Refrigeration Technologies for the 21st Century

5. September 2011

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Global Warming

Climate Change – the giant atmosheric experiment

2. July 2011 in Copenhagen

135,4 millimeter rain in 24 hours (DMI)
Foto: Bax Lindhardt

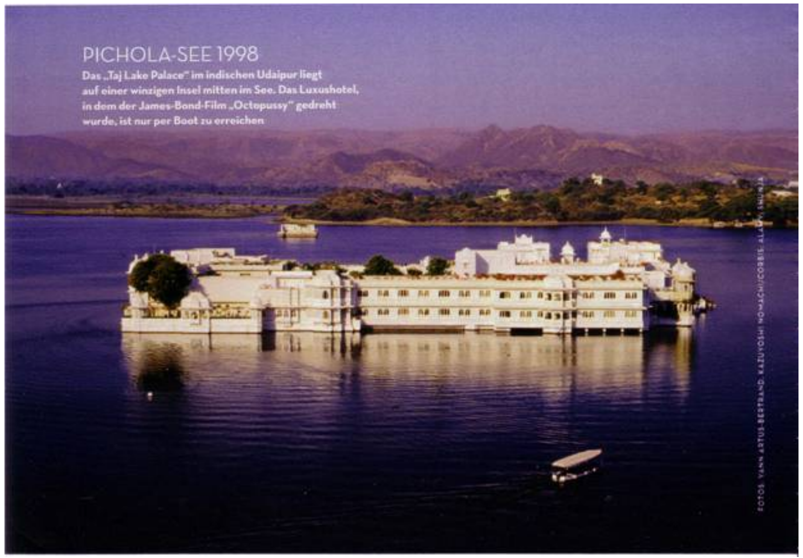
Istedgade *Foto: Anne Christine Imer Eskildsen*

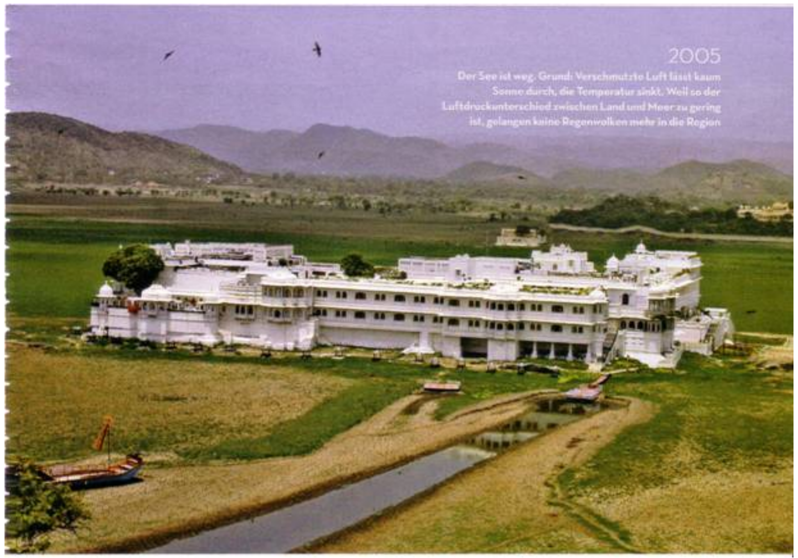
… and in Somalia

Foto: jared

Foto: Focus

Climate Change

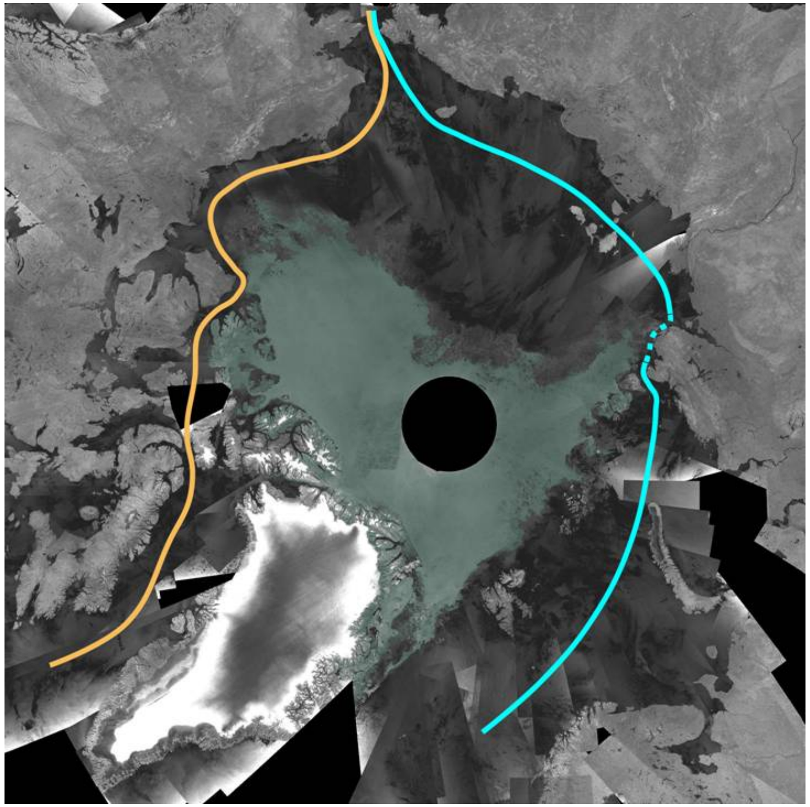




/VIEW 02/2007/

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 Sibiria, Canada and Alaska
- Northpole icefree in summer



The North-west passage (orange) was completely ice free for the first time in 2007

