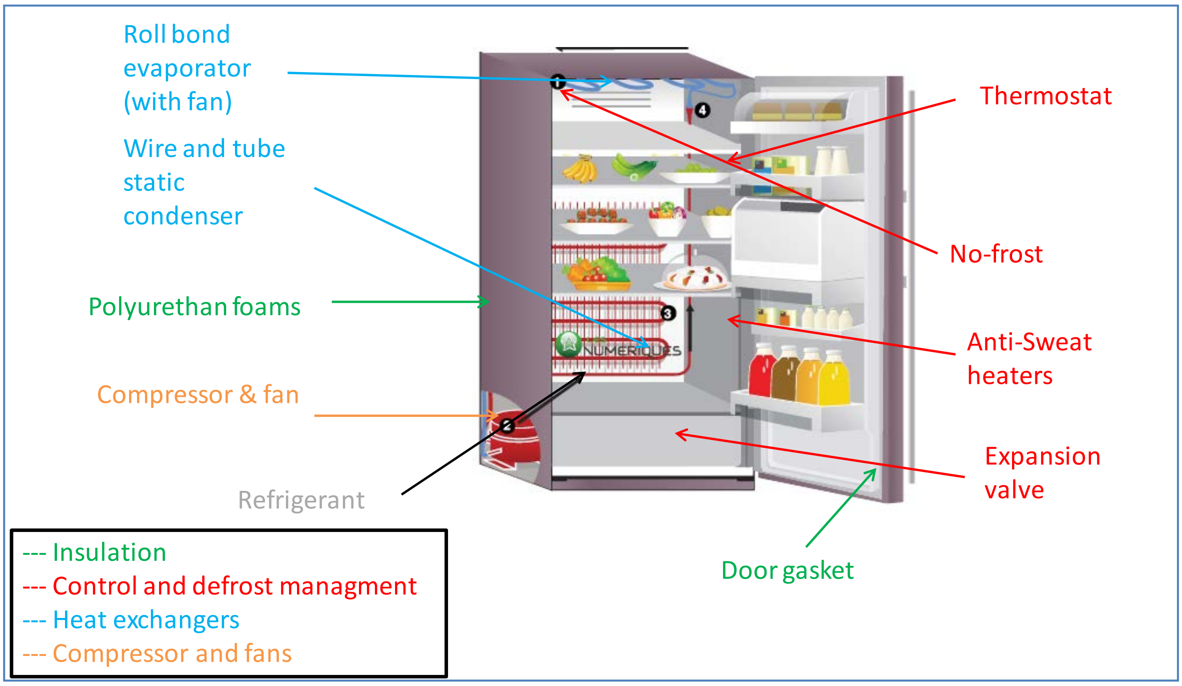


Figure 1 - Main components of domestic refrigeration appliances

Domestic refrigeration appliances, refrigerators, freezers and combination refrigerator/freezer, are used to store food at cold temperatures. A refrigeration system is used to maintain temperatures inside the appliances within acceptable temperature ranges.

Most products use a mechanical compression vapour cycle with an electrical compressor. The components of such a cycle are shown in Figure 2 and the refrigeration process is as follows:

- A cold refrigerant fluid, at low temperature and pressure evaporates in the evaporator, capturing the heat to be removed from the appliance indoor volume to maintain the cold temperature.
- The vapour refrigerant leaving the evaporator is sucked by the electrical compressor; it is compressed at high pressure and temperature.
- The high temperature and pressure refrigerant is cooled down and condensed to a high pressure liquid state in the condenser.
- The refrigerant then enters the expansion valve (a tube of small diameter which infers a pressure loss to the fluid). The refrigerant fluid leaves the expansion valve at low pressure and in biphasic state (partly liquid and vapour).
- The refrigerant finally flows back to the evaporator.

Hence, thanks to the electric input of the compressor, the refrigerant flows through the refrigeration circuit, capturing the heat of the indoor volume and rejecting it to the kitchen / room air.

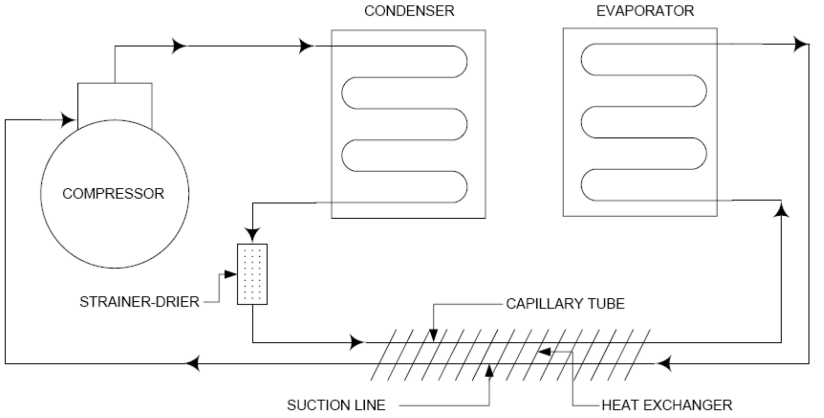
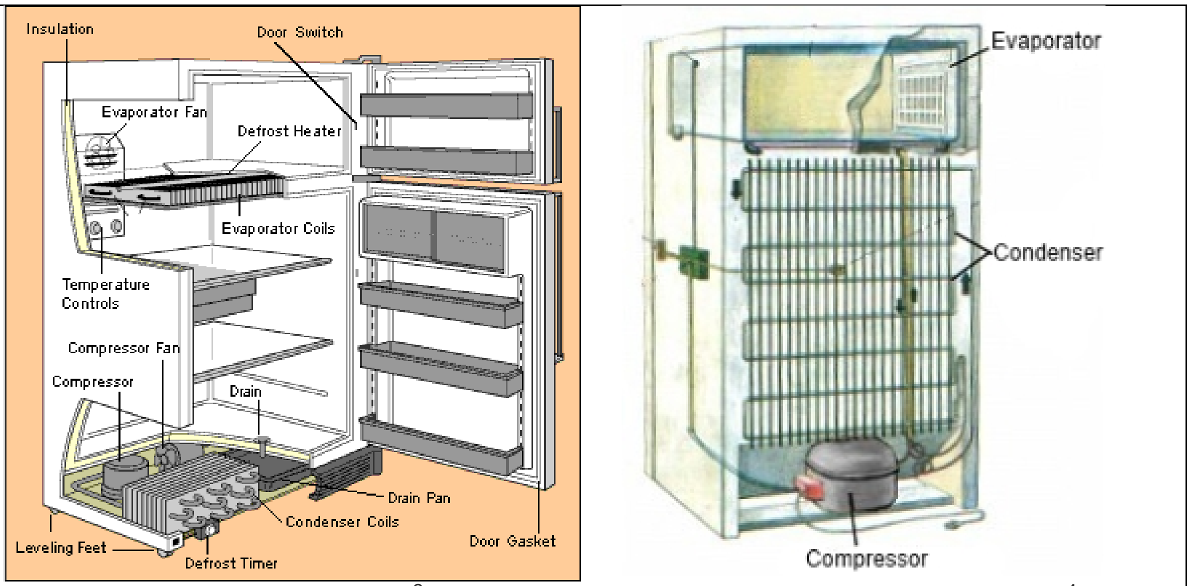


Figure 2 - Refrigeration circuit. Source: ASHRAE, 2006, extracted from (Greenblatt, 2011)[2]

A few products use the absorption cycle. In that case, the electric compression is replaced by a chemical compression based on the absorption principle. Electric energy input is replaced by a heat input from gas or liquid fuel combustion.
Figure 3 shows the typical physical arrangement of the different components in a typical top-mounted refrigerator freezer.



Source: RemodelGuide.com[3] Source : Solarhomestead.com[4]

Figure 3 - Typical refrigerator freezer top-mounted, with forced convection condenser and freezer (left) and static condenser (right)

[2] Greenblatt, Jeffery B.. Technical Support Document for the Final Rule on Residential Refrigerators, Refrigerator-Freezers and Freezers. U.S. Department of Energy, 2011.

[3] RemodelGuide.com. HomeTips, LLC, Glendale, CA. <http://www.remodelguide.com/improve/appliances/refrigerators/refrigerators_works.html>

[4] Solarhomestead.com. Make Your Refrigerator More Efficient, March 8, 2013. <http://solarhomestead.com/make-your-refrigerator-more-efficient/>

3.2 Brief technical overview

3.2.1 Product categories

Categorisation of appliances include several parameters having an impact on energy consumption:

- temperature level of the different compartments (as it has a direct impact on energy consumption),
- free standing versus built-in appliances; built-in appliances having less space behind the unit are expected to have higher air temperatures at the condenser;
- frost-free versus static appliances; frost-free units require more energy for defrost but enable the freezer evaporator to be without frost while in static appliances implying manual defrost, the freezer evaporator is likely to be recovered with frost most of the time (which is not considered in standard testing).

3.2.2 Insulation

Heat losses are mainly linked to conduction through the walls of the appliances. Most refrigerators and freezers use polyurethane foam insulation for both the walls and the door. A door gasket is also used to enable the door opening while limiting the heat losses.

3.2.3 Refrigerant fluid

Refrigerators and freezers have been using CFC-12 then HFC-134a from 1995s. Some manufacturers made the choice of HC-600a which has progressively replaced HFC-134a in most domestic refrigeration appliances in Europe nowadays.

