Hochschule Karlsruhe
Technik und Wirtschaft
UNIVERSITY OF APPLIED SCIENCES

Technologies needed to cope with

HFC Phase Down and Climate Change

28 June 2018

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Institute of Refrigeration, Air Conditioning and Environmental Engineering
Karlsruhe University of Applied Sciences

Michael Kauffeld

1986 — NIST National Institute of Standards and Technology, U.S. Department of Commerce — Zeotropic refrigerant mixtures

Leibniz Universität Hannover — Zeotropic Refrigerant mixtures, Air Cycle

1992 — 1994 — HYDRO — Micro Channel HX, Flat Oval Tube Condenser
CO_2 Car Air Conditioner

DANISH TECHNOLOGICAL INSTITUTE — Small Ammonia Systems, CO_2, Ice Slurry, Air Cycle, Hydrocarbons, Water as Refrigerant

2002 — Hochschule Karlsruhe Technik und Wirtschaft, UNIVERSITY OF APPLIED SCIENCES — Ice Slurry, PCMs, Solar powered Ejector, Low Charge Systems, Mini Channel HX, Air Cycle, N_2O, Heat Pumps and Ground Probes

2008 — Danfoss — Smart Controls, Mini Channel HX

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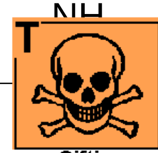
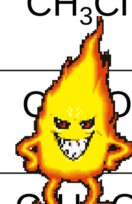
2018 — IKKU Institute of Refrigeration, Air-Conditioning and Environmental Engineering

Steinbeis-Transferzentrum Kälte- und Klimatechnik – ST2K

<u>Other Occupations:</u>

IIR President Commission B2 (2011 – 2015)
President IIR Ice Slurry Working Group (until 2005)
Vice President IIR Career in Refrigeration Working Group
Organizer of various IIR Conferences
Member UNEP RTOC (since 1997)

Traditional Refrigerants (approx. 1860 to 1940)

Substance	Refrigerant Number	Chemical Formula
Air [1)]	R 729	-
Water [2)]	R 718	H_20
Carbon Dioxide [3)]	R 744	CO_2
Ammonia	R 717	NH_3
Sulfur Dioxide	R 764	
Methyl-Chloride	R 40	CH_3Cl
Dimethyl Ether	E 170	 [illegible]
(Diethyl-)Ether	R 610	$C_4H_{10}O$

La historia del ozono

PNUMA

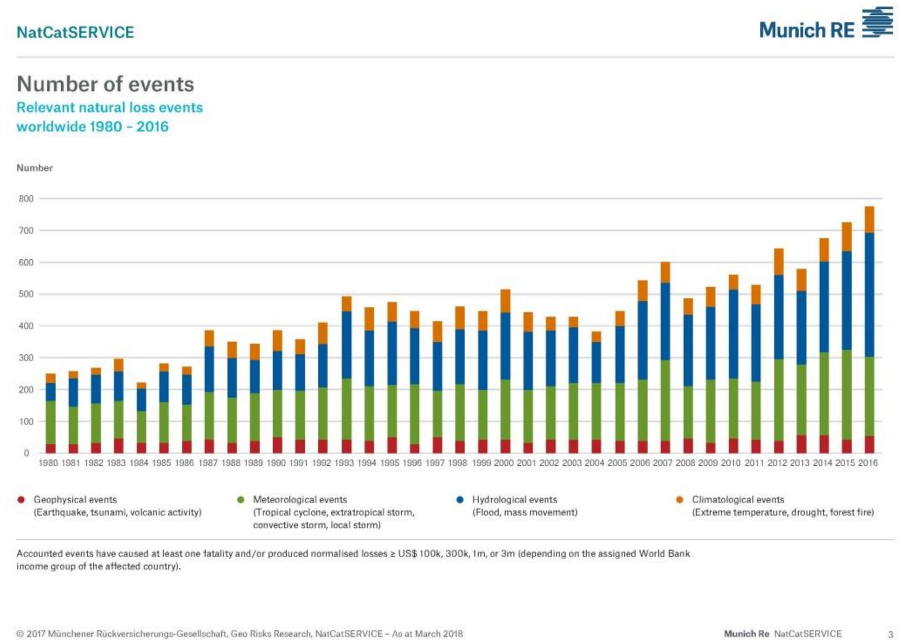
1930s: Development of CFCs

1) Joule-Process, first usage 1844 by John Gorrie (USA)
2) First experiments with H_20 for ice production 1755 by William Cullen (GB)
3) CO_2 used first time 1862 by Thaddeus Lowe (USA)

Consequences of climate change

- Dry zones will move South in southern hemisphere and north in northern hemisphere
- More heavy rain (storms) in northern and southern latitudes
- Water shortage due to the melting of glaciers which are drinking water reservoirs
- No longer Permafrost in Siberia, Canada and Alaska
- North pole ice free in summer
- Increased ice discharge from Antarctica due to higher snowfall and Melting of Greenland ice cap
  → Sea level rise 0.5 mm/y
- Warmer oceans
  → Sea level rise by 1.4 mm/y

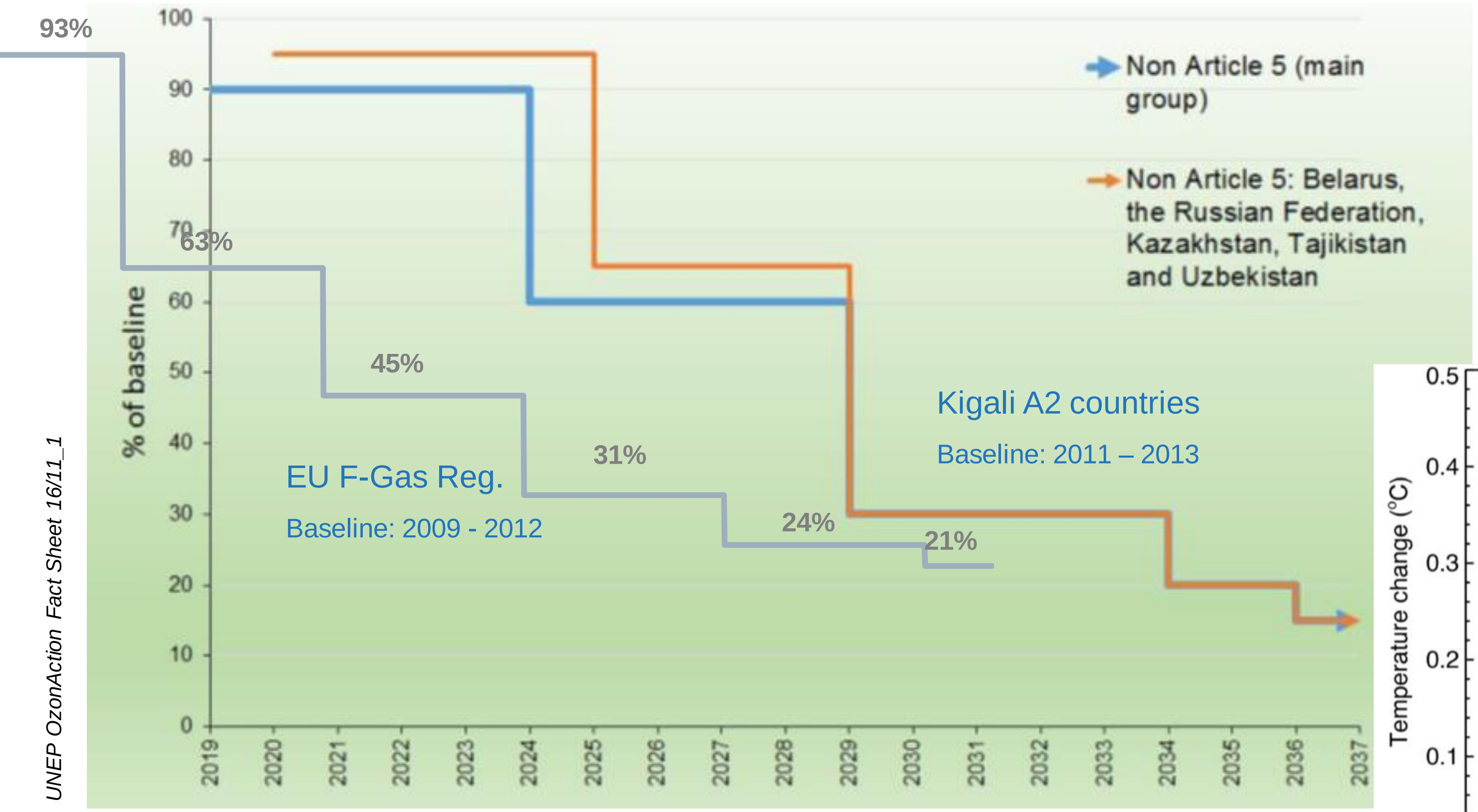
- More climate related disasters



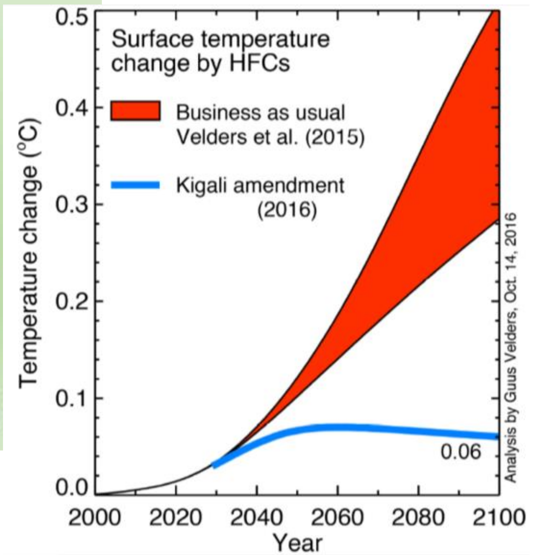
And that‘s without floods due to rising sea levels !

Kigali Amendment and EU F-Gas Regulation

or how to safe 0.5 K global warming

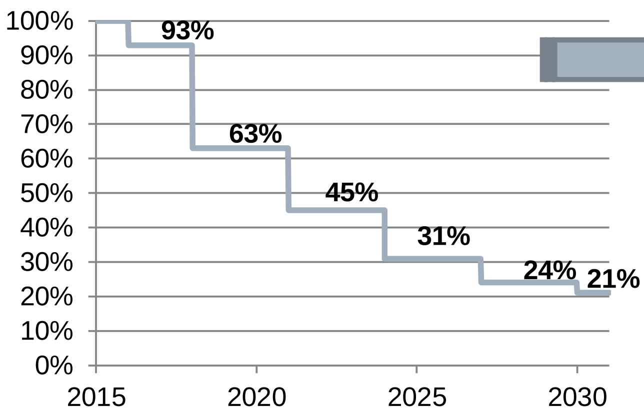


UNEP OzonAction Fact Sheet 16/11_1



#1: Reduce Refrigerant Charge

HFC phase down



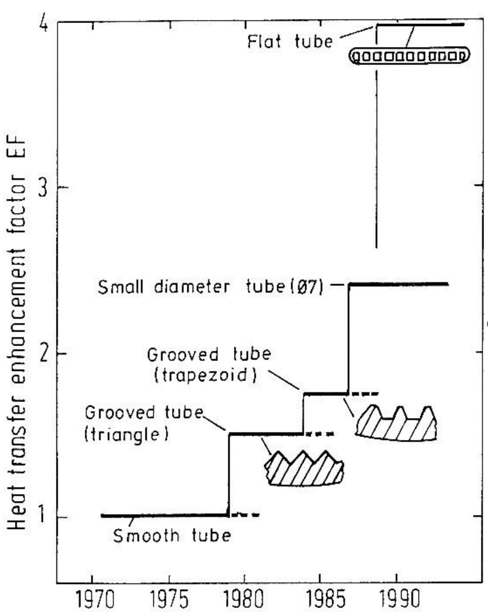
Price for F-Gases will increase	Increased use of flammable and toxic refrigerants	Leak control scheme based on CO_2 equivalent charge

System charge should be minimized

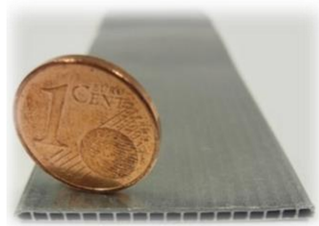
→ Mini channel heat exchanger

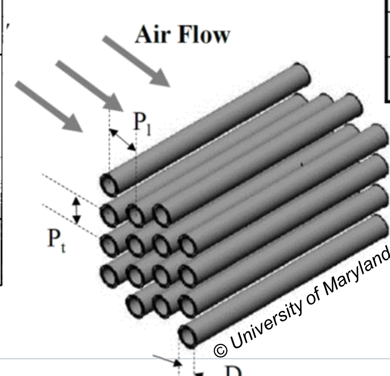
	Round tube and fin	Minichannel
Depth	100 %	28 %
Face area	100 %	75 %
Weight	100 %	42 %
Refrigerant charge – in Condenser in System	100 % 100 %	7 % 65 - 70 %
Air side pressure drop	100 %	74 %
COP	100 %	110 %