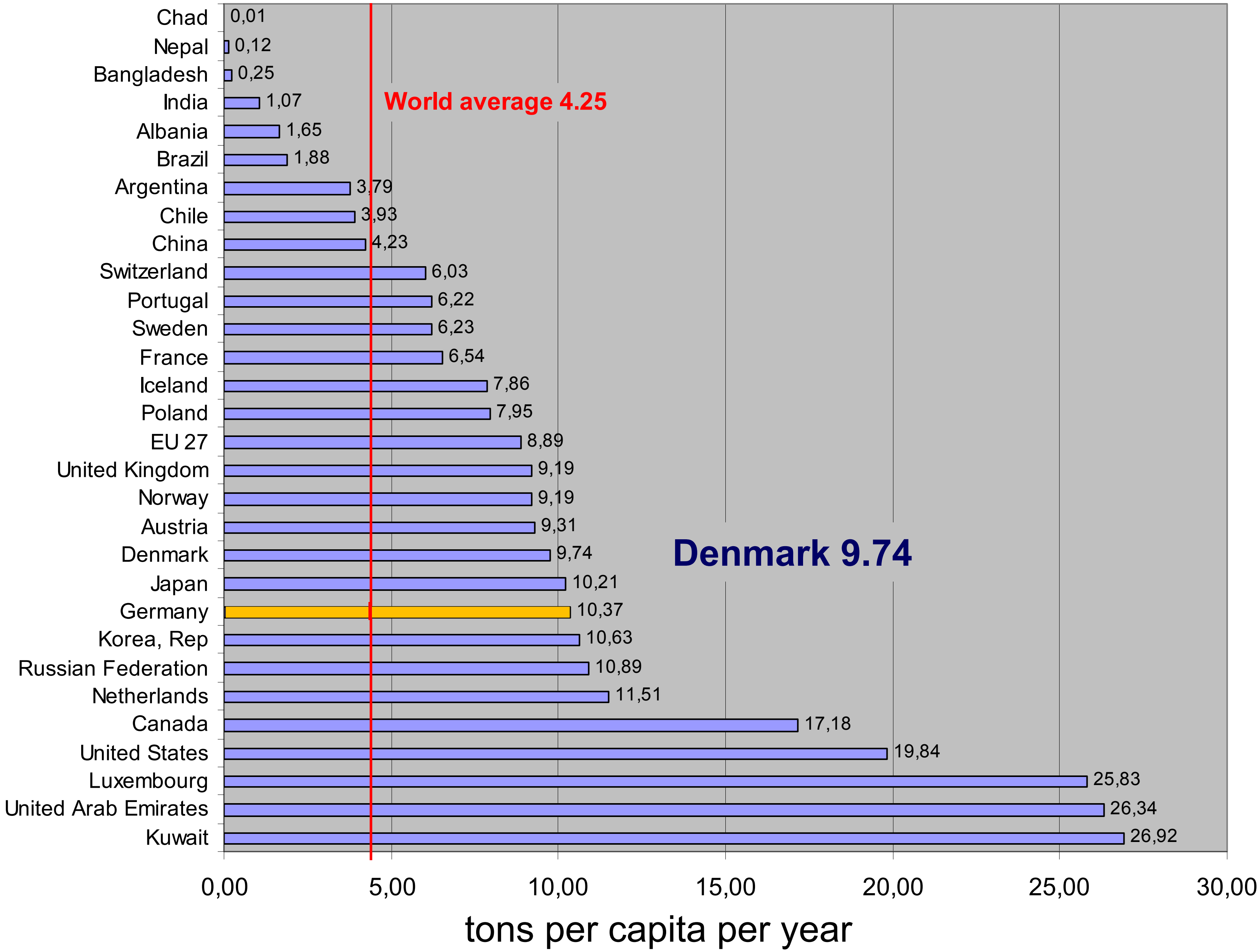
Ice losses of 1 Mio. km^2 since 2006

i.e. 23 times the area of Denmark

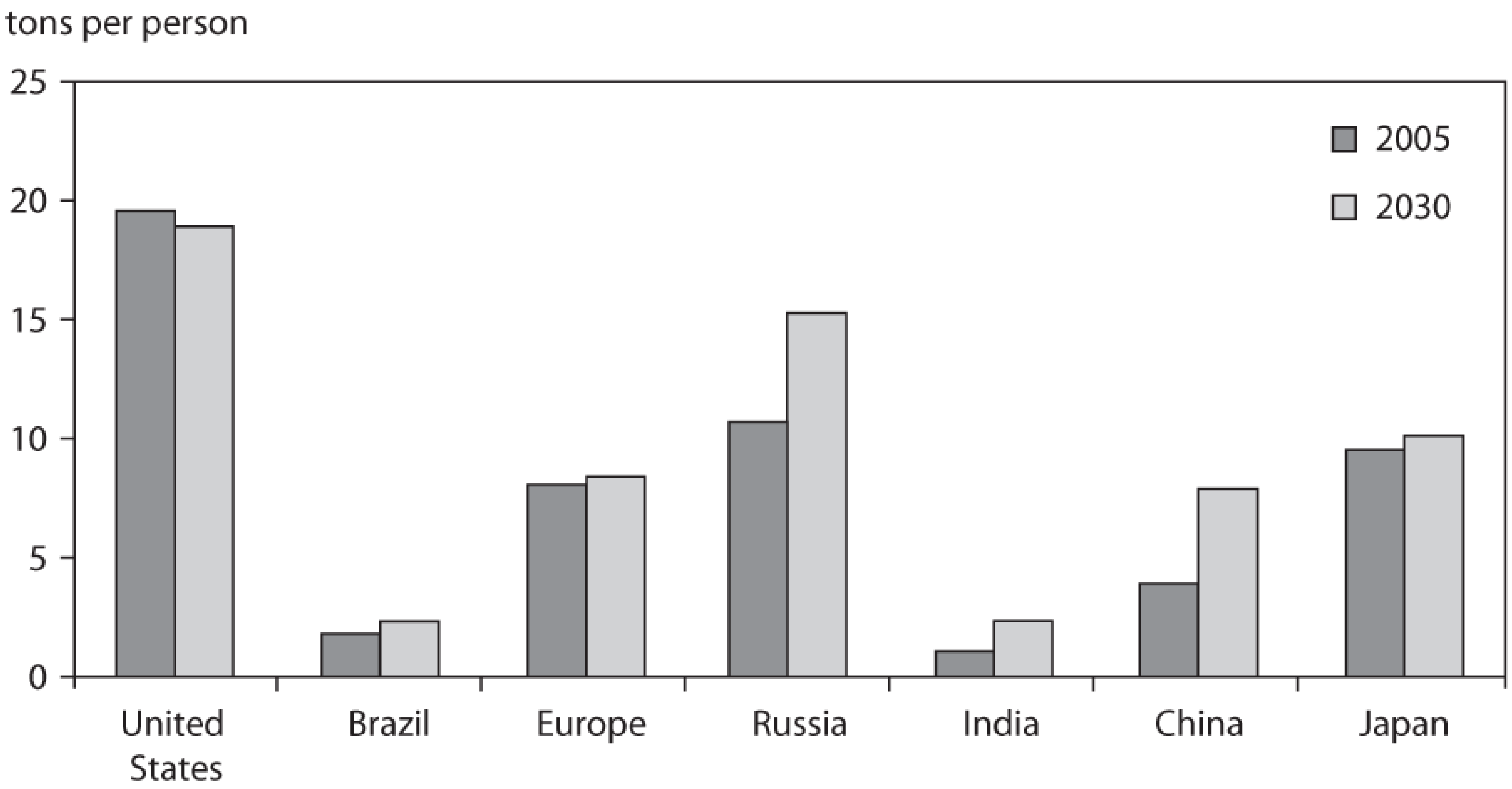
Denmark has 43,094 km^2

/www.esa.int/

Per Capita CO_2 Emissions in 2004

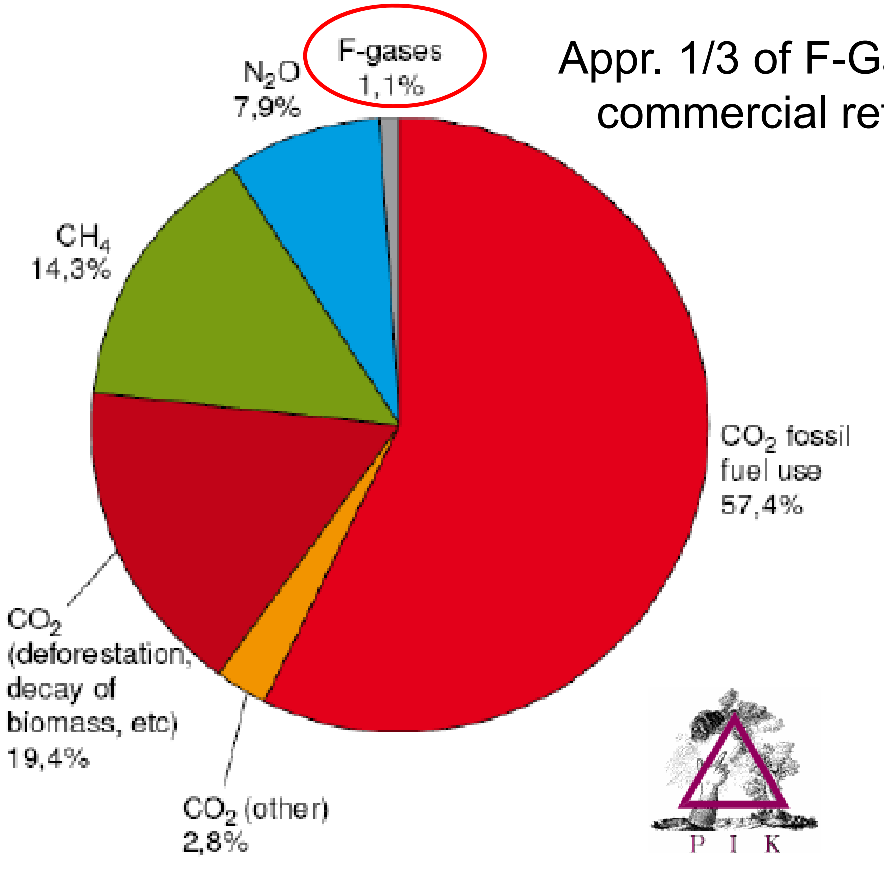


Per Capita CO_2 Emissions, current and projected



Sources: Economist Intelligence Unit Country Data, Bureau Van Dijk Electronic Publishing, 2007; IEA (2007b). Brazil 2030 forecast is from International Energy Agency, *World Energy Outlook 2006*.

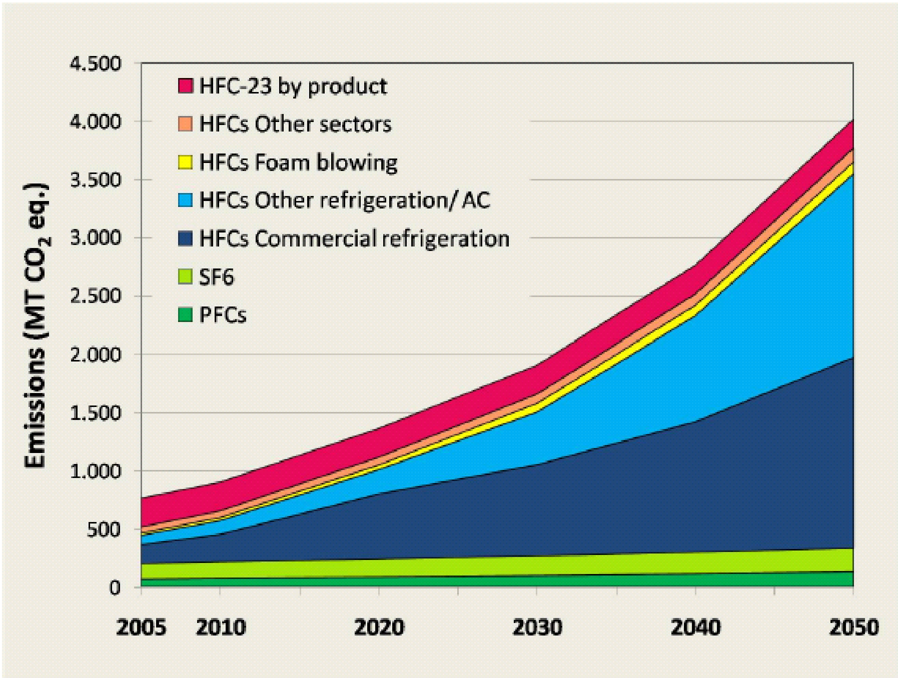
Global Emissions of manmade Greenhouse Gases in 2004



Appr. 1/3 of F-Gases from commercial refrigeration systems