3.2.4 Control and defrost management

<u>Temperature control</u>: mechanical or electronic thermostats ensure that the temperature in the cold volume is maintained at the adequate temperature. In the case of electronic thermostats, the electrical signal from the thermostat is sent to the control of the equipment through a PCB (printed circuit board). The controller then adjusts the compressor and fan (if any) power in order to supply the correct refrigerating capacity. In most cases, the compressor is simply cycled on and off, as well as the fans, if any.
Combined refrigerator / freezer appliances can be fitted with a single thermostat to control the temperature in both volumes or with two independent thermostat enabling independent control (and more for more zones).

<u>Frost and defrost</u>: inside refrigerators and freezers, the evaporator temperature is very cold and hence below the dew point of humid air. Thus, any vapour depositing on the surface of the heat exchanger is likely to freeze, which decreases the heat exchanger conductivity, which in turn requires higher temperature difference between cold air and refrigerant, which increases power consumption. Defrost is then required to minimize the energy consumption. Defrost can be manual (the end-user has to remove the ice manually), semi-automatic (the end-user has to trigger a defrost cycle pushing a button) or automatic (with a timer for instance every 12 hours, or using adaptive systems based on temperature and other parameters). In all 3 cases, once the defrost begins, the ice melts. Water is evacuated by the drain at the bottom of the refrigerator (Figure 3 left) or in a tube. It is then directed to a collector located above the compressor and water evaporates thanks to the heat of the compressor (note it

can also be vaporized over the condenser in case of forced air circulation condensers2).

Expansion valve and suction heat exchanger: the expansion valve is a capillary tube of small diameter, in most cases non insulated. It is soldered to the suction line. The heat losses from the capillary tube then help superheating the refrigerant fluid before it enters the compressor.

Anti-sweat heaters may be used in standard-size refrigerators and freezers to prevent water to condense with a risk to freeze the door gasket / avoid fogging on glass door when they are opened. It is thought to be rather uncommon in EU domestic appliances.

3.2.5 Heat exchangers

Condenser: The condenser is a heat exchanger which enables to extract the heat from the refrigerant fluid. In Europe, a wire and tube static condenser located on the rear wall of the refrigerator (Figure 3 (right)) is the standard design. Heat is released through natural convection (which creates air speed along the fridge rear wall and helps extracting the heat) and radiation. Freezers can use a hot wall integrated in the mounting of the unit2. In the US, the condenser is typically located below the refrigerator, using forced convection to extract heat (Figure 3 left).

Evaporator: the evaporator is a heat exchanger which extracts the heat inside the unit. There are 3 main different types. Cold wall evaporators, attached to the wall of the cooled volume, are static heat exchangers using natural convection. it is made of tube serpentines. Roll bond evaporators are typically used in refrigerator with a freezer part, where they enrol the freezer zone. In general, heat transfer is based on natural convection but in some cases, a fan can be added to increase the convection. Forced convection heat exchangers are aluminium or copper tube and fins located behind a panel or in the part separating the compartments. Units having freezers cooled by forced convection units are named frost-free or no-frost. With forced convection and more compact designs, it is necessary to defrost more often. An electric resistance mounted close enough to the coil is used to defrost periodically the heat exchanger.

3.2.6 Compressors

The compressor is normally located at the rear bottom of the appliance (Figure 3). It can be cooled by a fan. It normally does not accept liquid (or only a small amount for short periods of time) so that the vapour entering the compressor has to be overheated. In practice this is done thanks to the suction line heat exchanger. Domestic refrigeration appliances mostly use single speed reciprocating hermetic compressors. The nominal cooling power of single speed compressors typically ranges from 60 W to several hundred, depending on the size and efficiency of refrigerators.

3.2.7 Fans

In the case of "brewed-air" refrigerators, a fan is located inside the unit and starts each time the door is opened. It allows to homogenize the air temperature inside the unit. In the case of frost-free appliances with forced air condenser, two fans can exist: one, close to the compressor, to force air through the exterior coils; the second, usually inside the freezer, to move air in the whole unit, homogenize the air temperature and prevent the frost formation.

3.3 Reduction of the environmental impact

CO2 emissions

The two main environmental impacts of domestic refrigeration freezers are energy consumption and GHG emissions, which arise mainly from the electricity consumption during the product life but also from the fugitive emissions of refrigerants at the different life cycle stages. Because most appliances already use isobutane, which has a very low global warming potential index, greenhouse gas emissions are mainly linked to electricity consumption. So reducing electricity consumption is the main way to reduce GHG emissions.

Energy consumption

The refrigerating system has to maintain the indoor temperature of the inside volume which, without a cooling system, tends to increase, because of the heat losses though the appliance envelope. It is thus necessary to struggle against through the walls (conduction heat transfer) and gasket (conduction heat transfer and cold air leaks) heat losses. In some cases, when the door is opened (which is not the case in standard performance tests), strategies can be adopted to stop the cooling system, which would then become very inefficient.

Heat load of the coldest zones in the appliance can also be minimized, by ensuring proper insulation with neighbouring compartments at higher temperatures. The final gain in consumption then depends on the refrigeration system design.
Once heat losses are reduced to a minimum, the main energy consuming component of a domestic refrigeration appliance is the compressor. In order to reduce its consumption, it must work with the lower pressure difference between the low side and high side pressures.

Pressures are directly linked to the temperature levels of the refrigerant fluid in the heat exchangers. For the condenser, the condensing temperature is higher than the ambient from a few degrees Kelvin. More efficient condensers will allow to reduce that temperature difference, thus the refrigerant high pressure and in turn the electricity consumption of the compressor will be lower. The same is true on the evaporator side.

Of course, the efficiency of the compressor, including the component itself, its motor and control, can also be improved to reduce the consumption. This is also true for fans, for appliances incorporating one or several fan(s).

Further improvements can come from the control of the active components (compressor and fans) with for instance variable speed control, and of the defrost cycles.

The refrigerant system energy consumption can also be reduced through alternative cycle designs (for instance separate cycles for the refrigerator and freezer) and alternative technologies to mechanical vapour compression refrigeration systems (for instance magnetic cooling).

All these design options are discussed:
- in part 4, for standard and Best Available Technologies (BAT) options,
- in part 5, for Best Non Available Technologies (BNAT) options.

4 Product design options, from standard to Best Available Technologies (BAT)

4.1 Insulation

In the Ecodesign and Labelling Review report of this study, base cases have been modelled. Heat losses by conduction are estimated to represent between 80 (for static refrigerators) and 85 % (for static freezers) of all heat losses, based on industry and literature inputs. This is logically the main focus of present efforts to reduce heat losses.

To limit the **conduction heat losses through walls**, manufacturers search for walls / doors with lower thermal conductivity. Several techniques which are being used / developed are reviewed:
- alternative foaming agents,
- thicker insulation panels,
- use of triple glazing for wine coolers door,
- integration of vacuum insulated panels,
- integration of gas filled panels (BNAT)*,
- aerogel type insulation material (BNAT)*.

*: BNAT options are described in Part 5 of this report.

For different reasons, the heat losses are in fact more important than is foreseen by only accounting conduction heat losses through refrigerated volume and ambient air.
Other factors affecting heat losses include:
- door gasket heat losses (by conduction and air exchange),
- edge effect through the metallic frame,
- heat input due to condenser tube heat losses (which may be used to prevent condensation on refrigerator cold walls),
- Heat input due the fan (for brewed and frost-free appliances).

For static appliances, these losses are supposed to represent 15 to 20 % of total heat losses. Recent research may be found on door gasket heat losses. However, there is little information regarding technologies advertised to reduce these losses as extra-strong gasket magnet. Heat transfer through the metallic frame (known as edge effect) have been estimated to have limited impacts in standard designs in Europe[5].

Using best available insulation technologies, other losses than direct conduction through the walls / doors are estimated to represent between 20 % (for static freezers) to 30 % (for static refrigerators).

4.1.1 Alternative foaming agents

CFC-11 and HCFC-141b have been banned in Europe. Most refrigerators and freezers use polyurethane foam insulation with Cyclopentane and n-pentane (hydrocarbon).

[5] COLD II The revision of energy labelling and minimum energy efficiency standards for domestic refrigeration appliances, ADEME and PW Consulting, for the European Commission, Directorate-General for Transport and Energy, Contract no: XVII/4.1031/Z/98-269, December 2000.

According to CECED technical database year 2014, more than 78 % of the domestic appliances put on the market use HC foams (for 10 % of the models information is not specified). This trend is to be reinforced with the coming ban on HFC with GWP more than 150 in 2020 (European regulation N° 517/2014[6]). Cyclopentane foam is the most commonly used HC. For this cyclopentane PU foam, a standard foam conductivity of 0.020 $W.m^{-1}.K^{-1}$ has been used in the Task 4 (Chapter 9) of the study review report. This is close to the BAT values of 0.0185 $W.m^{-1}.K^{-1}$ for new panels[7].

4.1.2 Thicker insulation

Improvements in the sector of insulation began by increasing the thickness of foam to increase the energy efficiency of the products. Average and maximum insulation levels available in 2014 products have been identified in the Task 4 (Chapter 9) of this study review report. According to M. Janssen[8], 100 mm thickness is a technical limit to insulation because of the foaming process.