… at the cost of higher refrigerant side pressure drop



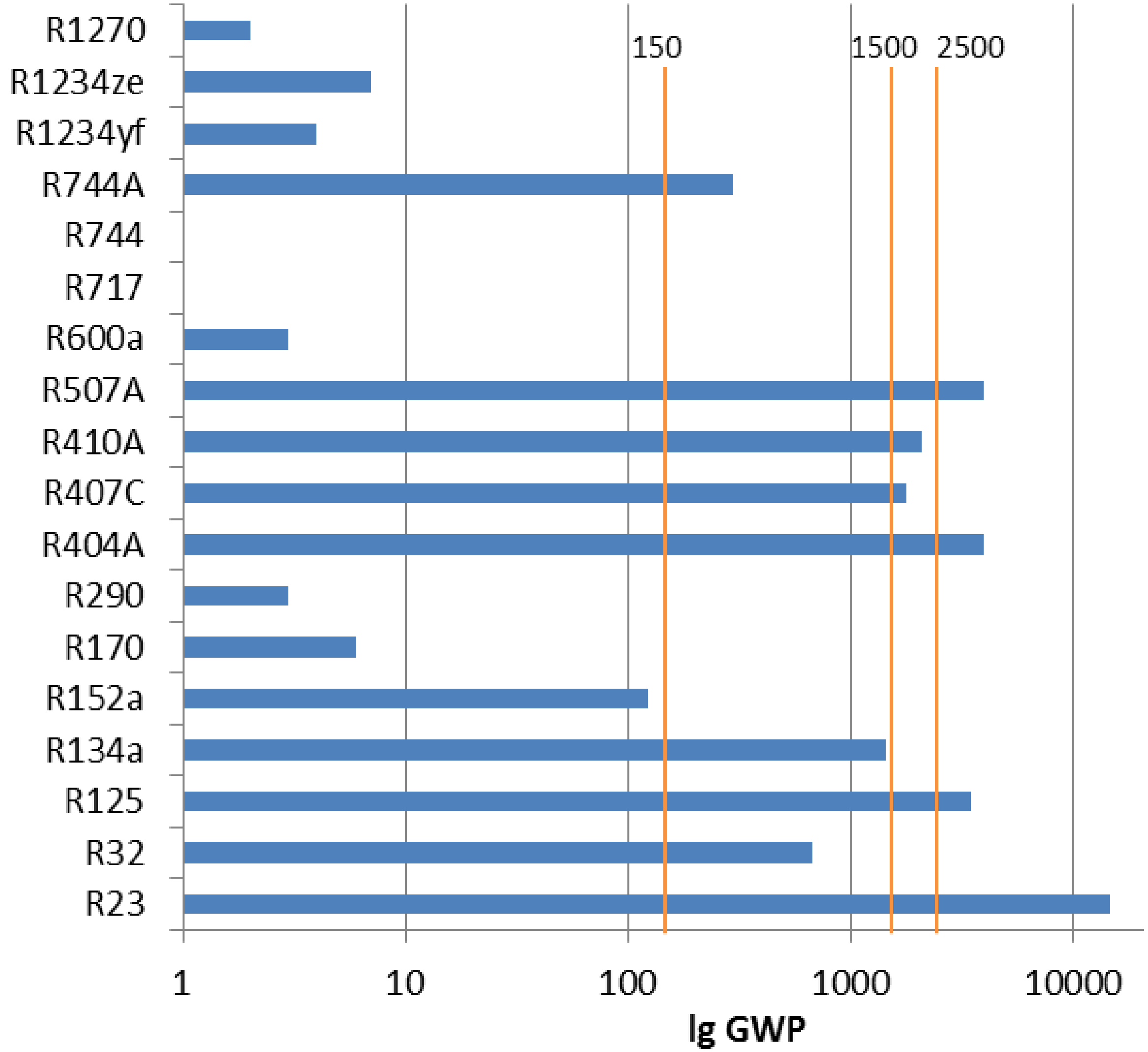
Marvillet, C.: Recent Developments in Heat Exchangers for Automotive Applications. in Recent Development in Finned Tube Heat Exchangers. Edited by Marvillet, C. et al., 1990, Danish Technological Institute, Denmark, S. 8 - 51





Bare tube heat exchanger (ID = 1.25 mm)

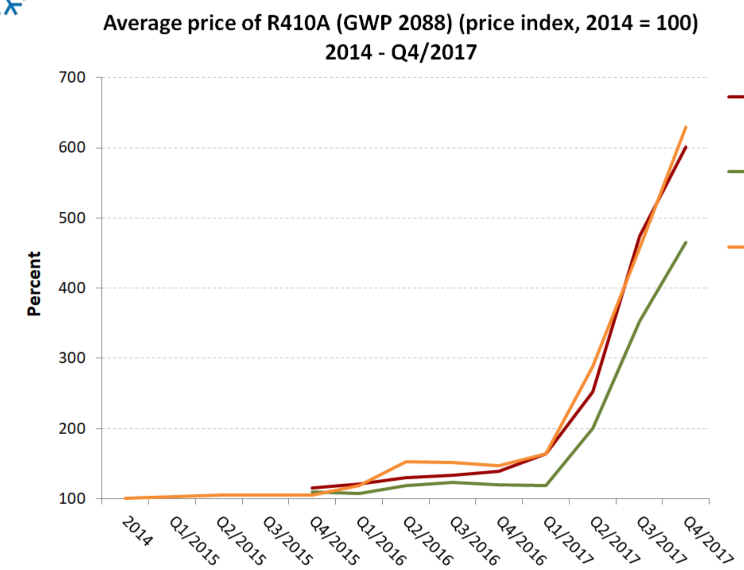
EU F-Gas Regulation → use low-GWP Refrigerants

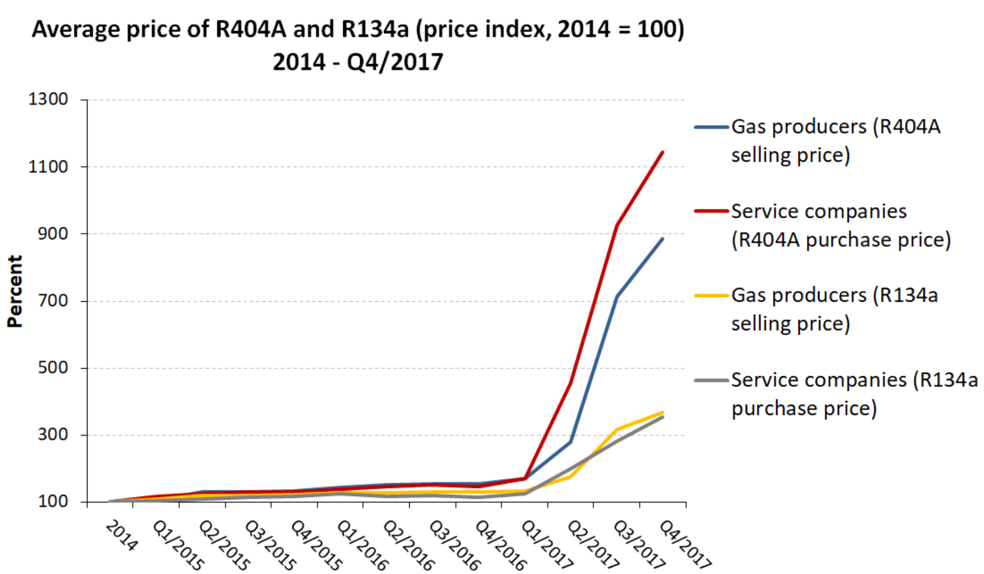


Other selected items

- Reporting of HFOs, HFEs, NF_3 and other fluorinated substances (Article 19 and Annex II)

European HFC prices shoot through the sky





Ökorecherche: Excerpt for participants: Monitoring of HFC prices in the EU. March 2018

Increase follows GWP:

Price increase until now

R134a: More than 3 times

R404A: More than 9 times

R410A: More than 6 times

R23: More than 30 times !

... much more than Bitcoin

European HFC prices shoot through the sky

- In the course of last year prices have however increased substantially
- The price increases are clearly related to the GWP of the substances.
- The developments therefore largely reflect what was expected to be the impact of the phase-down mechanism where successive quota reductions increasingly favour the use of low GWP HFC as well as non-HFC gases.
- Gas prices have reached levels of 20€/tCO_2e which is fully within the range that was considered to be a proportionate contribution by this sector to the 2050 roadmap.
- The existing price signal is clearly a good incentive for stakeholders to
  - switch to low GWP technologies wherever and whenever possible,
  - to prevent leakage and
  - to reclaim gases.

Briefing Paper: Progress of the EU HFC phase-down

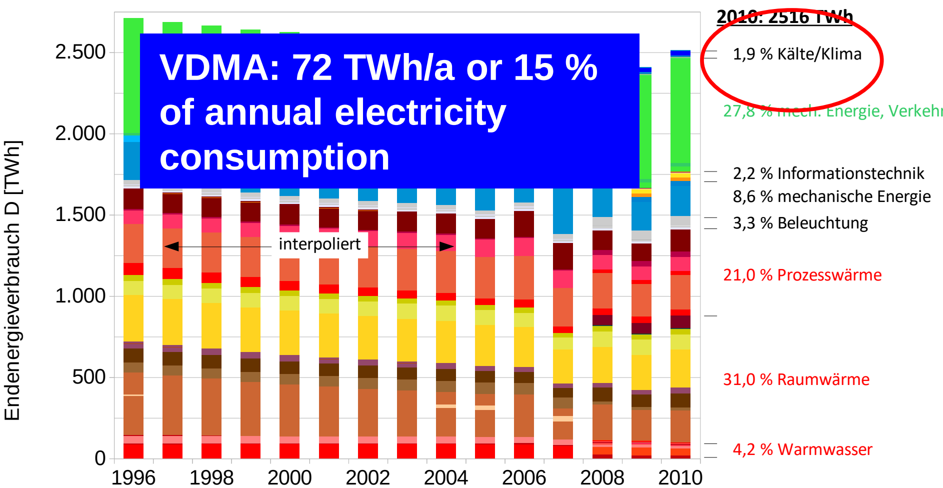
F-gas Consultation Forum Meeting on 6 March 2018

Refrigeration Systems Contribution to Global Warming

Also indirect contribution via energy consumption

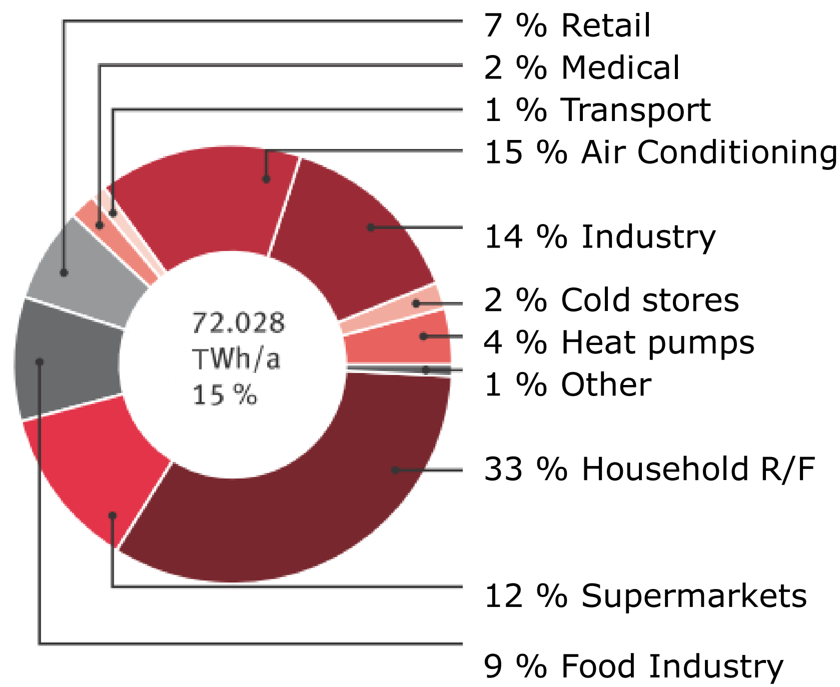
According to IIR worldwide 15 % of electricity for refrigeration and air conditioning