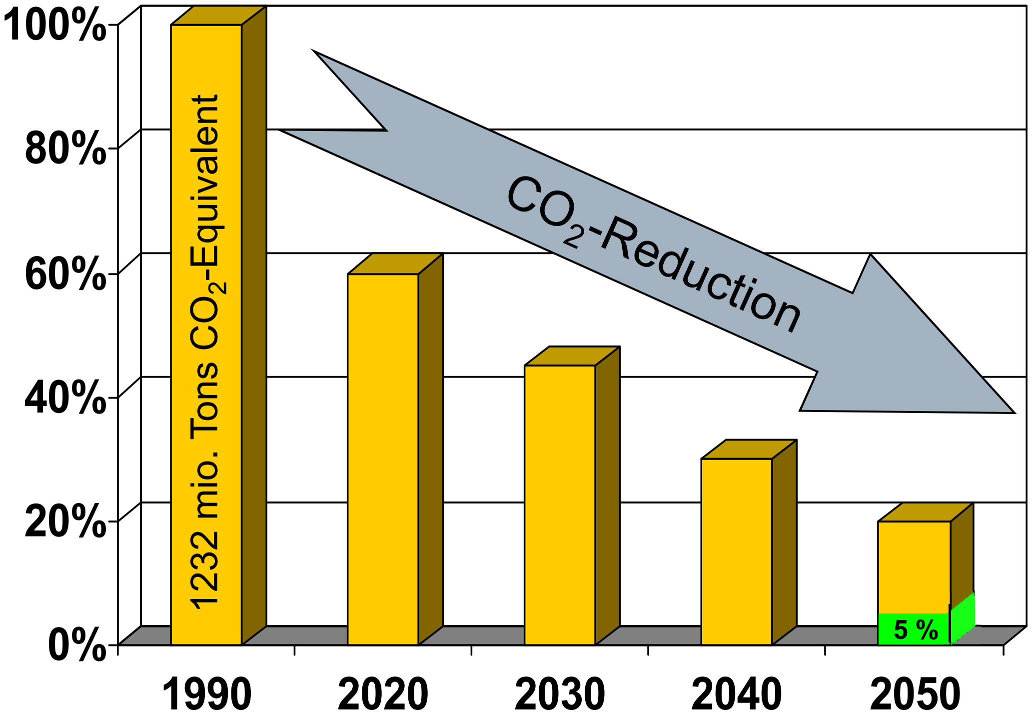
and projections

Diagram 4: Trend of global F-gas emissions until 2050 by sectors of application. The steep rise in F-gas emissions until 2050 is primarily caused by the expansion of the refrigeration and air conditioning sector, especially the commercial refrigeration sector



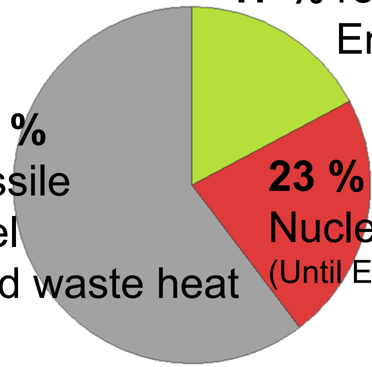
Gschrey, B.; Schwarz, W.: Projections of global emissions of flourinated greenhouse gases in 2050. Climate Change 17/2009

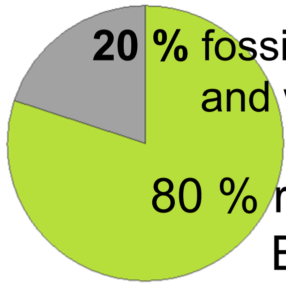
Germany top of the class ?
Climate saving strategy of German Government



Consumption of primary energy
To be reduced by 50 % from 2008 to 2050.