4.1.3 Wine cooler glazing thermal conductivity

For wine coolers, double glazing with conductivity of 1.7 $W.m^{-1}.K^{-1}$ is the standard situation. Lowest conductivity glazing possible is a triple window krypton fill, BAT for windows in general, with conductivity of 0.8 $W.m^{-1}.K^{-1}$.

4.1.4 Vacuum Insulation Panels (VIP)

VIP (Vacuum Insulation Panels) is a technology based on the reduction in conductivity which occurs in low vacuum. It enables to increase thermal insulation while losing less cold space than with simple increase in foam thickness.

Several options have been commercially available since 2000 with different core material such as polyurethane, polystyrene, silica powder or glass fibre. Depending on material, heat conductivity varies from 2,4 mW/m/K to 9,7 mW/m/K, that is to say an insulation up to 8 times higher than conventional foam. VIPs are susceptible to punctures. Suppliers are answering this problem with more durable, protective films which are already on the market[9]. Problems of durability seems to have been partly solved as VIP manufacturers propose guaranteed products, including for the effects of ageing. For instance, Evonik[10] uses "fumed" silica as core material which should achieve around 8 times better insulating efficiency than foams and have a lifespan of about 30 years.

First refrigerator models using VIP in the door appeared on the European market in 2005 (few models according to 2005 preparatory study[11]). Due to the high cost of the

[6] Regulation (EU) No 517/2014 of the European Parliament and of the Council of 16 April 2014 on fluorinated greenhouse gases and repealing Regulation (EC) No 842/2006. OJ L 150, 20.5.2014, p. 195–230
[7] The World Bank – New Oorg. HCFC replacement in foams – Report 11/2009
[8] M. Janssen, CECED Comments to Interim report (14.11.2015); Topic: technical model chapter 9, Re/genT Note:15423 / CE15 / V2, 8/12/2015.
[9] Lary Adams, Less Space, Better Insulation, Appliance design 2010. http://www.appliancedesign.com/articles/92394-less-space-better-insulation
[10] Evonik Industries, a VIP refrigerator. https://www.aerosil.com/sites/lists/IM/Documents/PS-50-A-VIP-refrigerator-EN.pdf
[11] Preparatory Studies for Eco-design requirements of EuPs (Tender TREN/ D1/ 40-2005), Lot 13: Domestic refrigerators and freezers, Task 6: Technical Analysis Rev 4.0, October 2007.

VIP, they are still in limited number on the 2015 market and only applied on products aiming at being installed in a limited space or when significant higher performance is targeted[12]. For that reason, they can be used only for door insulation in order to limit overcosts[13]. In the CECED Database, manufacturers usually do not specify if the models use or not VIP. In 2014, the answer is given for 10% of the models. Among them 49 % are A^{+++} models and 27% A^{++}. Exact pricing may differ but it is estimated that it would cost around 10-20 Euros per square meter in 2015. With 2 cm thick panel and 3.5 mW/m/K thermal conductivity, this makes it a cost effective solution, even if not the one with the lowest payback time. In the USA, VIP have been used in refrigerators for more than 20 years in high-end models and, more recently, in standard models thanks to a tax credit2.

In 2012, a US technological roadmap[14] including refrigerators and freezers recommended a high priority program research to understand the variations in VIP performances and on how to reduce the costs. It is not known whether such a research program was actually performed. Another limitation which appears in (Greenblatt, 2011)2 is the fact that not all the cabinet and door surface can be covered by VIP because of structural problems. This limits the potential energy efficiency gains to about 25 %. A larger coverage of 65 % as suggested in Yusuglofu (2013)[15], could enable to reach higher savings, up to 35 % (using panels with the lowest thermal conductivity).

The International Vacuum Insulation Symposium takes place every two years to deal with these subjects[15,16], as a testimony that research on VIP is still active.

To sum-up, VIP technology for refrigerators and freezers has been deeply tested for the past 20 years and shows a significant reducing energy consumption potential. It remains one of the BAT as the diffusion in the market is still low. Very likely, cost is one of the reasons explaining this.

4.2 Refrigerant fluid

Refrigerators and freezers have been using CFC-12 then HFC-134a from 1995s. Some manufacturers made the choice of HC-600a which has progressively replaced HFC-134a in most domestic refrigeration appliances in Europe nowadays. According to CECED product database, in 2014, at least 95 % of the refrigerator and freezer models put on the European market used the hydrocarbon R-600a (for 4 % of the model information is not specified). Studies have shown that the performance of

[12] Heinemann,U., Vacuum Insulation Panels - Potentials, challenges and Applications, 11th International Vacuum Insulation Symposium, September 2013, Empa, Switzerland.

[13] Barthel Claus, Götz Thomas, Technical background and design options to raise energy efficiency and reduce environmental impact of refrigerators and freezers, Appliances Guide, Get super-efficient appliances, December 2012.

[14] William Goetzler, Timothy Sutherland, Kevin Foley, Research & Development Roadmap for Next-Generation Appliances. Report prepared for: Oak Ridge National Laboratory, Oak Ridge, TN 37831, Managed by: UT-Battelle, LLC for the U.S. Department of Energy, Office of Energy Efficiency and Renewable Energy, Building Technologies Office, http://www.eere.energy.gov/buildings, Prepared by: Navigant Consulting, Inc. March 30, 2012.

[15] Y.Yusufoglu, Application of Vacuum Insulation Panels (VIPs) on Refrigerators, 11th International Vacuum Insulation Symposium, 2013.

[16] Brunner Samuel, Ghazi Wakili Karim and Johansson Pär, Vacuum insulation panels in refrigerator room, freezing room and fridge, 11th International Vacuum Insulation Symposium, September 2013, Empa, Switzerland.

refrigerators using R-600a was equal or better than refrigerators using R-12[17] and those using R-134a2.
In addition, the EU 517/2014 regulation requires that all the domestic refrigerators and freezers use a refrigerant with a GWP (Global Warming Potential) less than 150 starting from the 1st of January 2015. Therefore, all the refrigerators put on the market in 2015 should use R-600a as refrigerant, which appears to be the best available technology for domestic refrigeration appliances.

4.3 Controls and defrost management

Temperature control for refrigerator / freezers combined appliances

The majority of combined appliances use two distinct thermostats to control the refrigerator and freezer temperatures separately. For these two thermostat units, there are two principal cooling system approaches: the single-compressor, two-heat-exchanger design; and the two-compressor, two-heat-exchanger design5.

Standard single compressor design use the same (or close) evaporating temperature in both refrigerator and freezer circuits. However, an optimal design from a thermodynamic point of view, is to look for solutions enabling to lower the evaporating temperature in the refrigerator evaporator. This advantage could indeed lead to substantial savings, all things equal otherwise. The potential theoretical order of magnitude (estimated on the combined refrigerator / freezer base case of the review report of this study) is about a 20 % reduction in consumption.

For large fridge-freezer, two separate circuit designs are available. However, there is no recent works on the evaluation of the magnitude of the consumption reduction and the overcost is high (this requires two complete cooling circuits). In addition, the penalty for low capacity units would probably be high as compressor efficiency drops significantly below about 85 W cooling capacity.

From more than 30 years, literature reports several concepts / patents, modelling exercises and / or prototypes built in order to reduce the evaporator temperature with two evaporator systems using varied design circuitry and controls. However, there does not seem to be yet a convincing enough concept so that the development of a BNAT could be pushed.

Hence no BNAT solution was considered here. For the two remaining solutions, Lorenz-Meutzner and ejector cycles, these are discussed in the BNAT technologies in part 5.

Defrost

There is little publication regarding defrost and there does not seem to be published data to evaluate the interest of defrosting options for static refrigerators, whether alternative techniques or controls. The ISO 15502:2005 standard introduced a method to evaluate the impact of adaptive defrost, which is refined in the coming standard IEC 62552:2015. More information should be available once test data using this standard become available.

[17] Behrens, N., Dekleva, T.W., Hartley, J.G., Murphy, F.T., and Powell, R.L. "The R-134a energy efficiency problem, fact or fiction," USNC/IIR-Purdue Refrigeration Conference, 1990, pp. 365-372

4.4 Heat exchangers

Heat exchanger heat transfer capacity (in W) can be expressed as:
$Q = U * A * \Delta T$
where A is the surface area in contact with the fluids in square meters,
U the heat transfer capability of the heat transfer in $W.m^{-2}.K^{-1}$,
U*A is the global conductance of the heat exchanger in $W\ K^{-1}$,
and ΔT the average temperature difference across the heat exchanger in K.

In the review study of this report, only static appliances have been modelled. Heat exchanger technologies are known and no innovation has been found in their design. It has been checked that heat exchange surfaces supplied by the industry were close to the maximum feasible (condenser available surface is in general the limiting factor).

So only U value increase using low power consumption fans have been considered. This option is of main interest on condenser side, which gives gains up to 4 %.

For static appliances, to further decrease the temperature difference across the heat exchangers, it is necessary to reduce the compressor size or to use variable speed drive. This is discussed in the compressor section. Forced convection frost-free evaporators have not been evaluated.