Total energy consumption in Germany /BMWi/



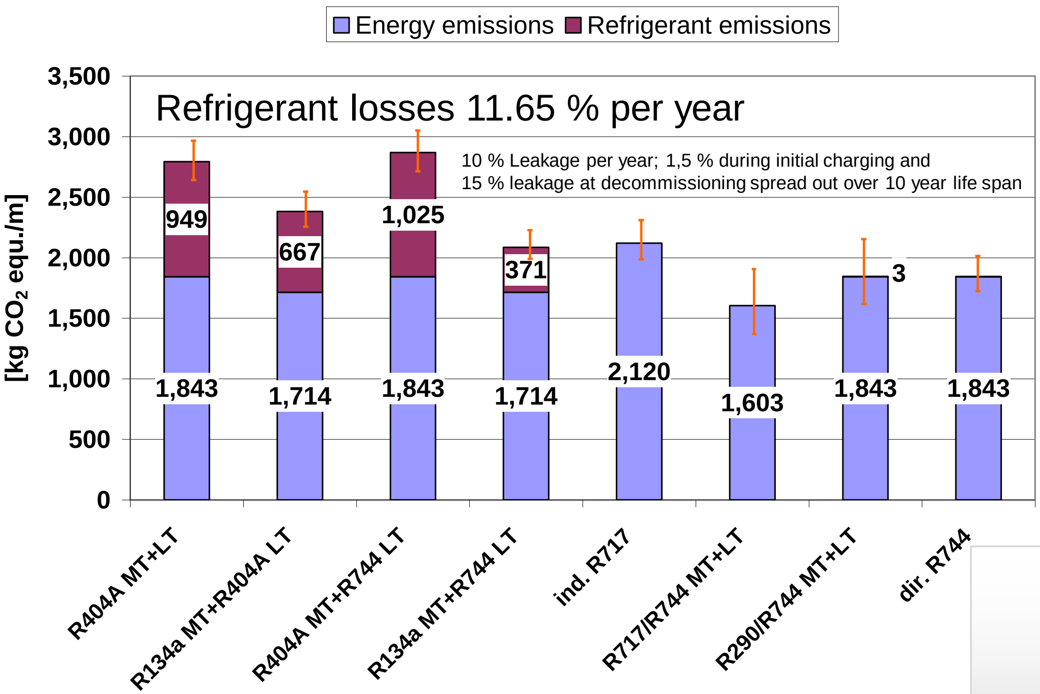
/Schwarz, J.: Energieeffizienz in der Kälte- und Klimatechnik. Energieeffizienz Kolloquium, Hochschule Karlsruhe, 12. Okt. 2012/

Electricity Consumption for Refrigeration and air conditioning



/VDMA/

TEWI Results Centralized Supermarket System

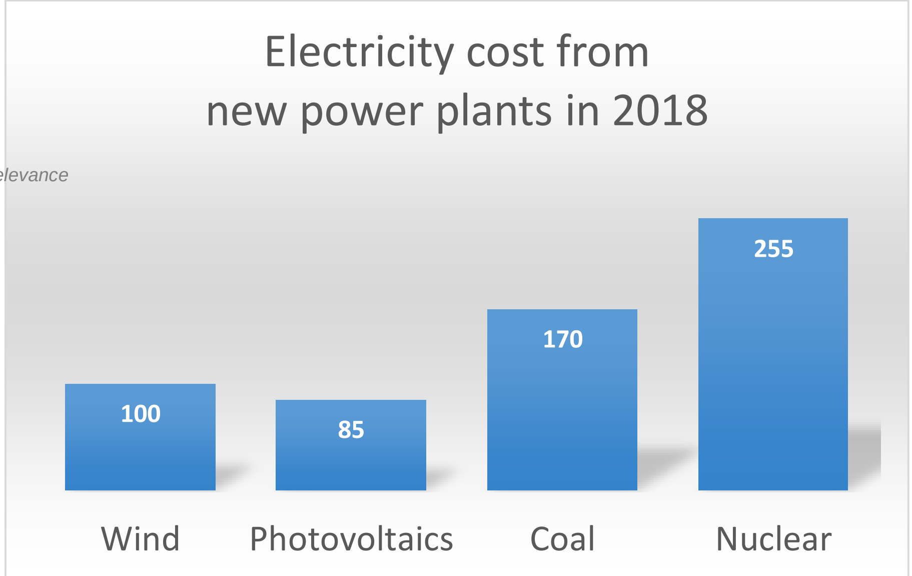


J.-M. Rhiemeier, J. Harnisch, C. Ters, M. Kauffeld and A. Leisewitz: Comparative Assessment of the Climate Relevance of Supermarket Refrigeration Systems and Equipment. Research Report 206 44 300 UBA-FB 001180e (2009)

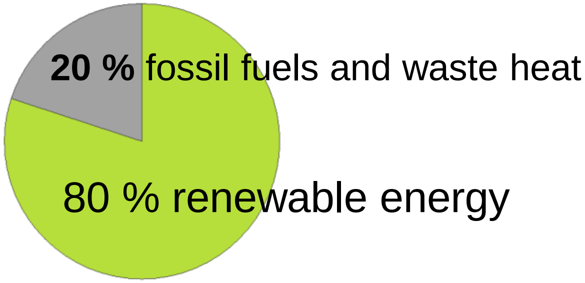
But:

2015, for the first time more newly installed wind and solar power capacity than conventional power plants

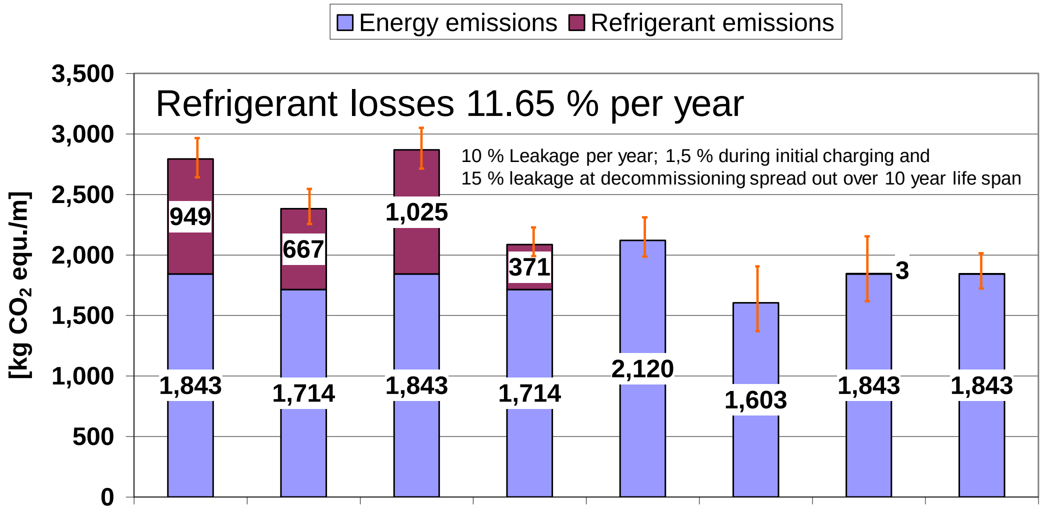
/SIEMENS 2016/



German Goal by 2050

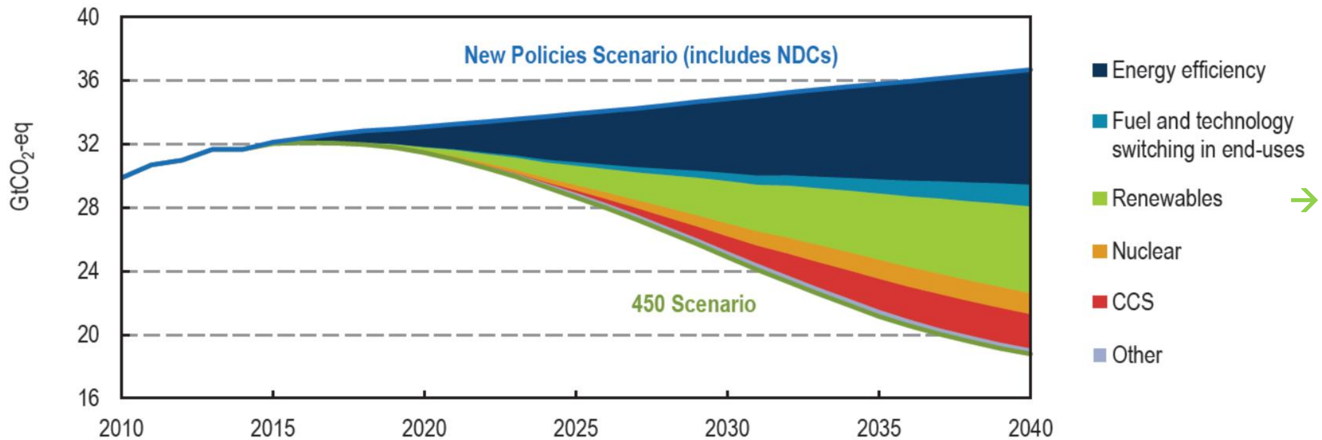


TEWI Results Centralized Supermarket System



Measures needed to surpass current NDCs to reach 2°C trajectory (450 Scenario), through 2040

NDCs - Nationally determined contributions



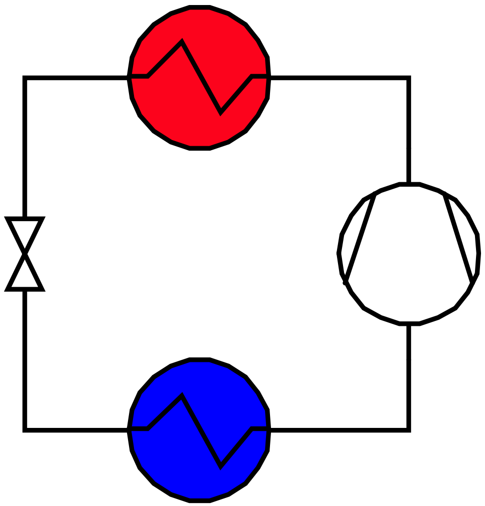
Largest Share !

→ Energy Storage needed !

Note: The New Policies Scenario (NPS) is the central scenario of the World Energy Outlook *and includes the energy-related components of NDCs submitted by 1 October 2015*

Source: Adapted from IEA (2015b), World Energy Outlook 2015.