Energy for electricity production





→ Energy storage necessary

Solutions from the RAC Industry

- **Energy Storage** in form of cold accumulation
- **Reducing Direct emissions** of greenhouse gases
  - Hermetically tight systems with control scheme
    → EU F-Gas regulation
  - Refrigerants without or with negligible GWP
  - Reduced refrigerant charge
    → e.g. mini-channel heat exchangers
    → indirect refrigeration systems
- **Reducing Indirect emissions** of greenhouse gases
  - Reduce energy consumption
  - Use renewable energy

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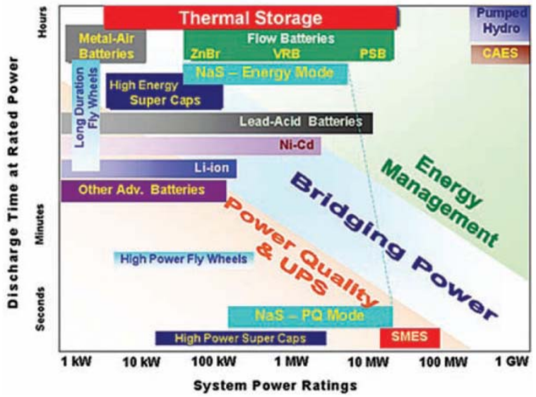
Energy storage

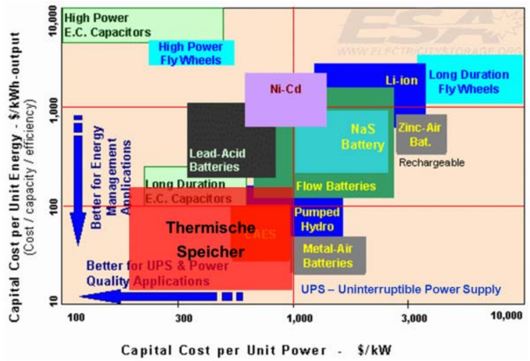
- Thermal
  - Accumulation of heat
  - Accumulation of cold
- Chemical
  - Inorganic, e. g. galvanic cell (Accumulator, Battery)
  - Organic, e. g. carbon hydrates or fat
- Mechanical
  - Kinetic energy: Fly wheel
  - Potential energy: Pumped hydro power
Pressurized air power
- Electrical
  - Capacitor
  - Super conducting magnet

Thermal Energy Storage

- Long storage time
  Hours to days
- Allow long discharge intervals
  Hours to days
- Can be realized in any size
  Few kW to several 100 MW
- Are comparably inexpensive
  Compared to power €/kW
  as well as to stored energy €/kWh
- Allow large no. of charge / discharge cycles
  several 10.000 to 100.000
- Achieve high efficiencies
  60 to 95 %



/Mark MacCracken: Energy Storage – Providing for a low Carbon Future. ASHRAE Journal Sept. 2010/



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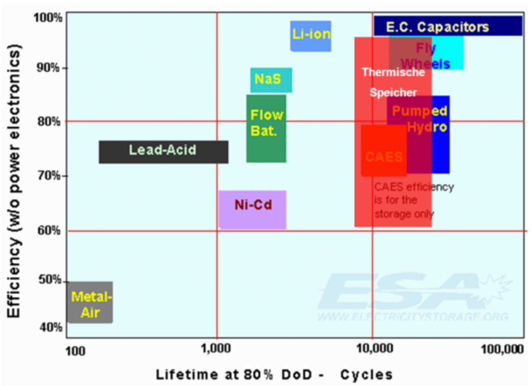
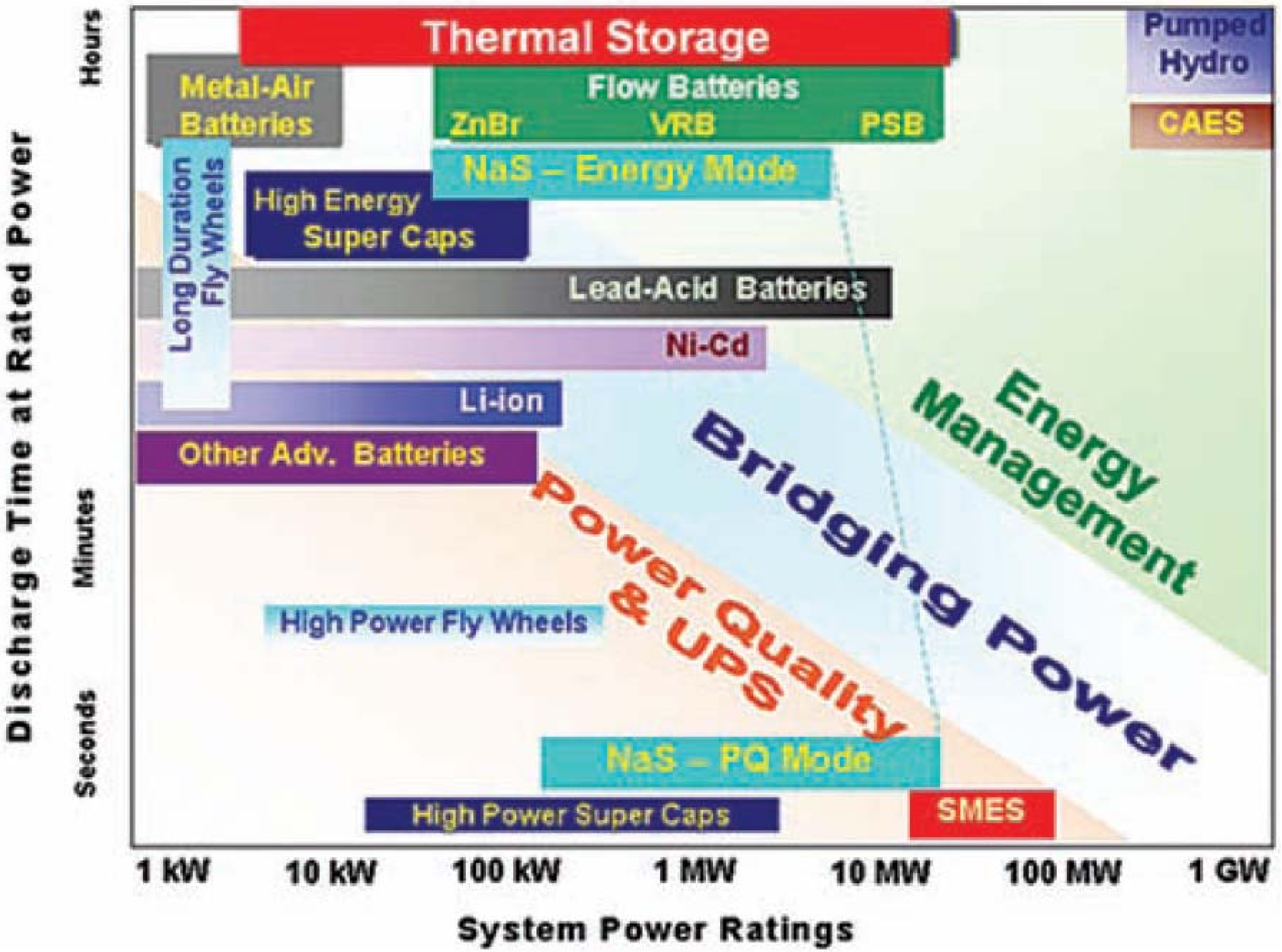