4.5 PCM

This technology consists in using latent heat storage elements (water, paraffin, copolymer) applied on heat exchanger surfaces. For an application at the evaporator, phase change material helps stabilizing the temperature in the refrigerated volume. When the compressor works, the phase change material solidifies, and absorbs the refrigerator heat when the compressor stops. The first consequence is that the cycling frequency of the compressor is divided by roughly 2[18], and so are cycling losses, as these are proportional to the cycle frequency. This roughly corresponds to a 5 % gain in efficiency. These latent materials also enable higher average evaporation temperatures to be achieved, which could turn into higher gains, depending on the coincident evolution of the condensing temperature. The impact of different heat storage elements on condenser temperature has been studied. An energy saving about 10 % can be obtained in using copolymer compound.

Payback times appear to be lower than the units' lifetime but still more costly than other design options. According to Vrabec[19], PCM are only used on a few models on the market: sensible (water) heat storage at the condenser and very small weights of eutectic solutions at refrigerator's evaporator.

According to M. Janssen[20], one of the issue is that it is difficult the time the PCM requires to melt / solidify with the variable times of the cycles.

Hence despite it is a proven technology, readily available on the market, it has a low diffusion and research works are still ongoing.

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[18] Y. Yusufoglu, T. Apaydin, S. Yilmaz, H.O. Paksoy, Improving Performance of Household refrigerators by Incorporating Phase Change Materials, International Journal of Refrigeration, 2015.
[19] Personal communication from J. Vrabec from Paderborn University
[20] M. Janssen, CECED Comments to Interim report (14.11.2015) Topic: Design options and LCC (chapter 12), Re/genT Note1:15424 / CE16 / V1, 11/12/2015

4.6 Compressor and drive

Domestic refrigeration appliances with cooling based on an electric vapor compression cycle use hermetic reciprocating compressors. Maximum efficiency levels reached are described here. There are also two alternative compression systems at different stages of development, linear compressor (BAT, see hereafter) and Stirling cycle compression (BNAT, see part 5).

4.6.1 Hermetic reciprocating compressor, single speed and VSD

In the 2000 (COLD II study5), the best R600a single speed hermetic compressors had a COP of 1.6 for cooling capacities of 50 W and above. This is to be compared with present values in Figure 4, which shows the maximum COP and capacity ranges for three of the main LBP R600a compressor manufacturers (SECOP, Jiaxipera, Embraco) in 2015. The maximum COP values that can be reached depends on compressor size below about 85 W (40 W - 1.72 / 60 W - 1.85) and is close to 2 above 85 W. Over 1 years, the progress was significant for cooling power larger than 85 W (close to 25 %) and much lower for low capacity (40 W, close to 6 %). With decreasing overall heat losses, the development of smaller capacity compressor of higher efficiency is crucial.

Progress in this field are expected from the development of efficient variable speed drive compressors, able to reach lower than 40 W capacity with still acceptable performances. Figure 5 gives some of the Embraco LBP R600a compressor efficiency levels with various operating frequencies. BAT VSD compressor enables to reach a minimum capacity of about 30 W with a COP of 1.5, and a COP of 1.85 for minimum capacity above 60 W (i.e. the same efficiency level than single speed compressor).

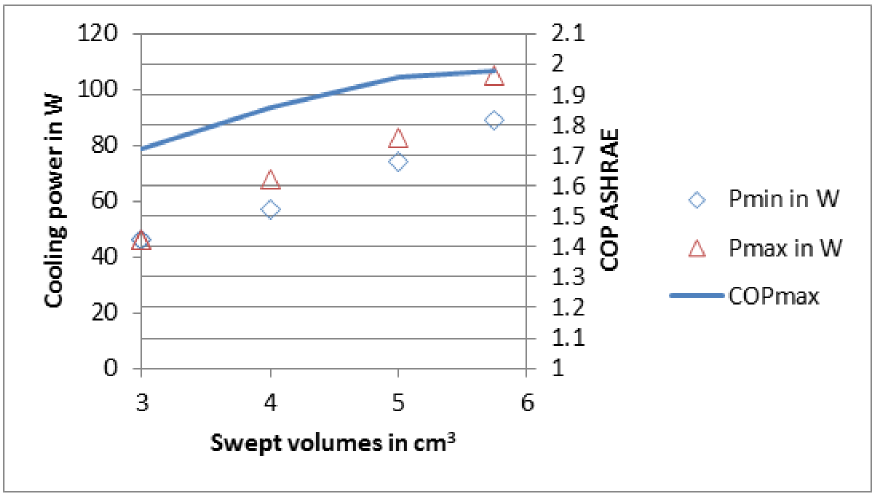

Figure 4. Best available compressor COP and capacity range (ASHRAE conditions) versus size (swept volume in cm3), LBP, R600a

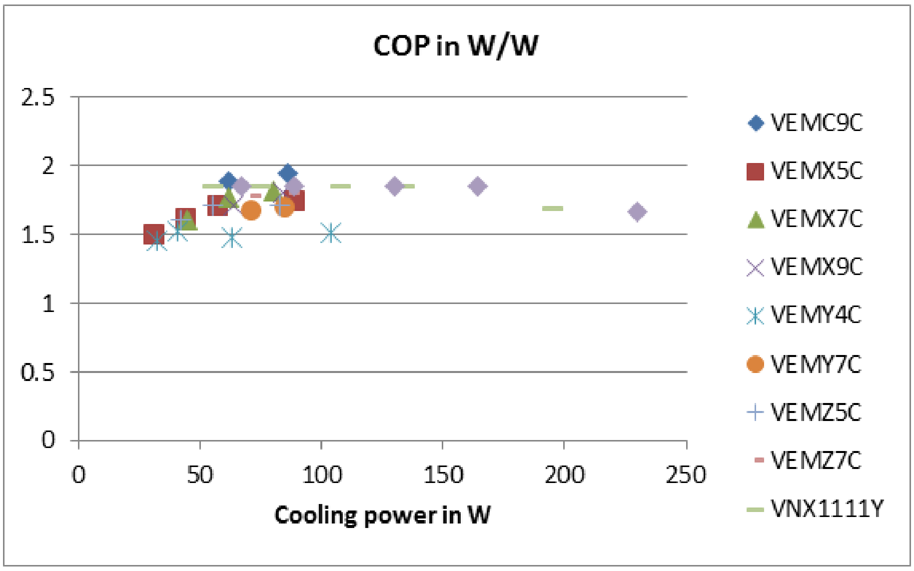

Figure 5. Variable speed compressor efficiency

4.6.2 Linear Compressor Vapour-Compression Refrigeration

Linear compressors enable to avoid mechanical losses existing in the conventional crank-driven compressors. The linear compressor uses electricity and a spring to oscillate a piston connected to a linear shaft, which compresses the incoming gas. Some of them are already on the market, on LG models. Experimental studies such as Ku&al[21] confirm the energy efficiency saving of this type of equipment, comparing linear compressor energy consumption with the one of brushless direct-current reciprocating compressor, both being compressors developed for refrigerators. Measures show that the linear compressor has an excellent energy efficiency and the energy consumption reduction is about 10 %, compared to a BLDC motor compressor. This is in line with another estimate of 9 %2.

The linear compressor from LG available on the market presently uses oil, while the initial design was planned to be oil free. On oil free design could help reaching higher efficiency values. Linear free piston compressors using gas bearings are still being developed[22,23].

It can be noticed that linear compressors are included as a medium priority topic for further research in the US technological roadmap of 2012 including refrigerators and freezers[14]. "*The recommended R&D program includes developing and testing an optimized compressor to demonstrate improved energy efficiency over currently available products.*"

However, since 2014, Embraco now advertises an oil free linear compressor for refrigerator / freezer using magnetic bearings, with a COP of 2.34 for 130 W within the

[21] Boncheol Ku, Junghoon Park, Yujin Hwang, Jaekeun Lee, Performance Evaluation of the Energy Efficiency of Crank-Driven Compressor and Linear Compressor for a Household Refrigerator, Purdue e-Pubs, 2010.
[22] US Patent 6966761 B1 published in Nov 2005/ linear compressor with aerostatic gas bearing passage between cylinder and cylinder liner.
[23] US Patent 20110097224 A1 published in April 2011/ linear compressor.

cooling capacity range [40 W - 245 W][24]. For the conditions given (Tev=-23,3 °C, Tcond = 40,5 °C, supposing ASHRAE conditions for suction and subcooled temperatures, this would give an equivalent ASHRAE COP of 1.9). Performances at low cooling capacity are not yet known but only at best efficiency point. Embraco announces there is still improvement potential for its compressor, which already enables volume (and material use) and noise reductions. An integration project with ORNL has been advertised to be launched in 2014 or 2015. No product is known to use this compressor on the EU market.

With LG compressor being only integrated in LG products, and the only competitor not yet at the level of top BLDC hermetic reciprocating compressors, although close to it, this option has not been considered into the BAT options to improve base case units in this study review report.

4.7 Fans

No specific research has been done regarding potential fan efficiency improvement as only static appliances were modelled in the review report of this study. It was found possible, based on recent literature, to improve significantly the static heat exchangers heat transfer capability (+40%) by using less than 1 W fans. However, this does not apply directly to fans of heat exchangers using forced convection because of head losses in that latter case.

4.8 Smart refrigerators

"Smart" is also a trend for refrigerators although this covers very different concepts such as an internet connected fridge, a fridge able to automatically buy food on line (this was not a success). One of the promising options for energy efficiency is online automatic diagnostic to ease the maintenance of the refrigerator. However, impact on energy efficiency is not known.