Energy Efficiency



Every degree

lower condensing temperature

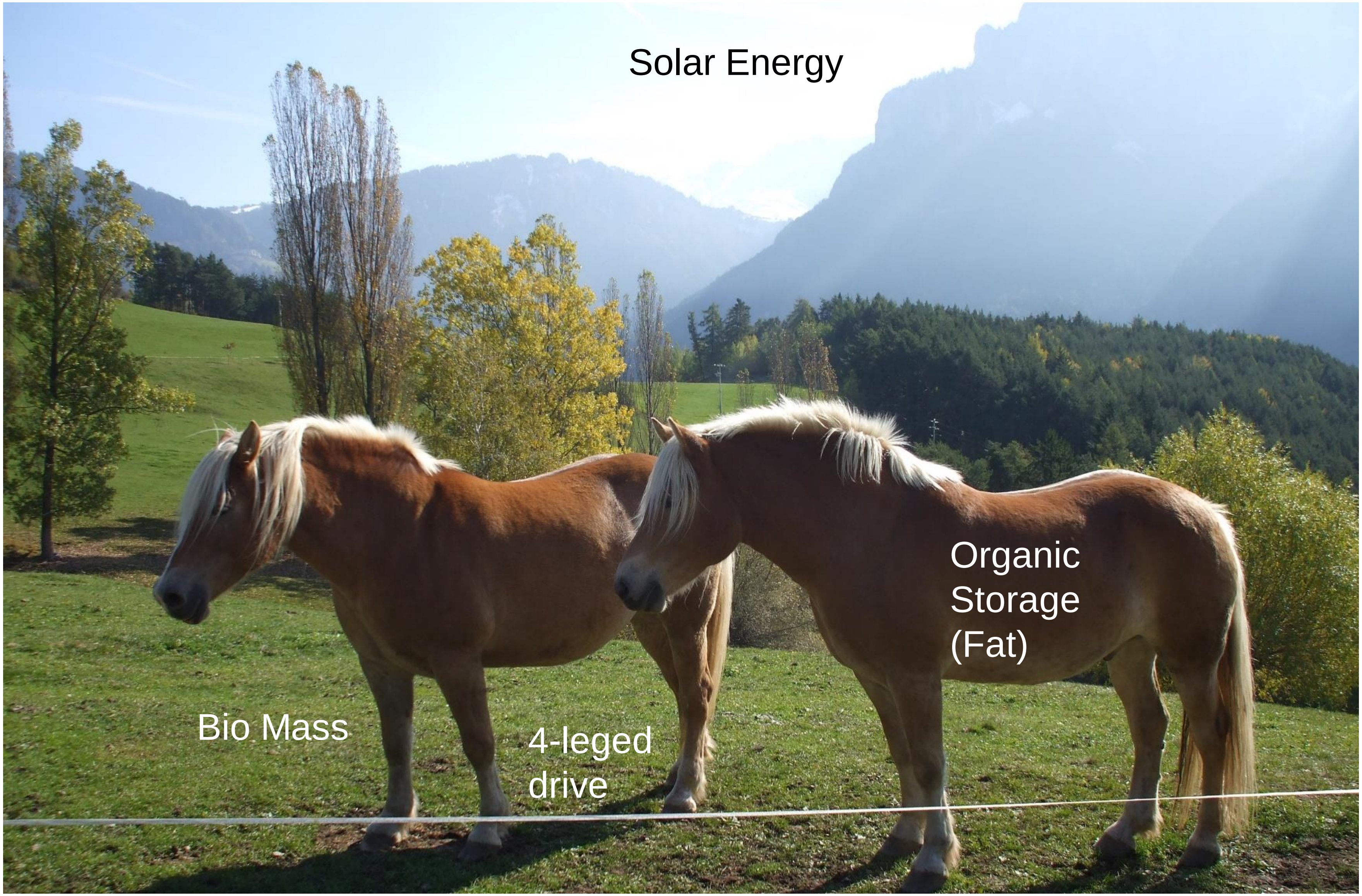
or

higher evaporation temperature

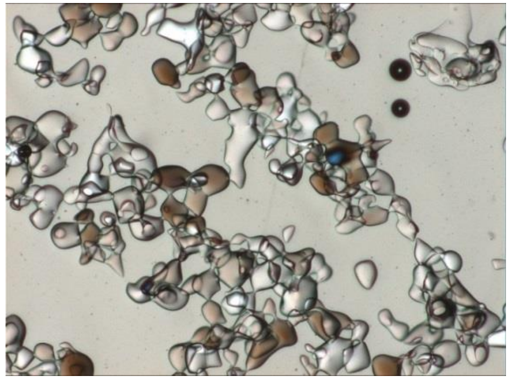
→ **2 to 3 %**

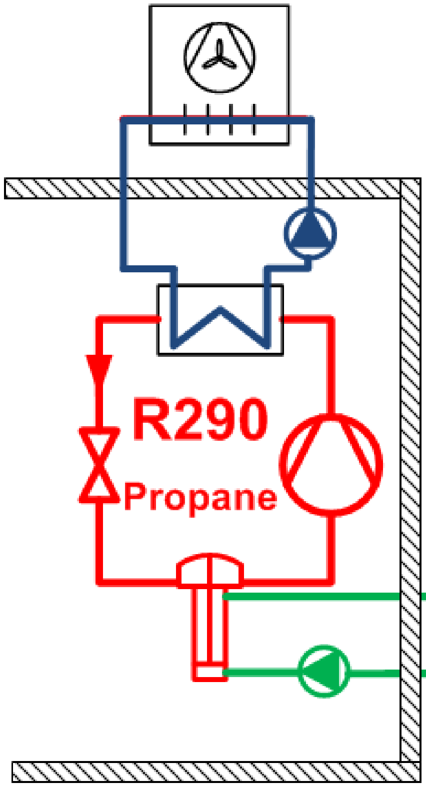
lower energy consumption

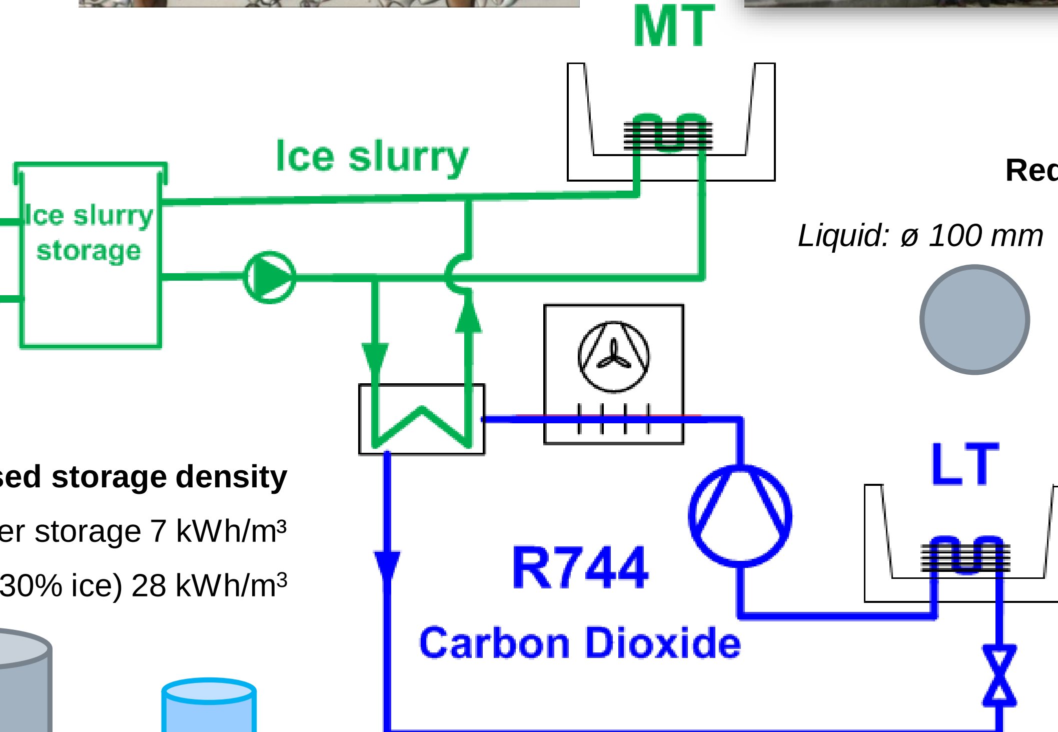
Renewables → Energy Storage Needed



Energy Storage at KIT Karlsruhe







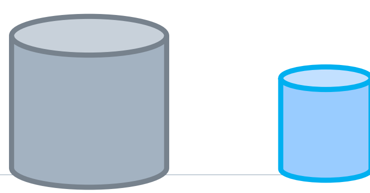
Reduced pipe diameter

Liquid: ø 100 mm → ø 35 mm ice slurry

Increased storage density

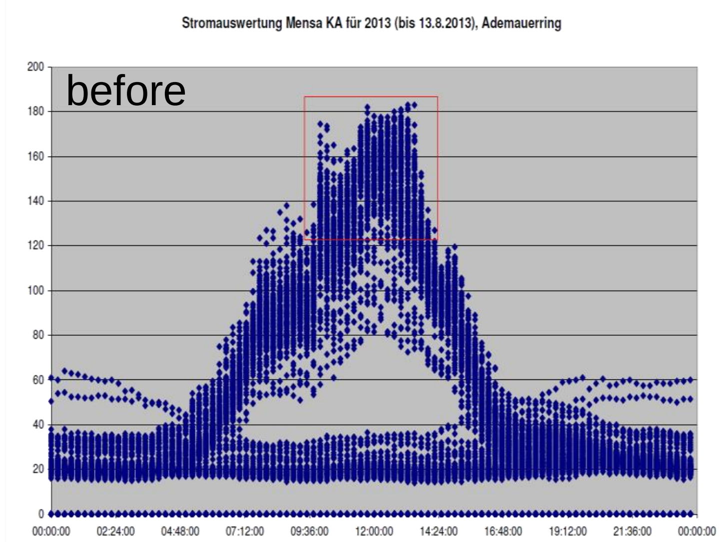
Chilled water storage 7 kWh/m³

Ice slurry (30% ice) 28 kWh/m³



R290/Ice Slurry/R744 Refrigeration System

6 ice generators with scrapers at 14 kW refrigeration capacity (approx. 3.5 Tons ice per day each)



3 separate R290 circuits, 10 kg each

Cooling of condensers by Ethylen-Glycol-loop

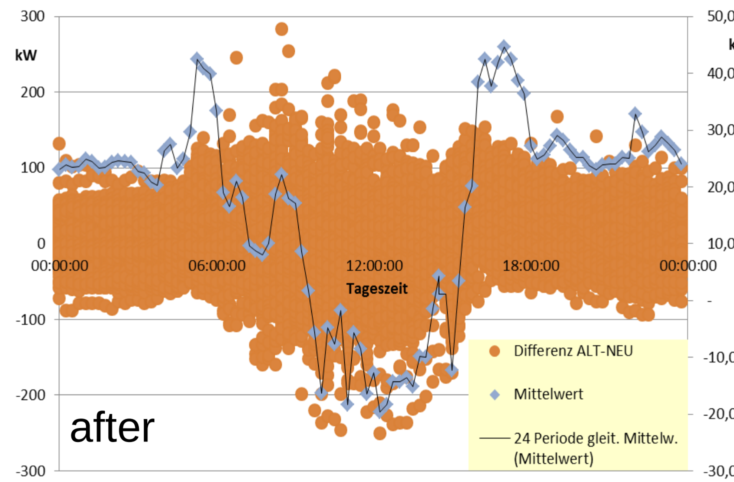
Approximately 8 % Ethanol

Ice content 5 to 30 %

40 m³ cylindrical storage
(at 30 % ice approx. 1,100 kWh)

Ice production from 3 p.m.
to max. 9 a.m.

Propane refrigeration system off
from 9 a.m. to 3 p.m.

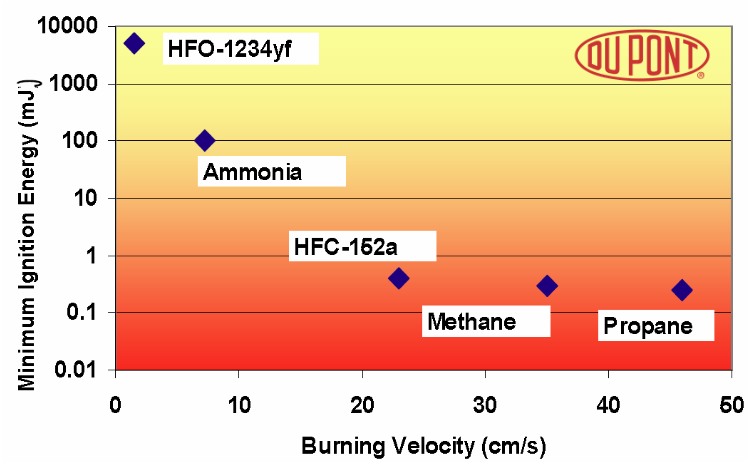


Low GWP Refrigerants

Answer from the Chemical Industry: HFO = unsaturated HFC

e.g. R1225ye(Z), R1225ye(E). R1234yf, R1234ze(Z) or R1234zf
or Blends of HFO + HFC *(Temperature Glide !!!)*