/www.electricitystorage.org/ESA/technologies/

Energy Storage



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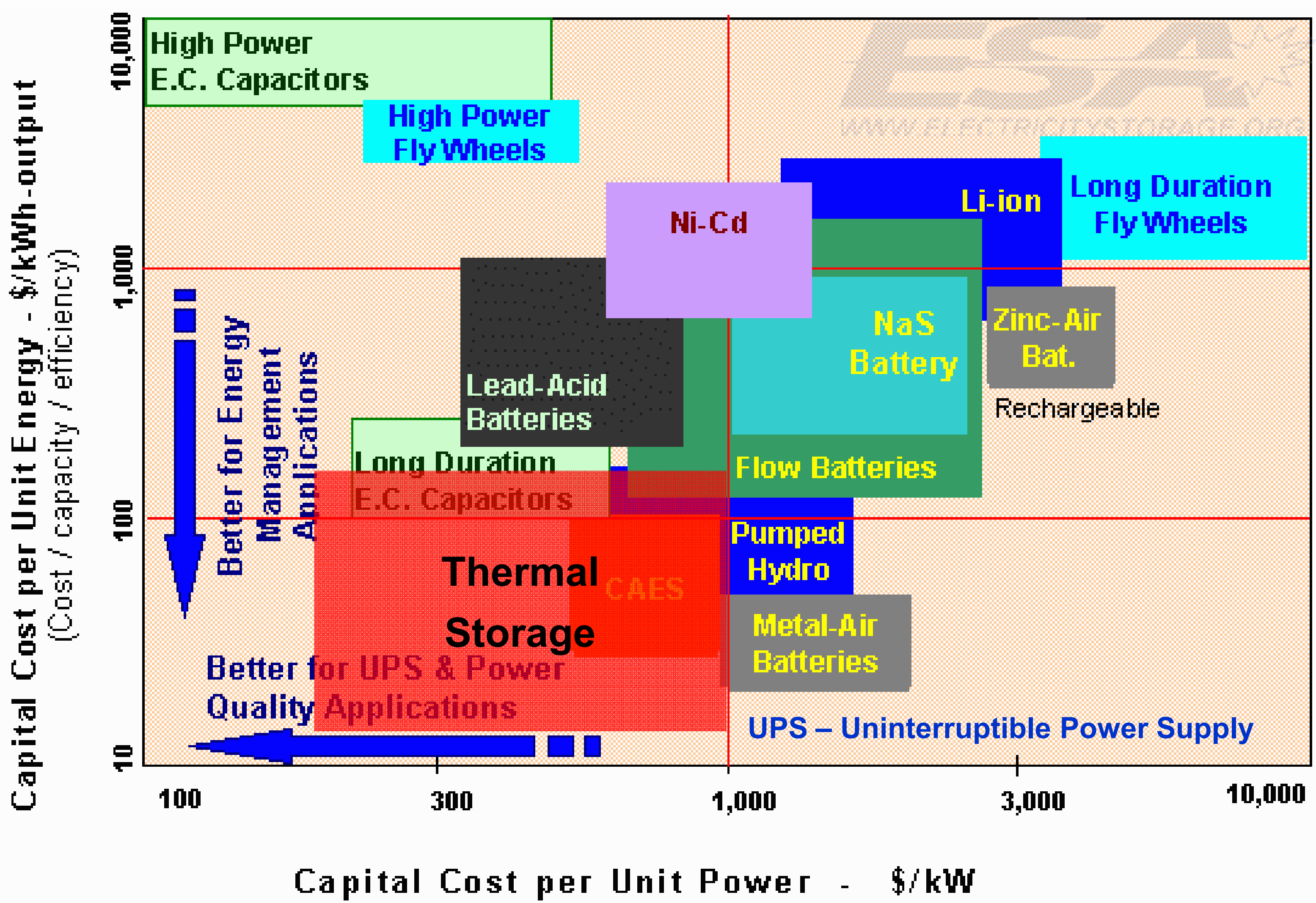
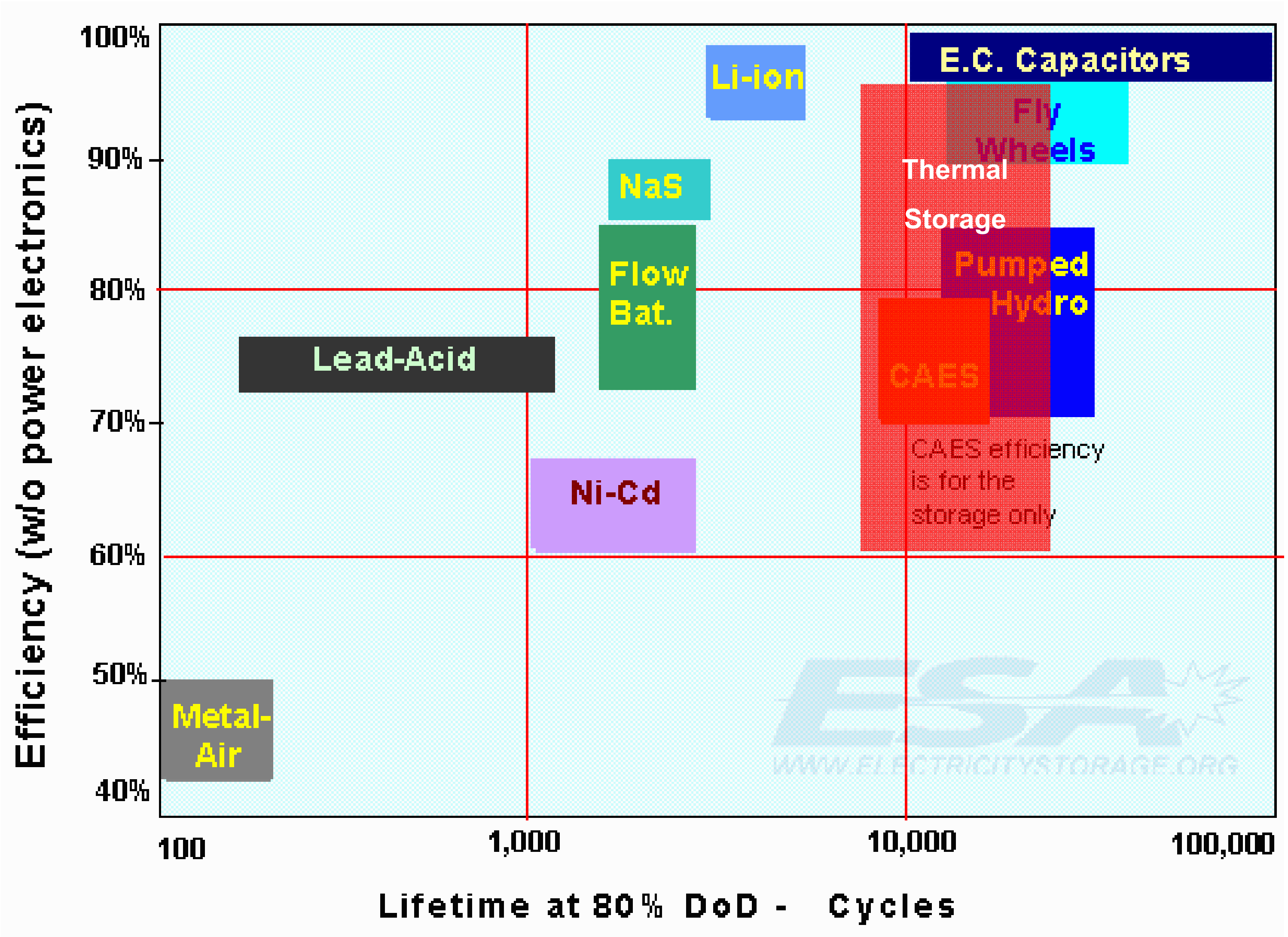
Cost of Energy Storage