[24] Embraco wisemotion compressor, http://www.embraco.com.cn/upload/0/8/0ee511651dc0232de162e0f0d99a332f.pdf consulted last time Feb 12 2016.

5 Best Non Available Technologies screening

All alternative technologies identified as relevant for domestic refrigeration are reviewed in this part following the same methodology:
- the technology principle is briefly described, including energy efficiency potential as well as available information on potential costs.
- Then information on recent research works are given;
- this helps understanding the Technology Readiness Level.
- Finally, potential of the technology and future research topics are given.

5.1 Insulation improved thermal resistance: gas filled panels

- **Description**

According to the US technical support document2, works aiming at improving the resistivity of insulation are still carried out. Black carbon addition[25] was already studied and not adopted in the 2000s. Detailed information is not available, this point is to be confirmed.

The option of Gas filled panels (GFP) has been identified in the previous Preparatory study review[11]. This technology was developed at the LBNL (Lawrence Berkeley National Laboratory) in the 1990s[26]. It consists of thin polymer films filled with low thermal conductivity gas such as argon, krypton or xenon to create a system with high thermal insulation properties[27].

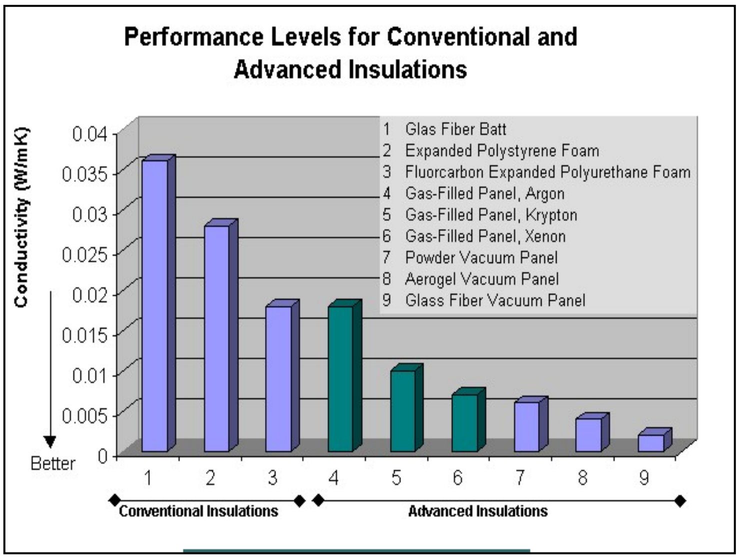

Figure 6. Comparison of thermal conductivity depending on insulation type (source: http://gfp.lbl.gov)

[25] Pisipati, J.S. and Godbey, J.A. "Performance of Carbon Black-Containing Polyurethane Foam in Domestic Refrigerators," Journal of Cellular Plastics, 1996. Vol. 32, No. 2, 108-138.
[26] Griffith Brent, Aratesh Dariush, Advanced insulations for refrigerator/freezers: the potential for new shell designs incorporating polymer barrier construction, Energy and Buildings 22 (1995) pages 219, 231.
[27] Gas Filled Panels high performance insulation. http://gfp.lbl.gov/default.htm

According to Berkeley Lab newsletter[28], Berkeley Lab researchers and Oak Ridge National Laboratory, performed experiments using prototype refrigerator doors and cabinets equipped with GFPs. Results showed that the use of GFPs in door panels increased the overall energy efficiency of the refrigerator by 6,5%. It is also said that "Projected savings could reach as high as 25 % when GFP insulation is used throughout the entire refrigeration cabinet as well as in the door panels".

(Greenblatt, 2011)2 underlines that a significant problem of this technology is the lack of structural integrity of the product. This parameter as well as a cost which is similar to VIP could explain that no gas filled panel products have been identified in the refrigeration industry (neither prototype nor commercial products) so far. Still according to (Greenblatt, 2011)2, this technology allows less energy savings than VIP but its cost is similar and no gas filled panel products have been identified in the refrigeration industry.

- **Recent development and research**

According to S. Li from LBNL, GFP was licensed to Coleman for further development at one point. Unfortunately the license is expired and it is not known if other manufacturers are making products with GFP. The patent is also expired.

- **TRL: 3**

- **Conclusion for domestic refrigeration**

Gas Filled Panels technology does not appear mature and is supposedly less cost-effective than VIP for equivalent gains.

5.2 Insulation improved thermal resistance: aerogel panels

- **Description**

An aerogel is a gel in which liquid component is replaced by air. It has a very low density and excellent insulation properties. Researchers try to use these properties to design building or refrigerator components with very low thermal conductivity.

- **Recent development and research**

In 2013, BASF announced it had developed panels with thermal conductivity of 0.016 $W.m^{-1}.K^{-1}$, acceptable structural integrity and easy to work[29]. This would be a 20 % reduction in thermal conductivity of standard cyclopentane PU foam used for refrigerators and freezers. This represents a significant energy efficiency potential for refrigerating appliances which do not yet use VIP, up to 25 % (20 % lower conductivity + 5 % because of the gain in insulation thickness).

Main foreseen hindrance of the technology is the manufacturing cost of the aerogel and then of the panels, which, for refrigerating appliances, will have to compete with

[28] Lawrence Berkeley National Laboratory (LBNL). Environnemental Energy Technologies Division. News 2005. http://eetd.lbl.gov/newsletter/nl20/eetd-nl20-tt.html

[29] BASF, The first PU high-performance insulating material as a ready-to-use panel, Consulted Feb 11 2016, http://www.plasticsportal.net/wa/plasticsEU~ru_RU/portal/show/common/plasticsportal_news/2013/13_313?doc_lang=en_GB

cyclopentane foam and VIP. The next step, which is to build a pilot plant, is thus crucial to evaluate the feasibility to reach the appliance market.

- **TRL: 5**

- **Conclusion for domestic refrigeration**

A EU H2020 project, NANOHYBRIDS[30], is just starting in which the pilot plant is to be built. Arcelyk, a refrigerator manufacturer, is taking part in this project. This should end by year 2018.

5.3 Lorenz-Meutzner Cycle Refrigeration

- **Description**

This is a cycle built in for which a relatively simple series arrangement of refrigerator and freezer evaporators may enable those two heat exchangers to work with different evaporating pressures. This is done by using a zeotropic refrigerant mixtures having large temperature glides. Theoretical gains can reach 20 % gains, but this was modelled with HC mixture.

- **Recent development and researches**

A recent paper (Yoon et al, 2012)[31] indicates that with a R290/R600 mixture instead of R600a, a gain of 11 % can be reached. This is an experiment but for a large size refrigerator freezer appliance; the penalty for oversizing for smaller appliances may be more important. In addition, the gain is only evaluated at one outdoor temperature condition. Hence the consumption reduction may be considered limited considering the overcosts associated with the whole industrial process. In any case, there is no information relating to such design development on-going.

- **TRL: 4**

- **Conclusion for domestic refrigeration**

This an old concept. There is now a proof of concept in laboratory identifying adequate refrigerant fluids (similar to the ones presently used) for EU refrigerator and freezer appliances. However, the overall potential is thought to be relatively low for lower capacity units with relatively important overcost.

5.4 Ejector Cycle Refrigeration for combined refrigerator / freezer

- **Description**

[30] NANOHYBRIDS EU H2020 Summary (in French), available on line at http://www.dep.mines-paristech.fr/Actualites/Agenda-partage/NANOHYBRIDS-un-nouveau-projet-europeen-sur-materiaux-aerogels/2670

[31] Yoon, Seo, Chung, Lee, Kim, Performance optimization of a Lorenz-Meutzner cycle charged with hydrocarbon mixtures for domestic refrigerator-freezer, International Journal of Refrigeration, 2012.

"A typical ejector consists of a motive nozzle, a suction chamber, a mixing section, and a diffuser." "The working principle of the ejector is based on converting internal energy and pressure related flow work contained in the motive fluid stream into kinetic energy"[32]. It can be used to generate cool from low grade heat or to recover the work which is lost in the expansion valve of refrigeration cycles. However, a specific design has also been proposed to improve the efficiency of refrigerators and freezers having two different temperature evaporators, i.e. single-compressor-two-heat-exchanger refrigerator/freezer[33]. *"The ejector cycle gives an increase of up to 12.4% in the coefficient of performance (COP) compared to that of a standard refrigerator-freezer refrigeration cycle. The analysis includes calculations on the optimum throat diameters of the ejector. The investigation on the off-design performance of the ejector cycle shows little dependency of energy consumption on constant ejector throat diameters."* The cycle used to do so is presented below.