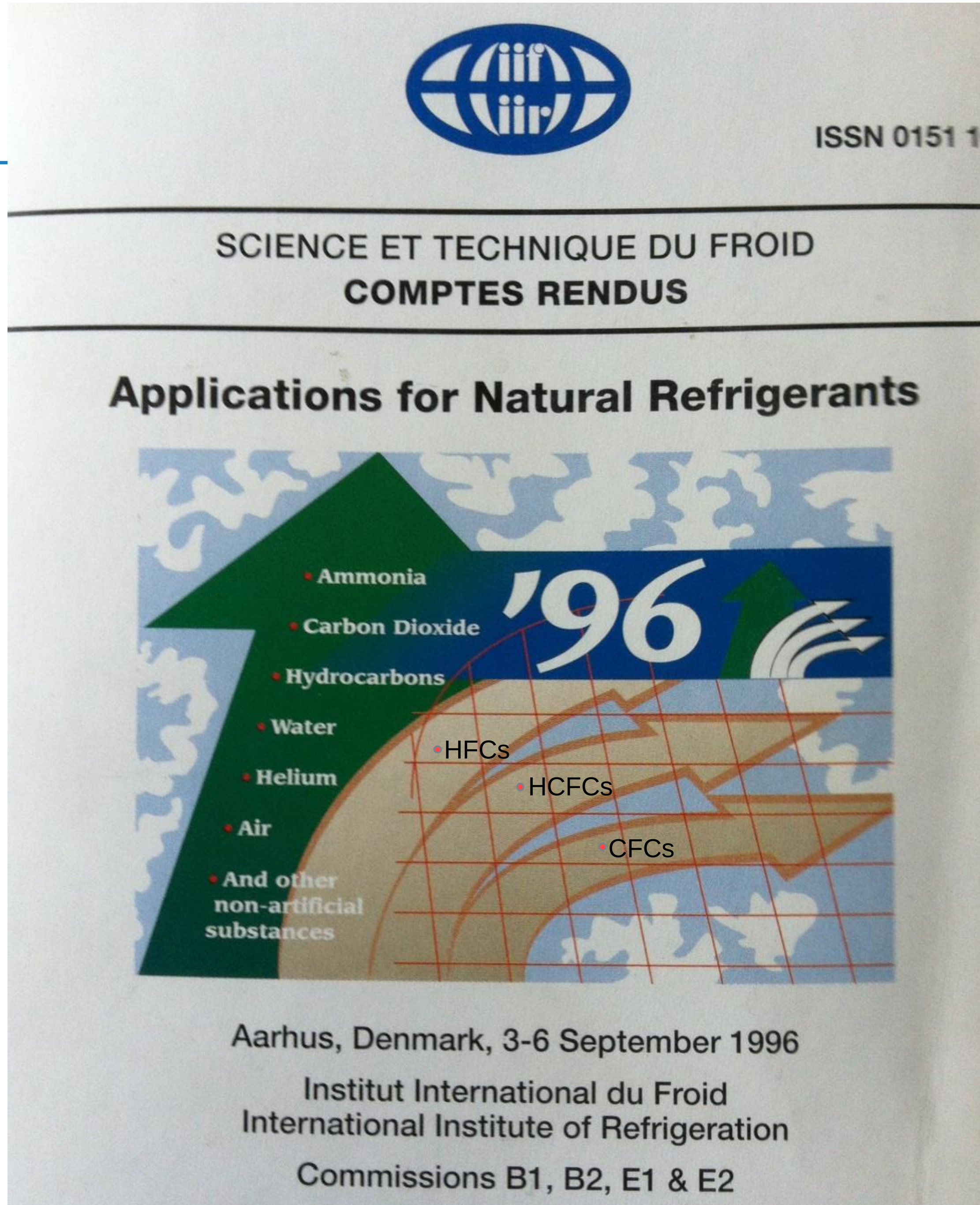
- ☐ Quick break down in atmosphere
  - → GWP of 1 - 5
- ☐ 4 – 5 times more TFA after break down in atmosphere than R134a
  - → From car air conditioning alone up to twice the TFA-concentration in atmosphere than before (natural + man made)
  - → TFA is very stable in environment → Accumulation in terminal water bodies
- ☐ (Mildly) flammable
  - Flame propagation velocity lower than for HCs (1.5 cm/s instead of 46 cm/s)
  - Required ignition energy much higher than for HCs (5,000 – 10,0000 mJ instead of 0.25 mJ)
  - Heat of combustion 5-times lower than HC
  - Auto ignition temperature similar to HCs, i.e. ≈ 400 °C
  - → ASHRAE class 2L
- ☐ Forms Hydrogen Fluoride (HF) upon combustion
- ☐ Health issues at high concentrations for prolonged time periods due to high reactivity
- ☐ HCFC by-products during manufacturing
- ☐ Still very expensive



HFO – a personal View

60 – 30 – 15

- It took 60 years (1930 to 1990) to find out that CFCs damage the ozone layer
- It took 30 years (1990 to 2020) to acknowledge HFCs contribute noticeable to global warming
- It will take 15 years to accept that HFOs are harmful to the local environment *(fitter's health and terminal water bodies)*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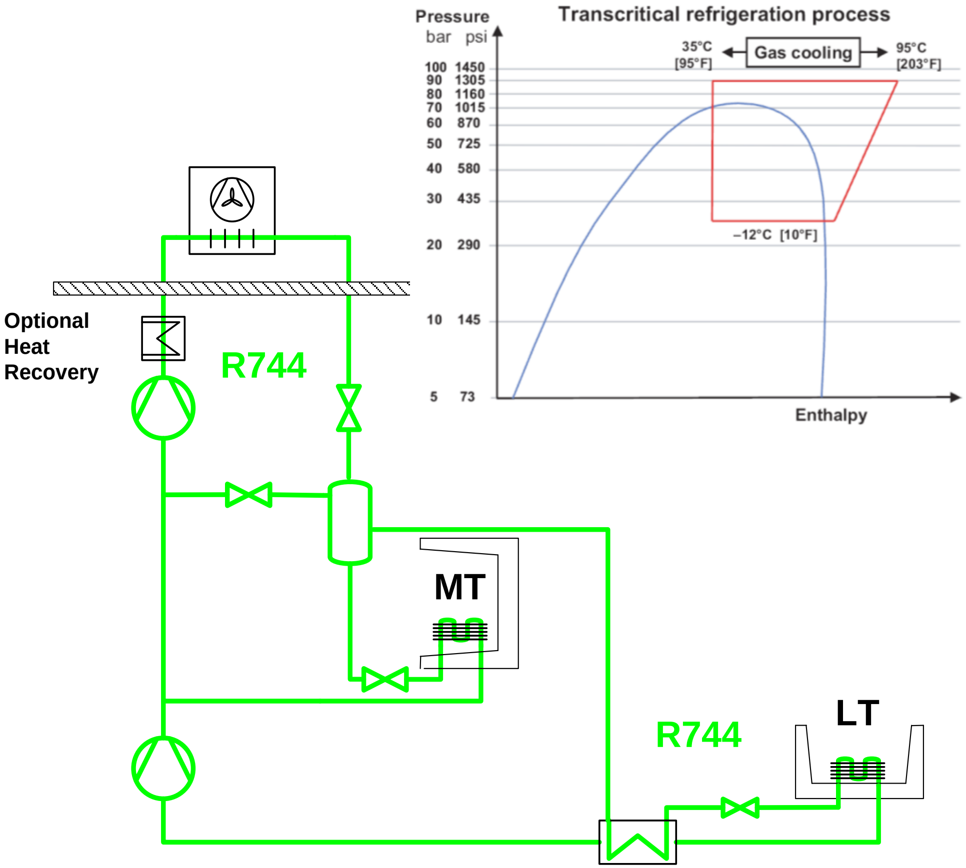
ISSN 0151 16
SCIENCE ET TECHNIQUE DU FROID
COMPTES RENDUS
Applications for Natural Refrigerants
Ammonia
Carbon Dioxide
Hydrocarbons
Water
Helium
Air
And other non-artificial substances
'96
HFCs
HCFCs
CFCs
Aarhus, Denmark, 3-6 September 1996
Institut International du Froid
International Institute of Refrigeration
Commissions B1, B2, E1 & E2

Refrigerants

	GWP	Flam-mability	Toxicity	Price of refrige-rant	Price of system	Volumetric refrigeration capacity	Theoretical system efficiency
HFCs	high	no	no	moderate	low	medium	good
HFOs	low	moderate	?	high	Medium	medium	good to medium
Hydrocarbons	low	yes	no	low	medium	medium	good
Carbon Dioxide	low	no	only at high conc.	low	medium	high	good to medium
Ammonia	low	can be ignited	yes	low	high	medium	good
Water	low	no	no	low	medium	Low	good

… but many other aspects to be considered,
e.g. oil miscibility, real system efficiency etc.

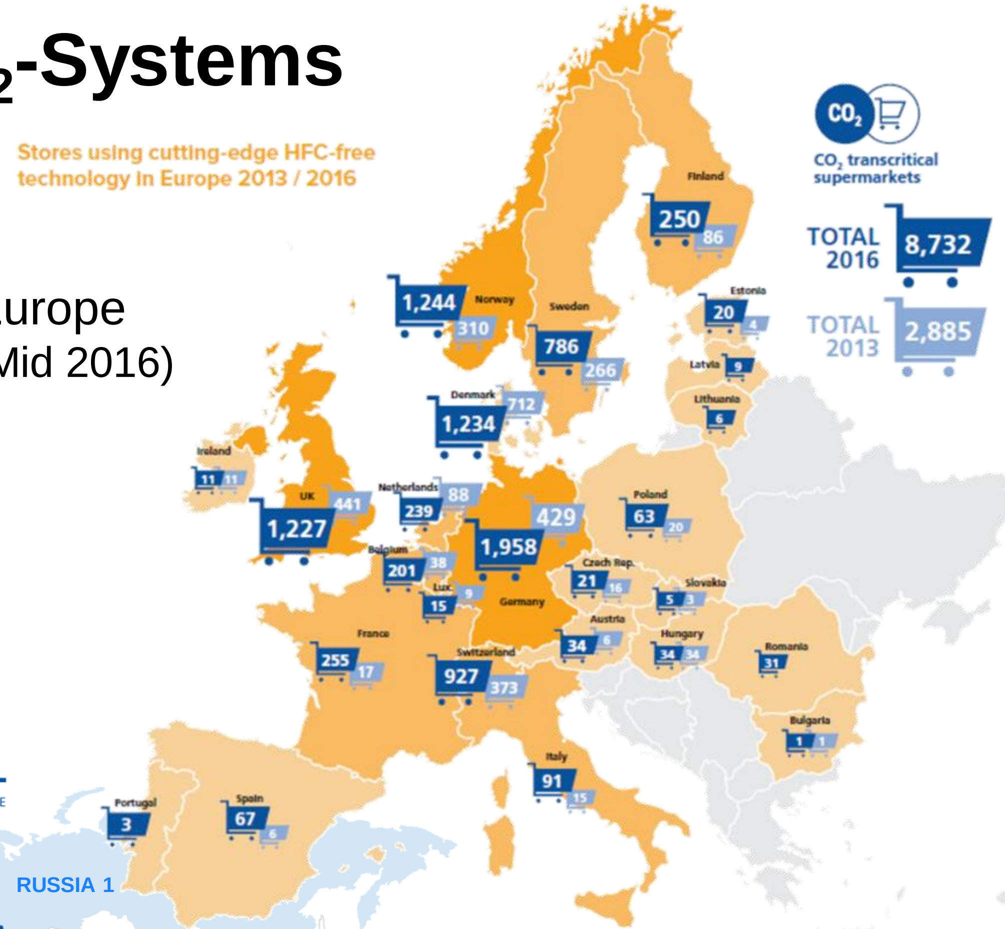
CO_2 transcritical



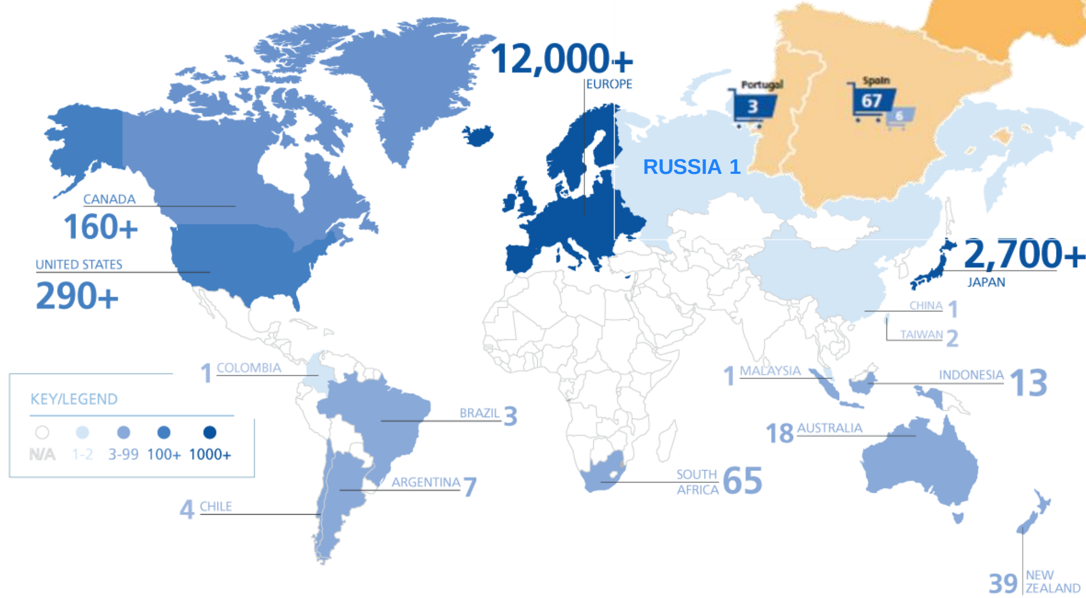
- More than 15 000 transcritical centralized systems built worldwide until 2017