/Mark MacCracken: Energy Storage – Providing for a low Carbon Future. ASHRAE Journal Sept. 2010/

Efficiency of Energy Storage



/www.electricitystorage.org/ESA/technologies/

Thermal Energy Storage

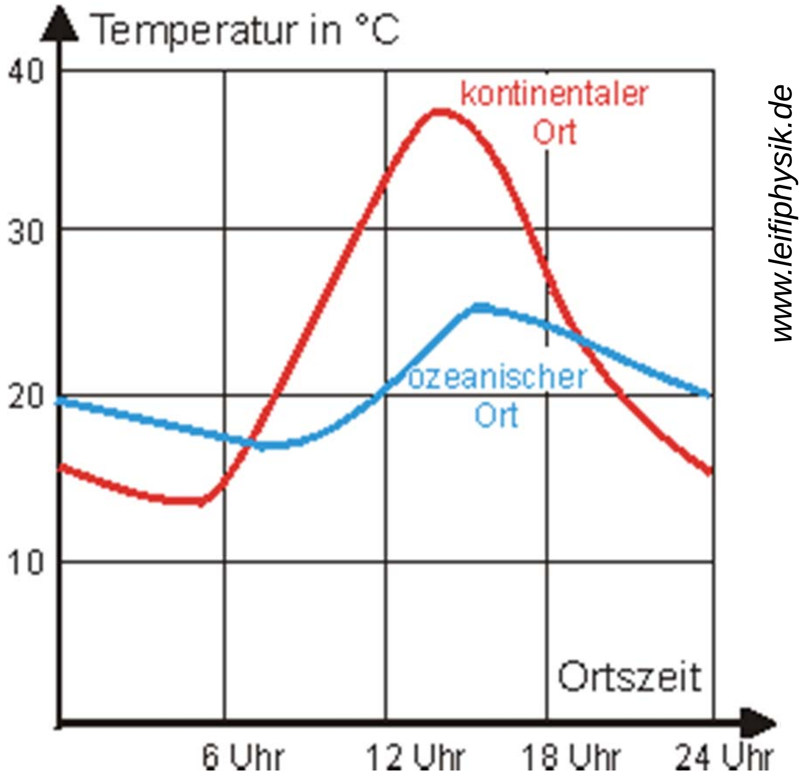
- Storage of sensible or latent heat
- Water c = 4,2 kJ/(kg K) ≈ 1,1 kWh/(m³ K)
- Paraffin c ≈ 2 kJ/(kg K)
  Δh_v= 200 – 240 kJ/kg
- Storage density: Paraffin 55 kWh/m³
  Water 40 kWh/m³ at Δt = 35 K
- Efficiency of 60 (district heating) to 95 % (locally in building)
- e. g. district heating storage Theiß Power Station / district heating Krems V = 50.000 m³, Capacity 2 GWh per charging cycle
  → 40 kWh/m³

- Storage of latent or sensible heat
- Water c = 4,2 kJ/(kg K)
  Ice c = 2,3 kJ/(kg K) Δh_v= 334 kJ/kg
- Storage density:
  Latent up to 84 kWh/m³ (100 % Ice)
  Sensible only 7 kWh/m³ at Δt = 6 K
- Efficiency of 60 (district cooling) to 95 % (locally in buiding)
- e. g. Herbis Osaka V = 1600 m³, Capacity 80,75 MWh per charging cycle (50 % Ice)
  → 50 kWh/m³

Efficiency of refrigeration system rises …

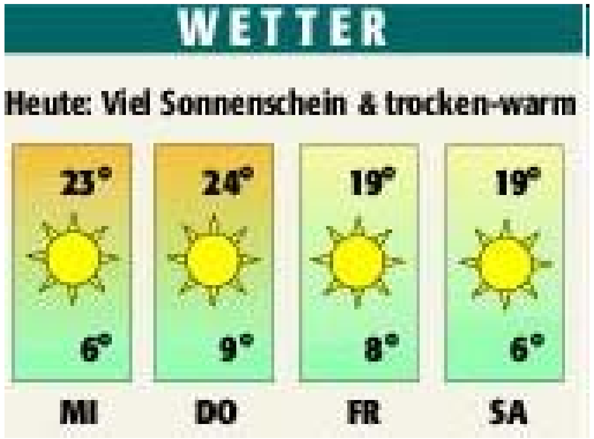
… with reduced condensing temperature (appr. 2 – 3 % per Kelvin)

In addition, many refrigeration systems operate at higher cop under design conditions than at part load, i.e. resulting in higher specific energy consumption at part load