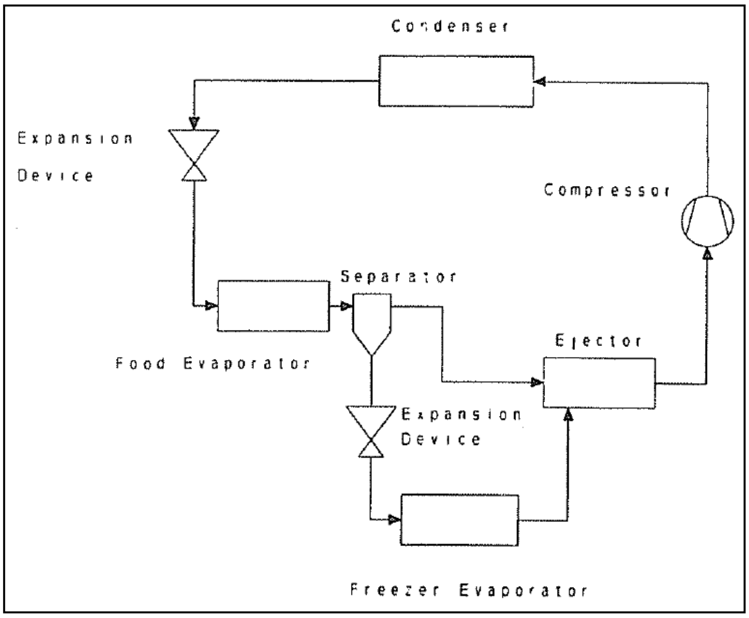

Figure 7. Scheme of a refrigerator-freezer cycle with ejector. (Source: Tomasek and Radermacher, 1995)[33]

- **Recent development and researches**

No recent research on this specific design could be found. Greenblatt (2011)2 explains that US refrigerators' manufacturers did not consider it a proven concept to increase refrigerator / freezer energy efficiency.

- **TRL: 3**

- **Conclusion for domestic refrigeration**

The building and test of a representative refrigerator / freezer prototype seems to be the next step to confirm / infirm the potential of this technology.

[32] Elbel, Stefan and Hrnjak, Predrag, "Ejector Refrigeration: An Overview of Historical and Present Developments with an Emphasis on Air-Conditioning Applications" (2008). International Refrigeration and Air Conditioning Conference. Paper 884. http://docs.lib.purdue.edu/iracc/884

[33] Tomasek M.-L., Radermacher R., 1995, Analysis of a domestic refrigerator cycle with an ejector, ASHRAE Transactions, Vol. 101, pp. 1431-1438

5.5 Stirling Cycle Refrigeration

- **Description**

A free piston Stirling refrigeration cycle is a Stirling regenerative engine working in reverse mode: the Stirling engine is a heat engine; it converts a temperature difference between a hot and a cold source into work; the working gas is alternatively heated and cooled; respective compression and expansion phase generate shaft work via a piston. This close cycle cyclic engine is reversible so that if supplied with work it can be used as heat pump / refrigeration unit.

Free piston Stirling domestic refrigerator prototypes have been built in the past. In principle, it should be the most efficient cooling cycle. However, their performances for low temperature differences between the refrigerated volume temperature and the ambient temperature have proven to be lower than the one of the traditional vapor compression cycle. This technology has been developed with success for cryo-cooling (large temperature difference are very much in favor of this technology) and for portable coolers. It can also be used with solar photovoltaic panels for solar refrigeration.

- **Recent development and researches**

No development could be found in recent years dedicated to domestic refrigeration. Hence, the technology is available but not considered proven for domestic refrigeration.

- **TRL:** 4

- **Conclusion for domestic refrigeration**

Refrigerator using Stirling cycle are included as a low priority topic for further research in the US technological roadmap including refrigerators and freezers[14]. Authors advise to develop and optimize a complete Stirling refrigeration cycle refrigerator in order to demonstrate the savings. It still appears necessary to be done.

5.6 Magnetic Refrigeration

- **Description**

Unlike conventional systems, magnetic refrigeration requires a solid magnetic material as refrigerant. The operation principle of magnetic refrigerators is based on the magneto-caloric effect (MCE). The MCE is the ability of the material to change its bulk temperature when undergoing changes in the applied external magnetic field. This means that the magnet, preferably permanent, changes its position alternately. The operation cycle is an alternate heat transfer cycle: exothermal and then endothermal.

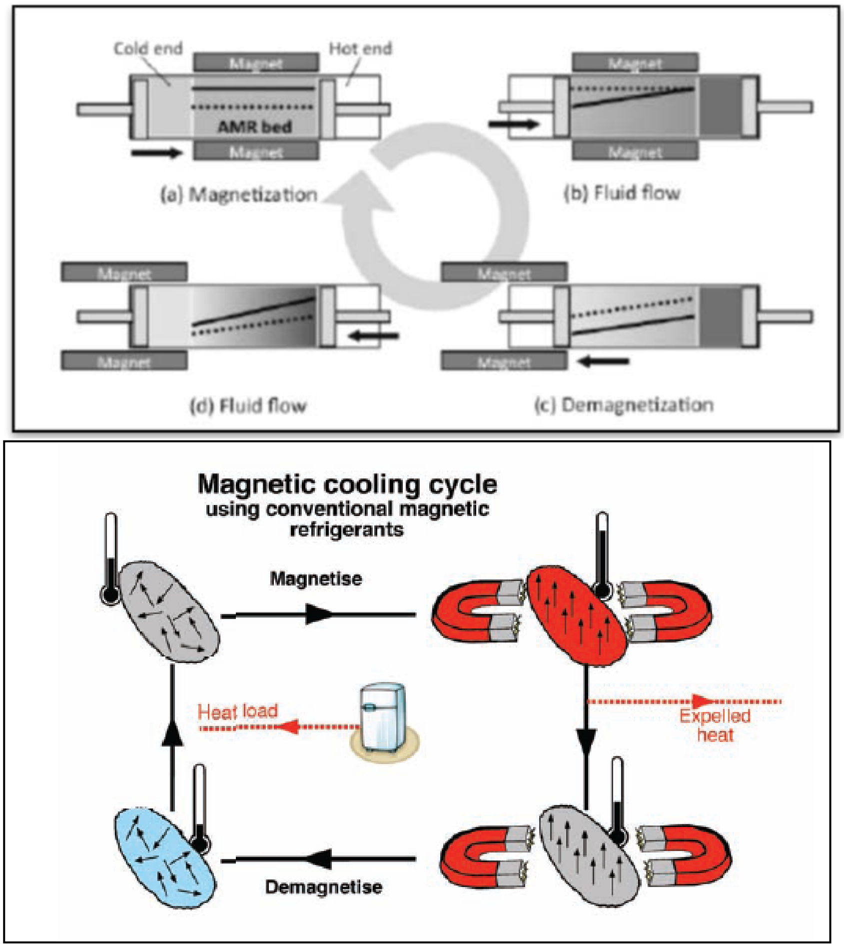

Figure 8 - Magnetic refrigeration principle. Source (Kawanami 2010, Sandeman, 2011)[34]

The magnetic material chosen for operation at temperature close to ambience is the gadolinium (Gd_5(Si2Ge2)), which is a rare earth, or alloys such as Praseodymium alloyed with nickel ($PrNi_5$). Therefore the process does not require a compressor or expansion valve, instead the mild temperature material is put through an electromagnetic field which aligns the molecules and heats up the material, this hot material under the presence of the magnetic field is put through a heat exchanger which expels the thermal energy from the material into the surrounding and then the material is taken out of the magnetic field so the resulting temperature is much less than the original. At this point it is placed back into the refrigerated space where it absorbs thermal energy from the inside of the refrigerator and heat the material to the original temperature where the process starts all over. The MCE implies that the temperature of suitable materials increases when exposed to a magnetic field and decreases when it stops. By applying a magnetic field, material magnetic properties are changed and they release or take in heat, depending on whether the field is being applied or removed.

Magnetic fields of at least 2 Tesla are required with permanent magnets to obtain significant results. To reach such a magnetic intensity, the quality of materials and the use of rare earths is essential, which should be taken into account in the case of a life cycle analysis. Researches on materials focus on the replacement of gadolinium by other alloys.

[34] Sandeman, K., Gas free refrigeration, Magnetics Technology international, 2011.

The coefficient of performance is very sensitive to temperature variations that are related to both the Curie point of the material and the variation of magnetic susceptibility of the material depending on the temperature.

Compared with conventional refrigeration technologies, magnetic refrigeration presents advantages such as compact configuration, low noise (no compressor), high efficiency and longevity. The thermodynamic efficiency of magnetic refrigeration can reach 30 % to 60 % of Carnot cycle theoretically, i.e. values comparable to the efficiency of best vapour compression based refrigerators and freezers[35], and much higher than standard cycle for large temperature difference. Cui et al.[36], basing on literature review, state that MCE refrigeration cycle can reach 70% of the Carnot COP, versus 60% for vapor compression cycle.

- **Recent development and researches**

Langebach et all[37] establish an overview of the recent progress in magnetic refrigeration for domestic refrigeration appliances at mid-2014 and analyzes some prototypes. It is showed that even if higher COP and lower energy consumption are promising, some requirements of domestic refrigeration have not been experimentally proven. The existing prototypes don't allow to consider an industrialization because both cooling capacity and temperature range needed in domestic refrigeration can't be reached. There are also other challenges that need to be overcome such as the environmental impact of rare earth materials use in magnetic refrigeration.

In January 2015, Haier, Astronautics Corporation of America and BASF presented a Wine Cooler prototype at the Consumer Electronics Show of Las Vegas[38]. Haier said they were planning to introduce the technology on the market within the next couple of years[39].
The French company Cooltech[40] launched a fundraising campaign of € 8 million for the development of magnetic refrigeration. In collaboration with its German partner, Kirsch, Cooltech presented in November 2015 a pre-series medical fridge based upon magnetic refrigeration. However, no functional refrigerator prototype is available yet.