Transcritical CO_2-Systems

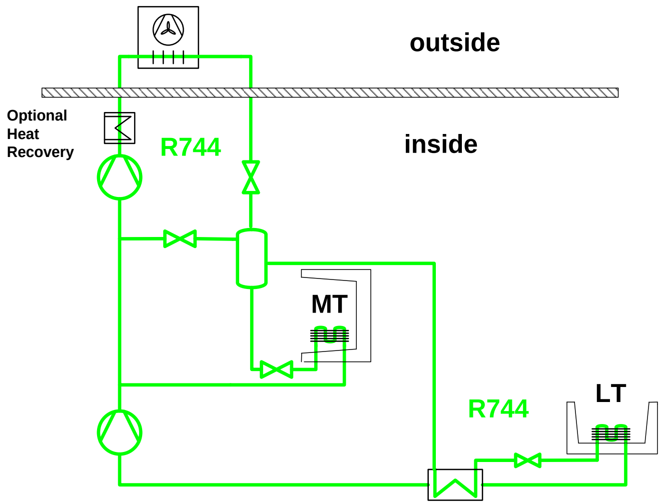
Europe
(Mid 2016)



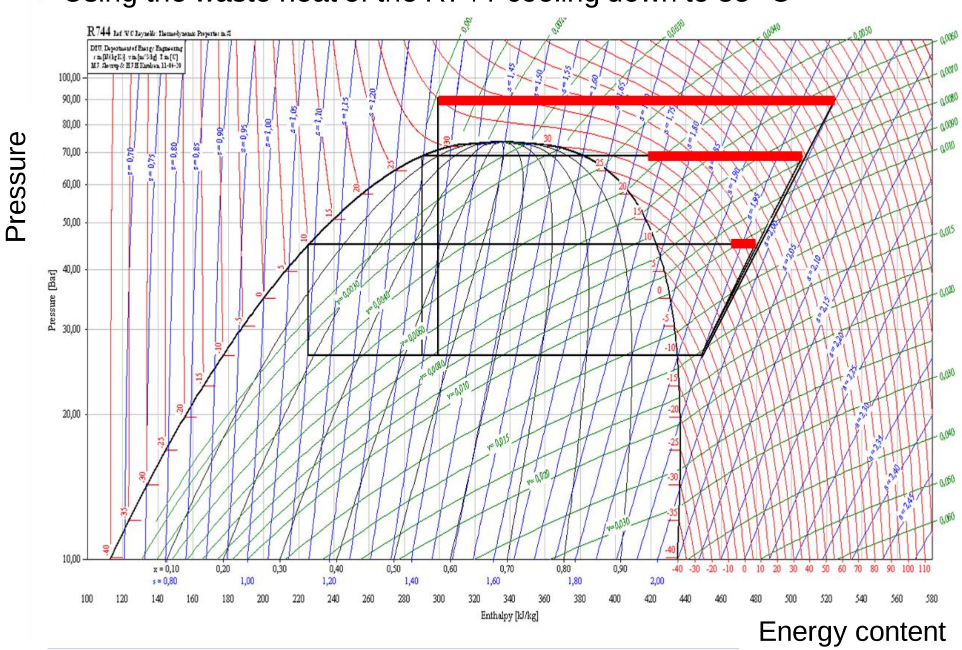
Worldwide (as of Oct 2017)



CO_2 transcritical



Using the waste heat of the R744-cooling down to 35 °C



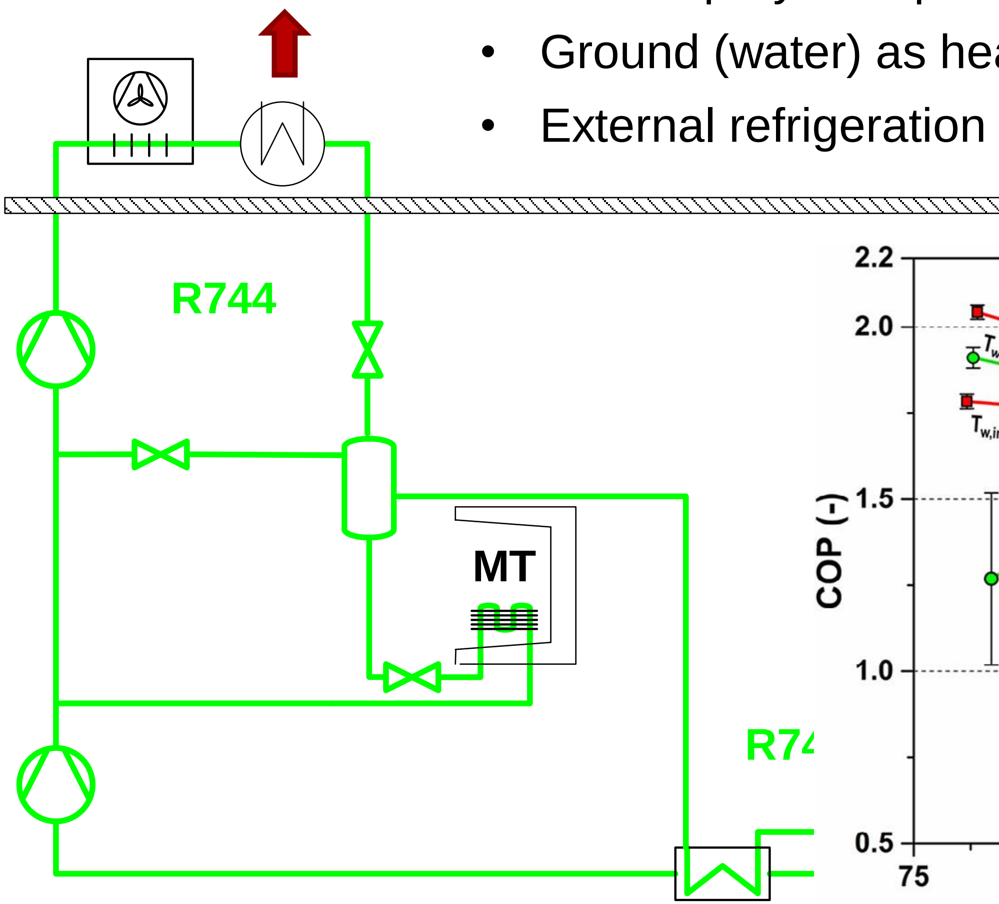
- More than 15 000 transcritical centralized systems built worldwide until 2017
- Energy efficiency good in cold and moderate climate, i.e. north of Switzerland
- energy efficiency of basic transcritical cycle lower than standard R404A system in warm climate
- Initial cost up to 10 % higher than standard R404A system
- CO_2 requires special knowledge due to high pressures – up to 120 bar in outdoor coil
- Indoor part of system can be kept below 40 bar during normal operation
- Take care of excessive pressures during longer stand still period
- Small pipe dimensions
- Good heat recovery

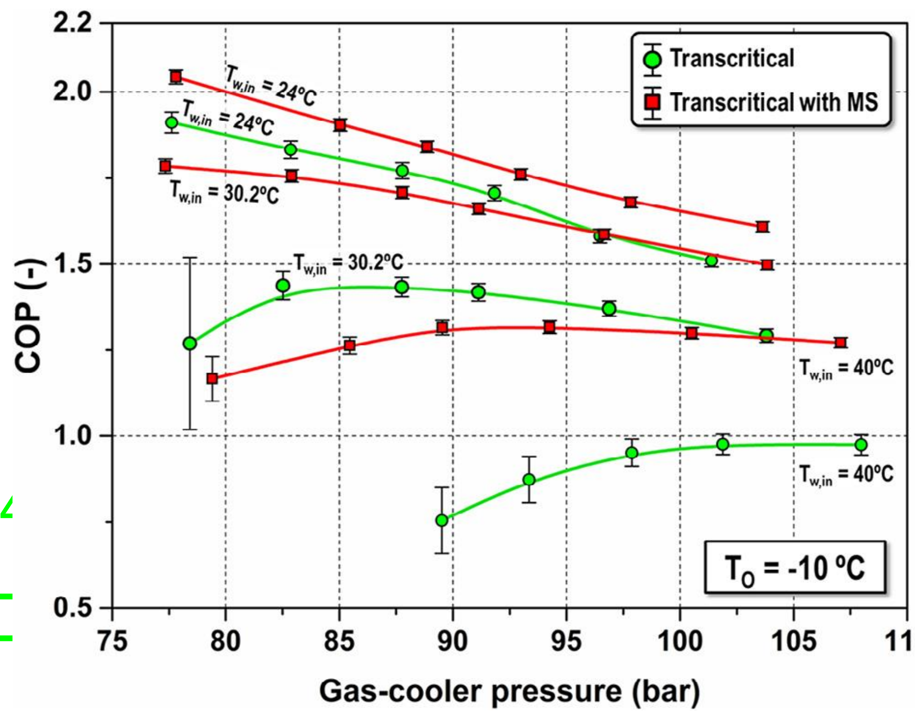
Optimization of transcritical CO_2-Systems

For high ambient temperatures:

Lower gas cooler exit temperature:

- Water spray / evaporative cooling
- Ground (water) as heat sink
- External refrigeration system (mechanical subcooling)

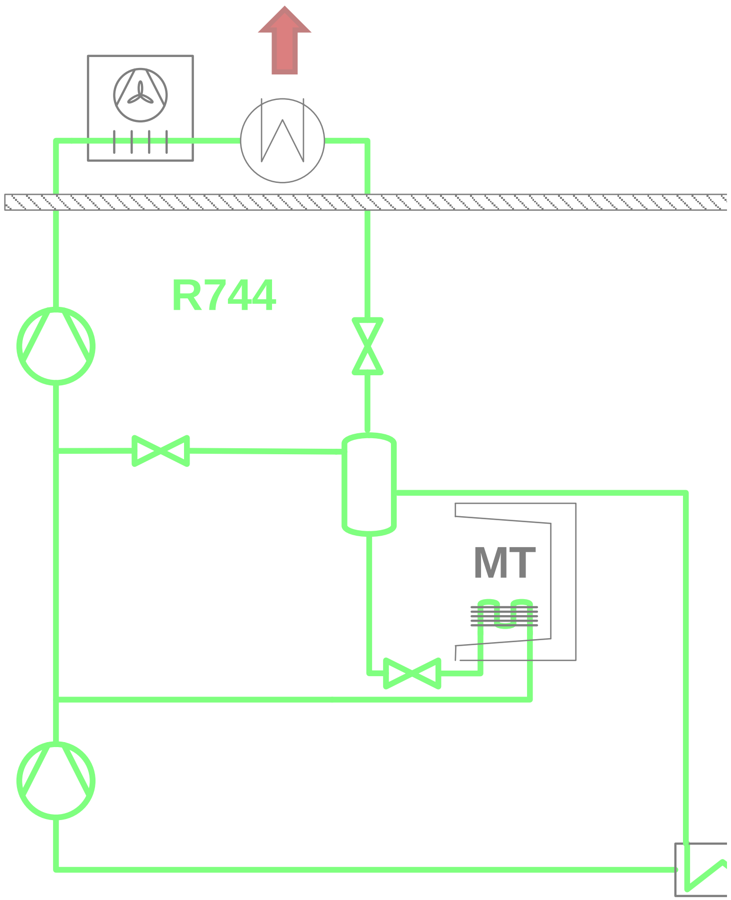




Llopis, R.; Nebot-Andrés, L.; Ramón Cabello, Daniel Sánchez, Jesús Catalán-Gil: Experimental evaluation of a CO2 transcritical refrigeration plant with dedicated mechanical subcooling. Int. J. Refr., Volume 69, Sept. 2016, P. 361-368

Optimization of transcritical CO_2-Systems

For high ambient temperatures:



Mechanical subcooling 1992 with R12

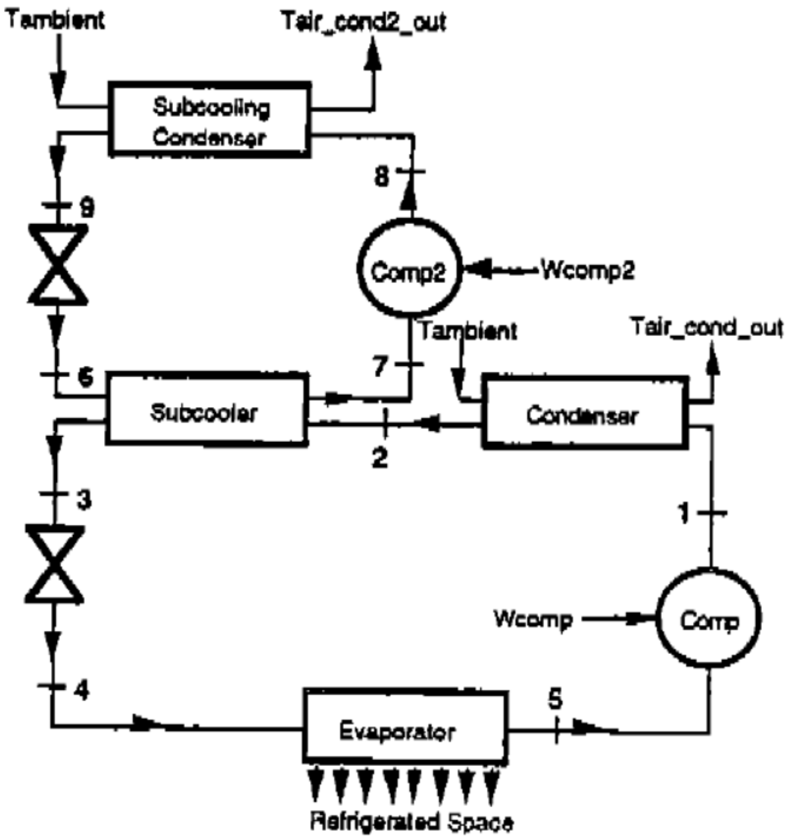


Figure 1: Component diagram for dedicated mechanical subcooling cycle.