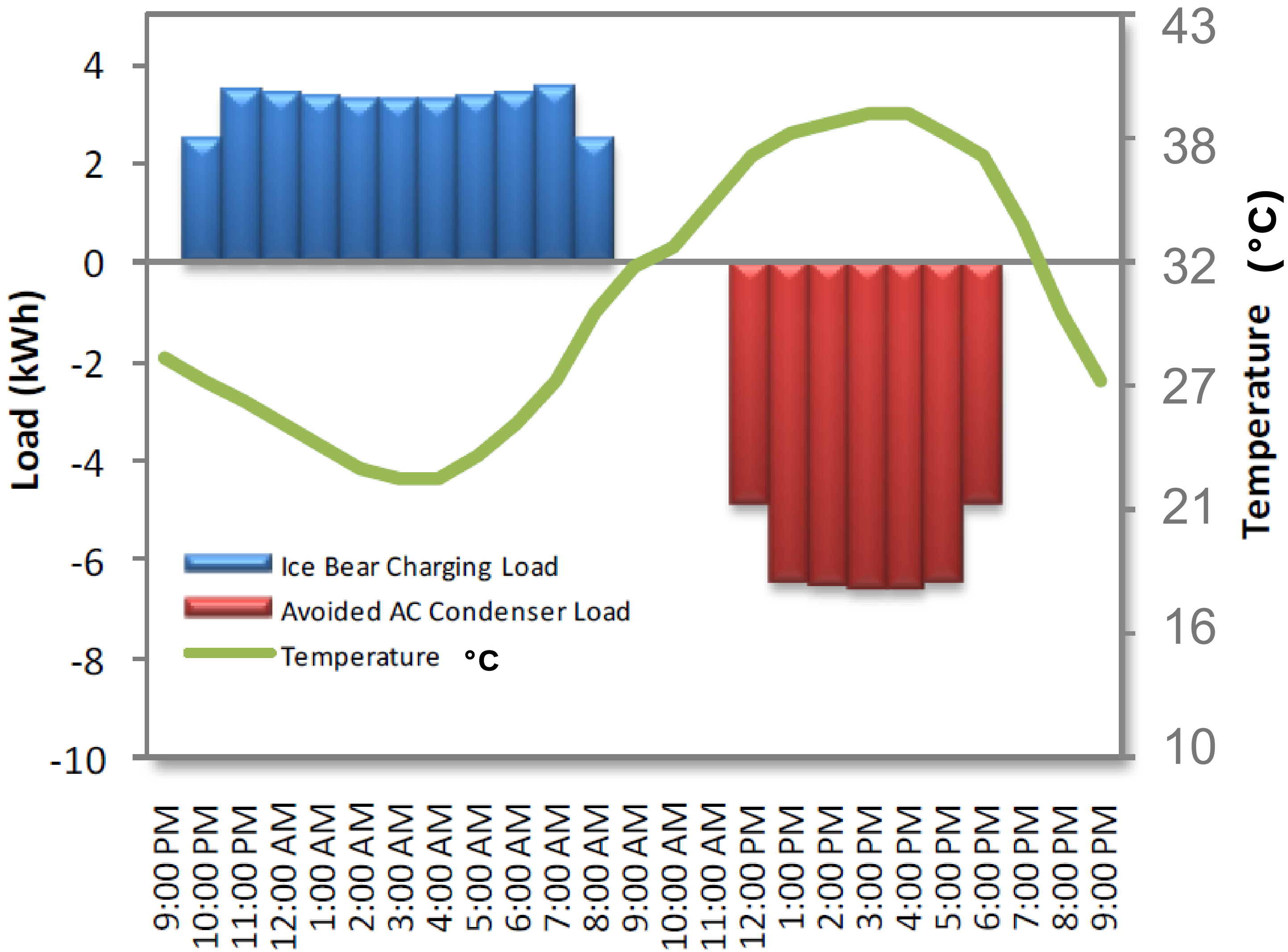


www.leifiphysik.de

Karlsruhe, 6. April 2011



Refrigeration load with Ice Storage



$\dot{Q}_0 = 6,6$ kW

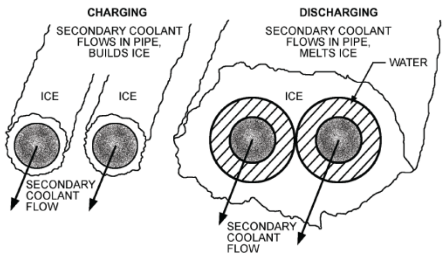
Savings :
7 kWh per day

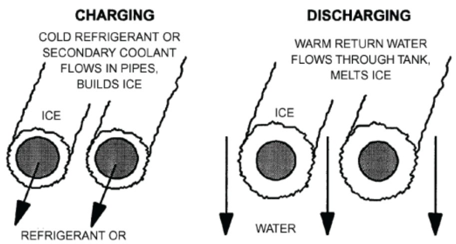
/Ice Bear Energy Storage System. Electric Utility Modeling Guide (2011)/

Ice storage

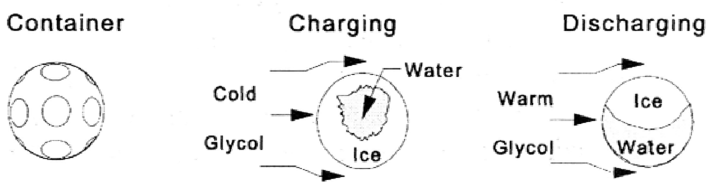
static

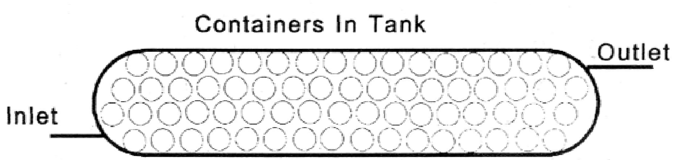
Tubes – freeze from inside and
melt from inside or outside





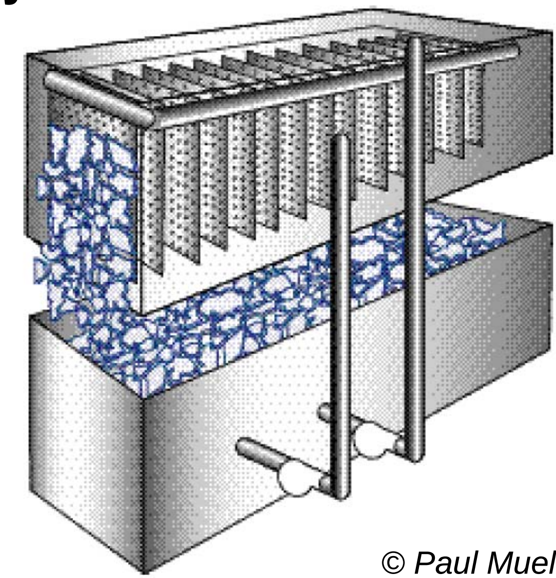
Ice sheres – freeze and melt from outside





© ASHRAE Handbook HVAC System 2008

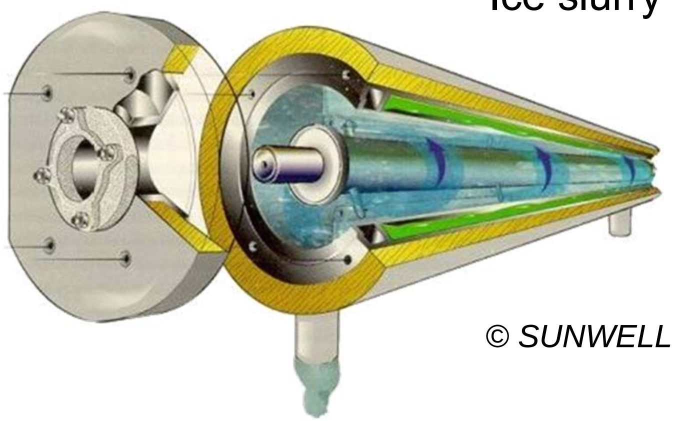
dynamic



© Paul Mueller Comp.