Recent experimental studies deal with rotary permanent magnetic refrigerator[41], or a heat transfer by liquid metal in a magnetic refrigerator[42]. These studies have been presented at the 6th International Conference on Magnetic Refrigeration at Room Temperature (Thermag VI).

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[35] Yu, B.F., Gao, Q., Zhang, B., Meng, X.Z., Chen, Z., 2003. Review on research of room temperature magnetic refrigeration, International Journal of Refrigeration 26

[36] Jun Cui, Yiming Wu, Jan Muehlbauer, Yunho Hwang, Reinhard Radermacher, Sean Fackler, Manfred Wuttig, and Ichiro Takeuchi, Demonstration of high efficiency elastocaloric cooling with large ΔT using NiTi wires, APPLIED PHYSICS LETTERS 101, 073904 (2012).

[37] Langebach, R., Klaus, M., Haberstroh, C., Hesse, U., Magnetocaloric Cooling Near Room Temperature – A Status Quo with Respect to Household Refrigeration, 15th International Refrigeration and Air Conditioning Conference at Purdue, July 14-17, 2014.

[38] Consumer Electronics Show, Prototype Wine Cooler using magnetic refrigeration. Las Vegas, January 2015

[39] http://www.chemistryviews.org/details/news/7261611/Prototype_of_Magnetocaloric_Wine_Cooler.html

[40] Cooltech Applications SAS, Gas Free Magnetic Cooling System for Commercial Refrigeration (MagFreeG), 2014. http://ec.europa.eu/environment/ecoinnovation/projects/en/projects/magfreeg

[41] Aprea, C., Cardillo, G., Greco, A., Design and construction of an experimental rotary permanent magnet magnetic refrigerator, September 2014.

[42] Tomc,U., Kitanovski, A., Tusek, J., Experimental analysis of a liquid metal as a heat transfer fluid in a magnetic refrigerator, September 2014.

The ELICiT (Environmentally Low Impact Cooling Technology)[43] project, began in January 2014, focuses on the application of magnetic cooling technology to domestic refrigeration appliances. Workshop on magnetic refrigeration organized in August 2015 at the ICR2015 Conference[44] in Yokohama presented first results of the program. The research works aim at developing a high efficiency and low cost magnetic technology. Results about compressors are promising[45]: energy efficiency level is twice compared to a gas compressor. Advantages such as no heat rejection at the back of the appliance and a decrease of the wall thickness are put forward in the presentation of the technology. Heat exchangers have been designed and performance tests are ongoing. However, cooling capacity and operating temperature range remain low. The project should end at the end of 2016.

According to private communication from Camfridge[46], further tests will be needed to optimize the energy efficiency of the final appliance and to reach levels of reliability and lifetime performance required by mass market domestic fridges. According to Camfridge, the tests should be achievable before the end of 2017 and first prototypes of fridge with magnetic refrigeration technology should be available around 2018. Cost reduction is improving and magnetic refrigerators should be in the range of current A^{+++} model prices; so, first models could be put on the market by 2020 depending on the commercial strategy of the different fridge manufacturers.

Researchers at the Rochester Institute of Technology explore alternatives to rare-earth magnets. They have just published the results of their study about an iron-based high entropy alloy (HEA) that could be used as a magnetocaloric material for magnetic cooling[47]. The $NiFeCoCrPd_x$ is cheaper, more eco-friendly and more readily available than metals made of rare earth elements. A enhancement of about 40 % of the refrigerating capacity seems to be achievable.

- **TRL: 3-4**

Even if some research works are promising and plan to develop prototypes or to put on the market magnetic refrigerators in 5 years, communicated data are not precise enough to conclude to a higher TRL level.

- **Conclusion for domestic refrigeration**

The potential of this technology for domestic refrigeration is probably high from an energy efficiency perspective. However, key points in the development of magnetic refrigerators are the cost of rare earth and that the exploitation of MCE around the room temperature is limited by the fact that existing MCE materials do not achieve high temperature differences. Research projects aiming at finding new materials adapted to refrigerator and freezer appliance should be supported.

It can be noticed that refrigerator using magnetic refrigeration are included as a high priority topic for further research in the US technological roadmap of 2012[14] including refrigerators and freezers.

[43] ELICiT, Environmentally Low Impact Cooling Technology, The FP7 EU Project ELICiT, 2014
[44] http://www.icr2015.org/
[45] Pastore, A., Second generation Magnetic cooling engine: Where are we?, Elicit Project, ICR2015, Yokohama, August 2015.
[46] Private communications from Camfridge for the CES MINES-ParisTech, December 2015.
[47] Belyea, D., Lucas, M.S., Michel, E., Horwath, J., Miller, C.S., Tunable magnetocaloric effect in transition metal alloys, Scientific Reports 5, Article number: 15755 (2015), doi:10.1038/srep15755.

- "R&D objective is to determine the cooling capacity required for a magnetic refrigerator".
- "Recommended R&D Activities are: Further understand magnetic refrigeration cooling principles, Optimize individual components of the system, Test optimized prototype to demonstrate required cooling capacity."

According to Scarpa[48], there are three main technological issues involved in the realization of magnetic refrigerators:
- the design of strong magnetic sources,
- the development of efficient active regenerators,
- the definition of optimized process arrangements.

These topics have to be considered in further research support.

5.7 Thermoelectric refrigeration

- **Description**

Thermo-electric refrigeration is based on the principle of associating in series electrically couples P and N of semi-conductor materials, usually bismuth telluride (Bi2Te3). Type N material is boosted so as to obtain electrons in excess, while others of type P are boosted so as to be deficient in electrons. The heat flux is transferred by the electron flow so as the thermal cooling of the bond from P to N and the heat release from N to P associate TE modules thermally in parallel whereas they are in series electrically.

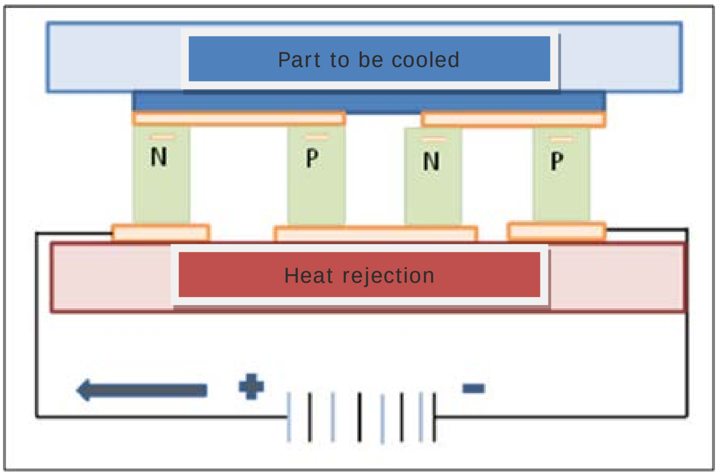

Figure 9 - Thermoelectric cooling principle.

The most usual cooling use of thermo-electric modules is the cooling of electronic components that have to be maintained at a given ambient temperature. The cooling capacity is low, at best a few hundred watts, and the energy efficiency decreases very rapidly with an increasing temperature difference. The reputed efficiency for refrigeration is supposed to be of max 10 % of Carnot COP according to Cui et al.[36] versus 60 % for the vapor compression cycle, with in addition a higher cost because of the materials used.

[48] Federico Scarpa, Giulio Tagliafico, Luca A. Tagliafico, A classification methodology applied to existing room temperature magnetic refrigerators up to the year 2014, Renewable and Sustainable Energy Reviews, Volume 50, October 2015, Pages 497-503.

- **Recent development and researches**

The COP of thermoelectric devices is limited as compared to the temperature difference ranges of refrigerators and freezers. This limits the scope of application to niche markets including portable coolers. There are manufacturers of coolers and small refrigerators (Samsung, Avanti, but also Chinese manufacturers), which are niche applications. Several compact refrigerators and small wine coolers using thermoelectric cooling are currently available on the market but their efficiency is lower than traditional vapor-compression models.

According to Goldsmid in 2013[49], the cost of the thermoelectric unit, which is quite proportional to its cooling capacity "makes it unsuitable for applications where a large cooling capacity must be provided". Haier recently advertized the first "sold state wine cooler" working with thermoelectric cooling and intends to extend this technology to refrigerators[50]. However, there is no test data on the energy efficiency gains of this specific product.

However, a former model has been tested by the US DOE2. A COP of 0.9 was measured for a temperature difference of about 18 °C and a maximum cooling capacity of 50 W. This is much less efficient than standard electric vapor compression refrigerator.

- **TRL: 4**

- **Conclusion for domestic refrigeration**

The potential of this technology for domestic refrigeration is probably low.