Thornton, J. W.; Klein, S.A.; Mitchel, J. W.: Dedicated ***Mechanical Subcooling*** *Design. Straregies for Supermarket Applications. Int. Refr. & AC Conf. Purdue, 1992*

Optimization of transcritical CO_2-Systems

For high ambient temperatures

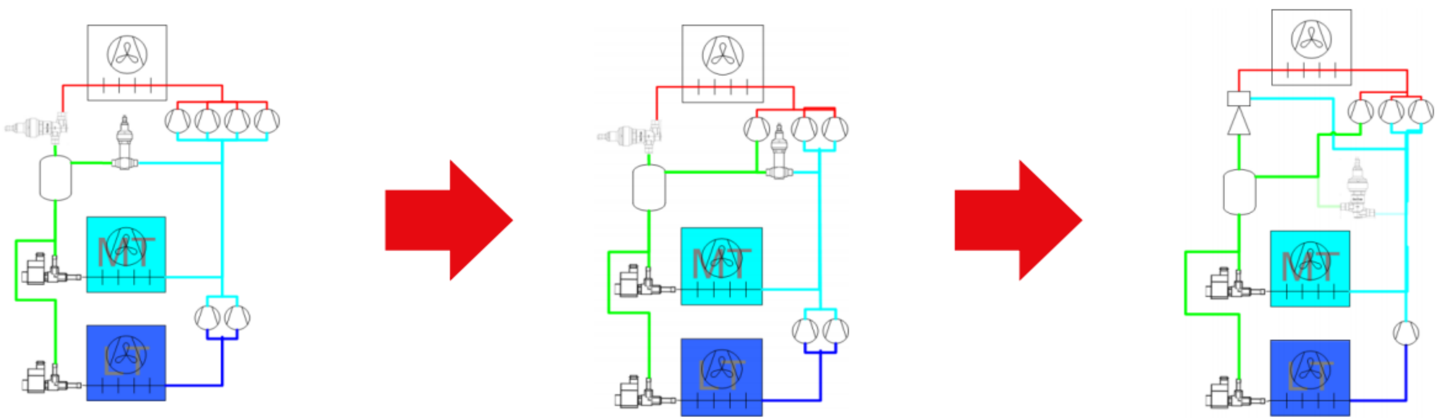
Madsen, K.B.; Knudsen, J.: Ejector Technology: The next generation in transcritical CO2. ATMOsphere America 2015

Temperature with higher efficiency compared to R-404A

Booster system (reference)	Parallel compression system	Ejector systems	Flooded systems
27°C/82°F	38°C/101°F	All ambient	All ambient
7,000 systems	**1,000** systems	**30** systems	**5** systems
2007 Commercially available	**2011** Commercially available	**2015** Semi-commercially available	**2015** Testing

EPTA: FTE
Full Transcritical Efficiency
17 % energy savings
due to flooded MT w/o ejector

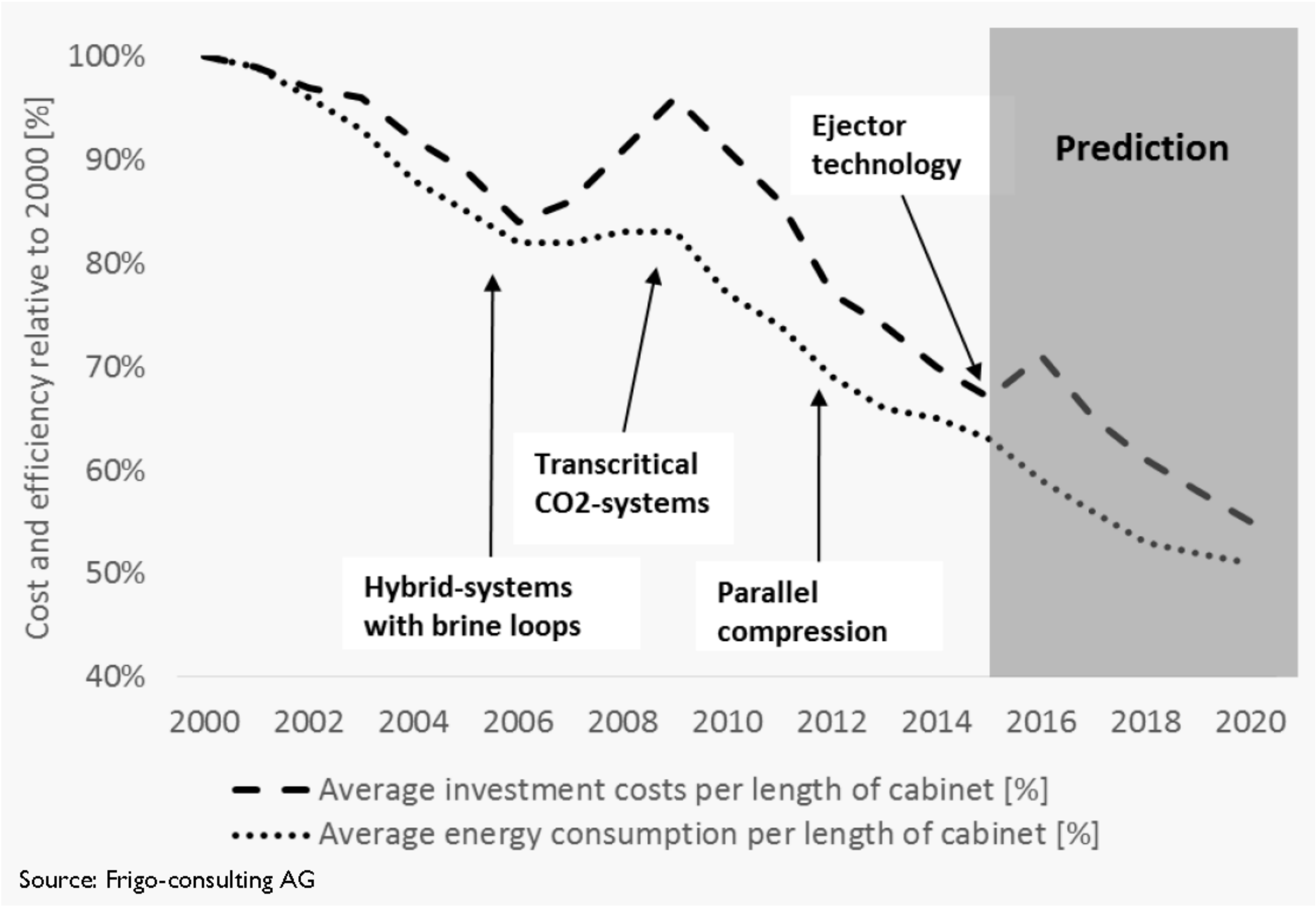
Torben Funder-Kristensen: Barriers and opportunities for selection of best low GWP technologies. ATMOsphere Europe 2015



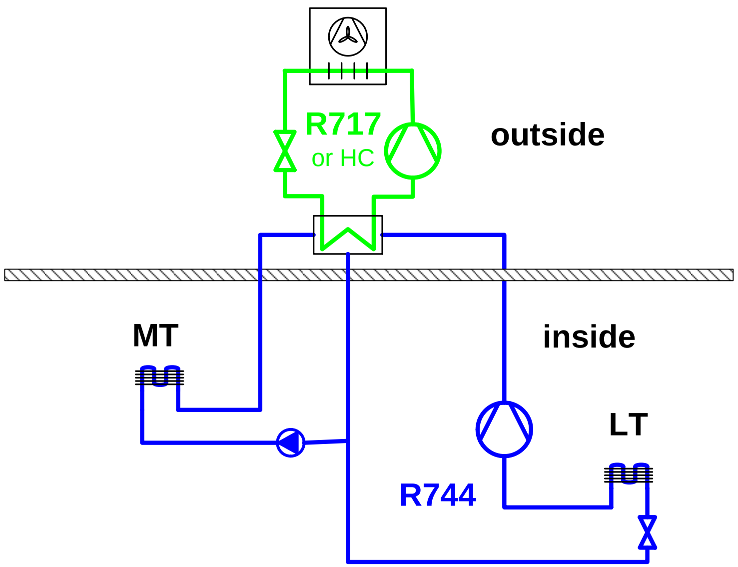
Traditional transcritical booster system → System with parallel compression → System with ejector and parallel compression

R744 Supermarket Systems

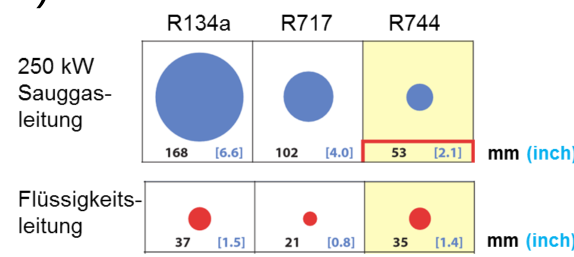
Cost and Efficiency



Cascade System with Ammonia and CO_2



- R717 charge only 10 – 20 % of all-ammonia system
- CO_2-Compressors are typically 8–12 times smaller than comparable ammonia compressors
- Energy efficient application of CO_2-cascade – MT and LT sub-critical *(18 to 25 % better than HFC DX system)*
- All components available; CO_2 pressure during operation below 40 bar
- Significantly, smaller suction pipes (typically 2 to 3 sizes smaller)



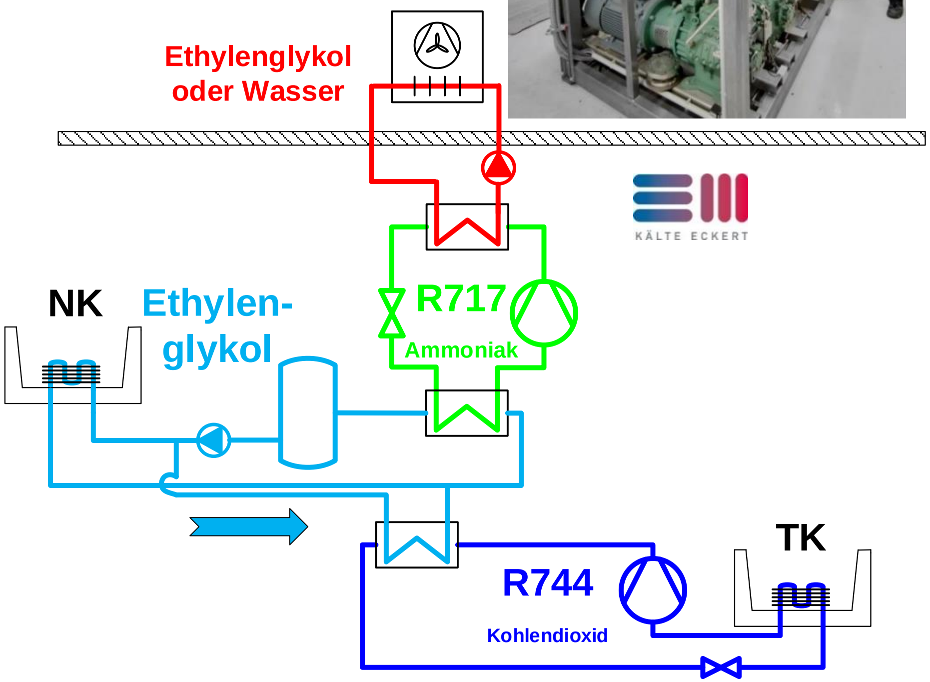
© Danfoss :CO_2 refrigerant for Industrial Refrigeration

- Lower maintenance cost due to fewer service checks and cheaper refrigerant
- Invest 10 – 20 % higher than HFC, but payback time often less than 2 years

Milligan, K.; Ali, M.: Ultra-low charge NH_3/CO_2 cascade system in a retail environment. Atmosphere America, 2016

Ole Christensen: System Design for Industrial Ammonia/CO_2 Cascade Installations. 2006 IIAR Ammonia Refrigeration Conference & Exhibition, Reno, Nevada