5.8 Thermo-acoustic refrigeration

- **Description**

Thermo-acoustic (TA) principle is to use the pressure variations of a gas (mixture of He and rare earth gases)[51] in which a sound wave is propagating. The system consumes electricity to generate the sound wave (acoustic power). According to Starr et ali[52], "a basic thermo-acoustic refrigerator is made of a stack of parallel plates housed in a resonator. Heat can be pumped from the cold to warm end of the stack by setting up a standing wave into the resonator. This effect, where heat is pumped up a temperature gradient by the use of sound, may be explained by considering an element of fluid as it oscillates back and forth along the stack. The element experiences a cyclic temperature oscillation about its mean temperature due to adiabatic compression and expansion of the gas. [...] There is a correct phasing between temperature and pressure. [...] the phasing is such that when the element is in its right-most position, it has been expanded to a temperature that is colder than the local stack and so absorbs heat from the stack, and when the gas parcel is

[49] Goldsmid H., Springer science and Business Media New York, Thermoelectric Refrigeration, 2013
[50] http://mashable.com/2015/09/03/haier/#mMNCl1TM8aqC
[51] D. Clodic, X. Pan, E. Devin, T. Michineau, S. Barrault, ALTERNATIVES TO HIGH GWP IN REFRIGERATION AND AIR-CONDITIONING APPLICATIONS, Study funded by ADEME, AFCE and Uniclima, FINAL REPORT, December 4 2013.

displaced up the plate to its left-most position, it is compressed to a temperature that is hotter than the stack, thereby rejecting heat to the stack."
The gas cycle is close to a Stirling cycle. Theoretical considerations have shown that similar performances as traditional vapor compression cycles could be reached for domestic refrigeration[52]. More recent research show that the efficiency of this technology for refrigeration is limited to 40%[36] of Carnot COP versus 60 % for the vapor compression cycle, with in addition a higher cost because of the materials / gas used.

- **Recent development and researches**

Several prototypes have been made at the university of Pennsylvania[53]. In 2006, a refrigerating vending machines prototypes have been built with a COP of 0.8 at -24 °C freezer temperature and a cooling capacity of 120 W, which is still far from standard products energy efficiency. Several EU funded projects have been led on thermoacoustics, including on the design of a heat driven TA engine and refrigerator. No specific recent project targeting domestic refrigeration could be identified, despite relatively high ratios of COP to Carnot COP promised by the technology.

- **TRL: 4**

- **Conclusion for domestic refrigeration**

The potential of this technology for domestic refrigeration is probably low to replace electric appliances and may be higher for thermally driven technologies.

5.9 Thermo-elastic refrigeration

- **Description**

Thermoelastic refrigeration is similar to magnetic refrigeration where there a magneto-caloric material is required here a shape memory alloy is required which releases heat when compressed and absorbs heat when expanded. The two phases are considered Martensite and Austenite. Here the refrigerated space gives thermal energy to the material as it goes through the cycle then the material is compressed to give off the heat to the surroundings then cycles back through after expanding and cooling once again.

- **Recent development and researches**

The supposed maximum efficiency of this technology for refrigeration appears to be the highest of all solid state technologies, with a maximum 83.7%[36] of Carnot COP versus 60 % for the vapor compression cycle, with in addition the advantage to be a low cost solution.
Research are at the design stage, including material choice, reliability and heat exchanger design.

[52] R. Starr, P.K. Bansal, R.W. Jones, B.R. Mace. 1996. The Reality of a Small Household Thermoacoustic Refrigerator. International Refrigeration and Air Conditioning Conference at Purdue, 1996. Paper 344.
[53] http://www.acs.psu.edu/thermoacoustics/refrigeration/benandjerrys.htm

- **TRL: 2**

- **Conclusion for domestic refrigeration**

This is probably the most promising long term BNAT option. The only hindrance identified at the moment is the reliability of material to a very large number of cycles[36]; cost appears as promising. R&D programs should aim at demonstrating the technology by designing and testing first prototypes.

6 Domestic refrigeration future technology options: mapping R&D needs

6.1 Improved insulation

Present insulation technology uses cyclopentane polyurethane foam with conductivity of 0.02 $W.m^{-1}.K^{-1}$, zero ODP and negligible GWP impacts. The best available technology is the integration of vacuum insulated panels with conductivity as low as 0.0035 $W.m^{-1}.K^{-1}$, which can cover up to 60 to 65 % of the inner refrigerator area. Because of structural problems, it is today not feasible to reach a higher coverage. R&D projects aiming at demonstrating mixed PUR foam / VIP insulation structure with higher than 70 % surface coverage could be encouraged, although VIP is a mature technology (TRL 9).

Two non-mature alternative technologies have been identified:
- **Gas filled panels** was seen as a promising option, before the maturation of vacuum insulated panels, as a lower cost and intermediate thermal conductivity technology. However, there is an issue of structural integrity of the panel which does not seem to have been solved yet. R&D program could thus address the development of a prototype in order to prove thermal insulation and structural integrity of GFP (TRL 3).
- **Aerogel panels**: An aerogel is a gel in which liquid component is replaced by air. It has a very low density and excellent insulation properties. A product has been validated with insulation properties of $W.m^{-1}.K^{-1}$, which is 25 % less than standard foam. The EU H2020 project Nanohybrids is just starting ; a manufacturing pilot plant is to be built which will then enable the test of the technology by appliance manufacturers. It should also demonstrate it can be a cost effective solution. The development stage is TRL 5. Next R&D steps will depend on the Nanohybrids project outcome.

6.2 Improved vapor compression cycle

Present cycle archetype is a classical vapor compression cycle using electric compressor (in most cases). Its efficiency is limited by the efficiency of the compressor. With the important reduction of heat losses, the cooling capacity required for the compressor is decreasing. The coefficient of performance (COP) of the commercially available compressors is decreasing from a maximum of 2 (ASHRAE LBP conditions) above 85 W to about 1.7 at the minimum capacity of 40 to 45 W. R&D projects aiming at the development of high efficiency and low capacity refrigeration compressors could be encouraged. This includes the optimization of oil free (gas bearings or magnetic) linear compressors.

Two modified vapor compression refrigeration cycles have been identified; they have the potential to improve the efficiency of combined refrigerator freezer appliances:

- **Lorenz-Meutzner** Refrigeration Cycle: in order to benefit from the higher evaporating temperature (and consequently higher COP), a zeotropic refrigerant mixture having a large temperature glide when it evaporates is used. An optimum HC mixture compatible with EU appliances has been identified and tested in a laboratory environment and results show an 11 % efficiency gain (TRL 4).

- **Ejector** Refrigeration Cycle: different ejector cycles have been proposed which offer two different temperature levels, the lower one for freezer evaporator and the intermediate for refrigerator evaporator. Gains of 11 % have been proven 20 years ago (TRL 4).

For these technologies including Lorenz-Meutzner and ejector cycle which can increase the efficiency of combined appliances, R&D programs could attempt to validate technologies in an industrial environment to confirm they are viable options (this would include different product sizes) (TRL 5 level). There may exist other simpler solutions to reach the same goal, which would need first to be validated on prototypes in laboratory environment (TRL 4).

Stirling Cycle Refrigeration is a reverse Stirling engine cycle, converting mechanical work into a temperature difference, here used to cool a refrigerator. The technology has not been proven to give higher coefficient of performance than standard electric hermetic reciprocating compressors in use for domestic refrigeration, although this is a very efficient solution for larger temperature lifts. Improved concept proof and prototype validation could be encouraged (TRL 3 and 4).

6.3 Solid state cooling

Solid state cooling encompasses several different technologies: magnetic, thermoelectric, thermoacoustic and thermoelastic refrigeration.

Among these technologies, magnetic and thermoelastic cooling appear as the most promising solutions to improve the energy efficiency of domestic refrigeration appliances in the future.

Thermo-electric uses the Peltier effect as a cooling means, which is the creation of a temperature difference at an electrified junction of two different conductors. The efficiency of devices based on this working principle is low as compared to standard vapor compression cycle for domestic refrigeration temperature differences. This principle is nowadays reserved to portable coolers that offer a limited temperature difference with the ambient. With no circulating fluid and no moving part, products working on this principle have low noise and vibration. This is one of the pros highlighted by one manufacturer to have developed a wine cooler prototype, with however very low performance as compared to standard refrigeration. R&D program could focus on the development and testing of prototypes to prove it can compete in efficiency in the wine cooler application range (TRL 4). Refrigerators and freezers seem to be out of reach.

Thermo-acoustic refrigeration uses the impact of wave propagation in a gas (mixture of helium and rare earth gases) to generate a temperature gradient, which may be used to build up a refrigerator. Prototypes have been built to prove the concept. However, their performance was limited in comparison to standard electric vapor compression cycles. Improved concept proof and prototype validation could be encouraged (TRL 3 and 4).

Magnetic refrigeration uses the property of some metals, to heat when put into magnetic field and to cool down when demagnetized. It may reach similar and potentially better performance than standard vapor compression appliances. Research on finding the right material (adequate temperature range, large temperature difference for acceptable magnetic field intensity) is still required as present materials may not enable to reach high enough capacity / temperature span and/or be costly as well as research regarding design of strong magnetic sources, efficient active regenerators and optimized process arrangements[48]. The development of a prototype and of its components (TRL 4) is being funded in Europe through the Elicit H2020 project. Higher TRL steps are also planned in the project. The design of further R&D programs could base upon the findings of this project.

Thermo-elastic refrigeration is similar to magnetic refrigeration where there a magneto-caloric material is required here a shape memory alloy is required which releases heat when compressed and absorbs heat when expanded. The supposed maximum efficiency of this technology for refrigeration appears to be the highest of all solid state technologies, with a maximum close to 84%[34] of Carnot COP versus 60 % for the vapor compression cycle, with in addition the advantage to be a low cost solution. Research are at the prototype design stage, including material choice, reliability and heat exchanger design. R&D programs should aim at demonstrating the technology by designing and testing first prototypes (TRL 3 and 4).

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