Dream Team: Ammonia CO_2-Cascade



Ammonia refrigeration for kitchen at Daimler

5.000 meals daily; Cook and Chill

MT System:

- 40 cooling sites and 15 refrigerated rooms (Ethylene glycol 35 %)
- Refrigeration capacity ca. 65 kW
- t_0 = -10 °C ; Ethylene glycol 35 %, t = -8 °C / - 4 °C
- t_c =+ 38 °C; cooling water +30 °C / +35 °C

LT- System

- 2 cooling sites and 1 LT-room
- CO_2 DX
- Refrigeration capacity ca. 8 kW
- t_0 = -32 °C ; t_c = -2 °C
- Brine -8 °C / -4 °C
- Safety cooling via small Propane system
- Invest ca. 20 % higher
- Energy consumption 0 to 5 % lower
- Total operating cost ca. 25 % lower
  due to easier service of piping system and lower refrigerant cost

Ammonia Chiller

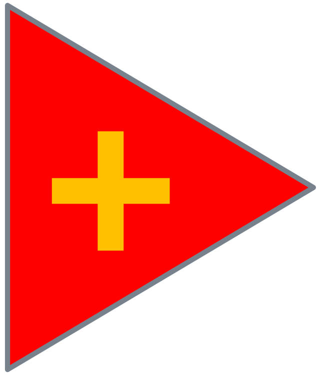
- Ammonia is poisonous – but it stinks !!!
  → Built-in leak detector
- Ammonia achieves highest COP
- Low charge possible (30 g/kW)
  indirect and cascade systems
- Examples of ammonia chillers in Aarhus:
  e. g. Scandinavian Congress Center (1200 kW),
  Salling department store,
  but also Shopping Center Fields in Copenhagen,
  Copenhagen Airport und Heathrow Airport

Hydrocarbons

- Zero ODP
- Low GWP
- Non-toxic
- Good thermodynamic properties, among others
  - Good heat transfer
  - Low pressure ratio
  - High volumetric refrigeration capacity
- High energy efficiency (+10 % comp. to HFC)
- Non-corrosive
- Oil compatibility
- Stable
- Flammable
- Available
- Affordable
- Possibly add odorant (Pyrazine)

Hydrocarbons - Flammability

Fuel = refrigerant leakage



Ignition source

Energy larger than 0.25 mJ or
Temperature above 440 °C

Practical limit for hydrocarbon refrigerants: 8 g/m³ air

Oxygen or flammable mixture with air

more than 2 % hydrocarbon, less than 10 %

	Flammability limit in air Vol.-%	Auto-Ignition temperature °C
Propane (R290)	2.1 – 9.5	470
n-Butane (R600)	1.3 – 8.4	370
Isobutane (R600a)	1.8 – 8.4	460
Gasoline	1.1 – 7.0	260
Ammonia (R717)	15.5 – 27.0	> 400
R152a	3.7 – 20.0	455
R1234yf	6.2 – 12.3	405
R32	14.4 – 29.3	650

GWP 32 = 675

Korean Air Conditioning and Cooking

Hydrocarbons Phenomenon

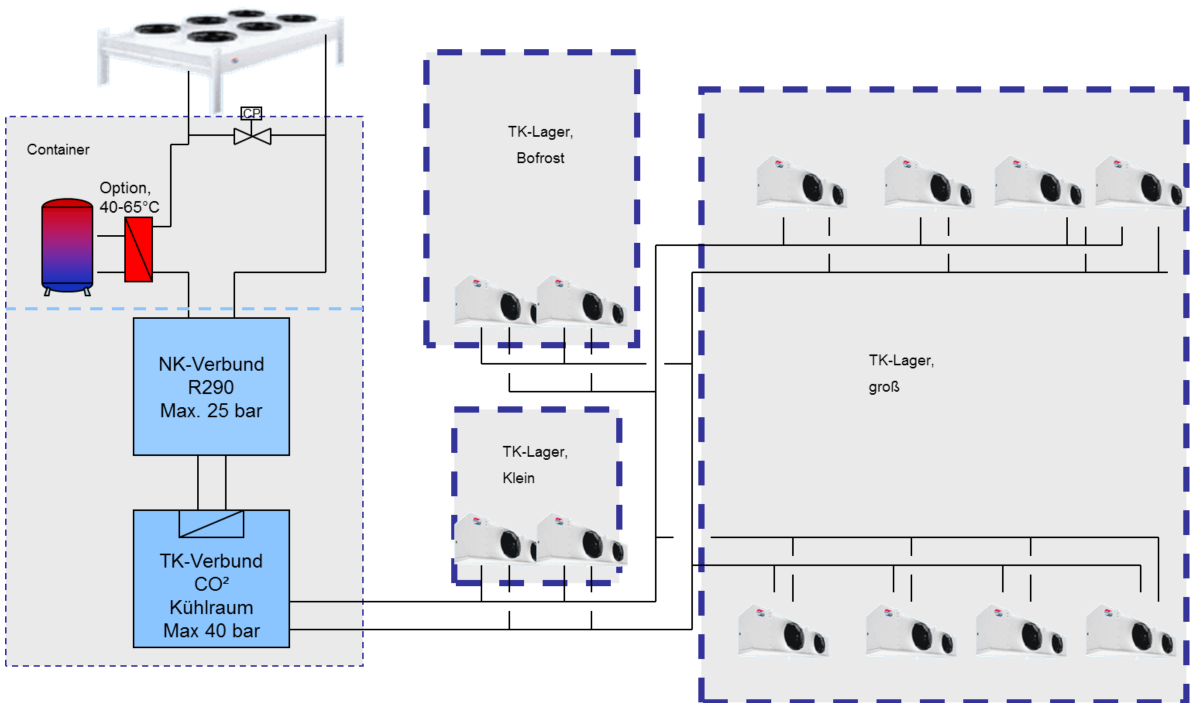
Propane:

It's easy to grill, …

… but hard to chill !

/Charly Huber/

Propane – CO_2 Low Temperature Warehouse



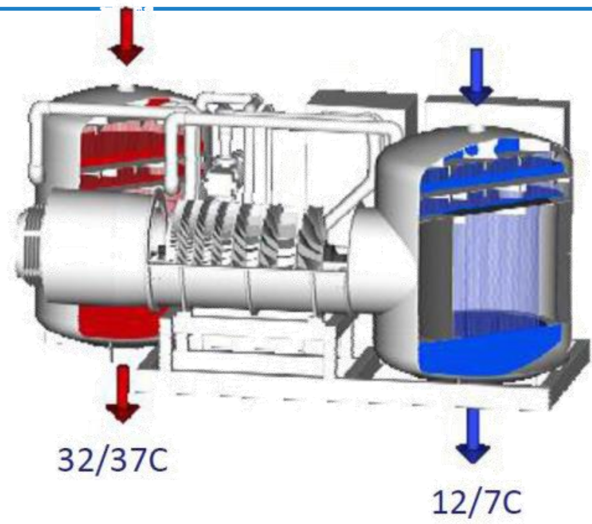
HAFNER-MUSCHLER
WIR KÜHLEN MIT SYSTEM

- 45 kg R290 200 kW @ -7 °C p_{max} = 25 bar
- 110 kg R744 155 kW @ -38 °C p_{max} = 40 bar
- 15 % lower annual energy consumption than R404A
- Same investment cost as R404A
  – for larger systems even cheaper

Water (R718) as Refrigerant

… for chiller

- Not flammable, not toxic
- System pressures below atmospheric,
  i.e. 10 °C → 12.3 mbar and 35 °C → 56.3 mbar
  → eliminate pressure drop due to flow losses
- Large vapor volume flow
- Separate developments at
  - IDE
  - ILK Dresden
  - Consortium of DTI / KOBE Steel / Johnson Controls / 3 Japanese Power Companies
    $\dot{Q}_0$ = 800 kW → 10 to 15 % lower energy consumption as HFC-system
  - Kawasaki Heavy Industries $\dot{Q}_0$ = 350 kW
  - Efficient Energy
    $\dot{Q}_0$ = 35 kW with chilled water temp. 22 / 28 °C
- Systems exist e.g. at:
  - VW Manufaktur in Dresden,
  - Nissan (Japan) and
  - LEGO in Denmark



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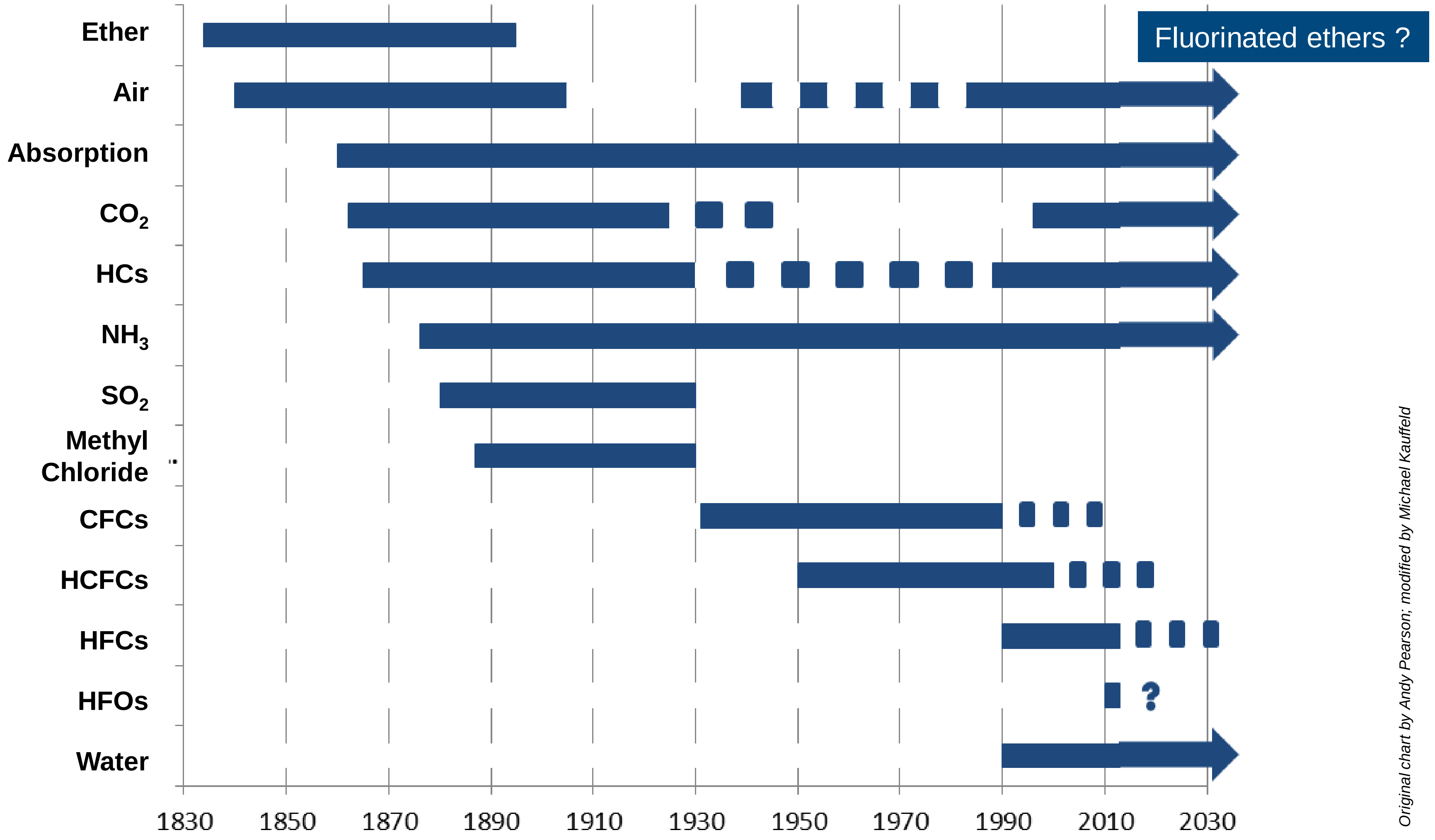
Time Line for Refrigerants



Original chart by Andy Pearson; modified by Michael Kauffeld

Summary

- HFC-free refrigeration systems are built with good energy efficiency – often better than HFC-systems

  Alternatives are:

  - CO_2 transcritical or as lower stage of a cascade system
  - Ammonia still # 1 in industrial refrigeration
  - Hydrocarbons for smaller systems and chillers
  - Water as refrigerant very interesting @ temperatures over 0 °C
- Refrigerant charges can be greatly reduced applying up to date technology (Mini-channel heat exchangers)
- Refrigeration systems offer energy savings potentials
  → utilize them !
- Accumulation of cold can save cost and energy

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