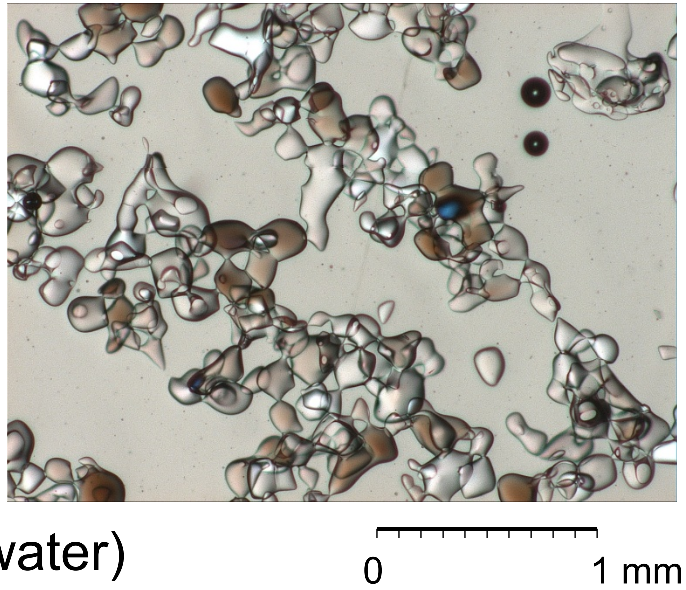
Flake ice ↑

Ice slurry ↓



© SUNWELL

Ice Slurry



- is a mixture of small ice particles (0.01 - 0.5 mm), water and a freezing point depressing agent such as ethanol, salt, glycol etc.
- is an environmentally friendly cooling agent with high energy density capacities (up to 8-times that of water)
- has high heat transfer coefficient (2- to 3-times that of liquid)
- Allows much smaller pumps than liquid systems
- allows the use of indirect refrigeration plants with small primary refrigerant charge
- gives possibility for ice storage
- can be used in direct contact cooling/freezing

Summary Thermal Energy Storage

Accumulation of cold can save energy due to

- Load shifting and operation with reduced condensing temperature at night
- Reduction of start/stop-losses (up to 8 % energy savings)
- Avoidance of part load operation
- Usage of electricity at low load times
  - Higher power grid efficiency
  - More even load on nuclear power plants
  - Avoiding peak load power plants which have low efficiency
- Storage of excess power from renewable energy

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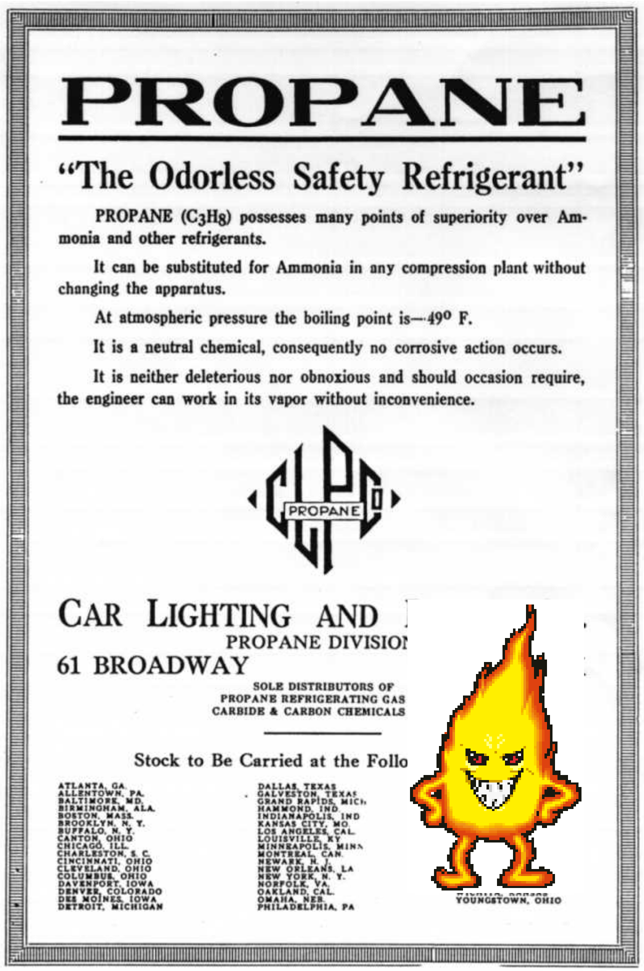
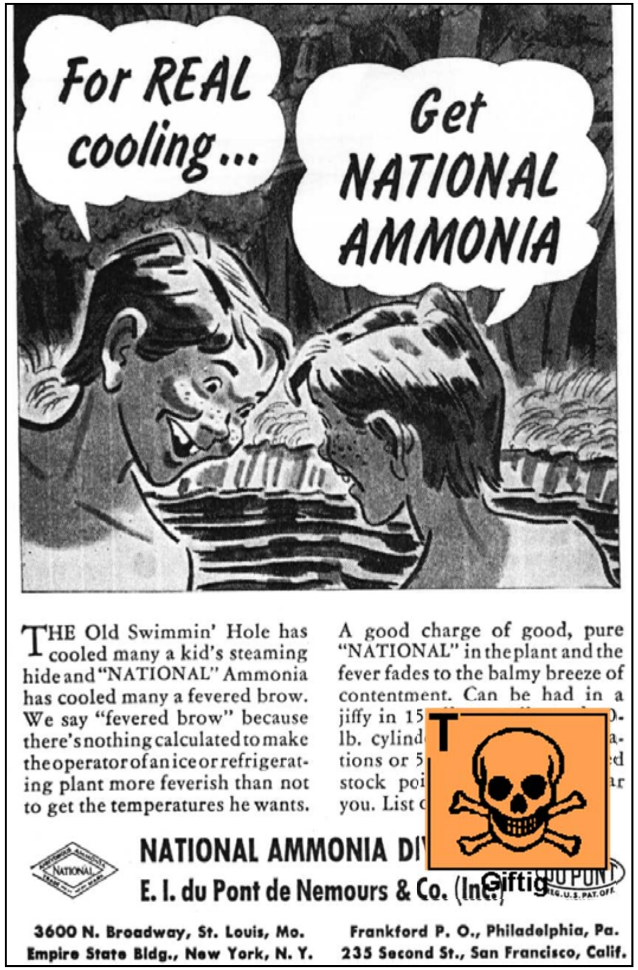
Back to the future: Natural refrigerants ?



◂ Ad in American refrigeration magazine 1922



Ad in American refrigeration Magazine 1943 ▸

Other „old friends“: Water, carbon dioxide, isobutane and air

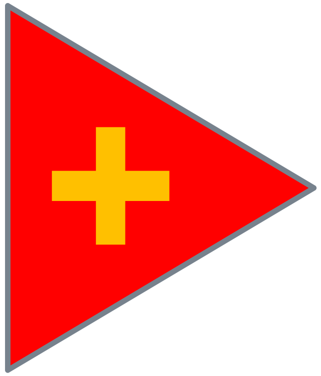
Refrigerants

	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
Hydrocarbons	low	yes	no	low	medium	medium	good
Carbon Dioxide	low	no	only at high concentr.	low	medium	high	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. real system efficiency

Hydrocarbons - Flammability

Fuel = refrigerant leakage



Ignition source

Energy larger than 0.25 mJ or
Temperature above 440 °C

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

Examples for charges

2,52 g	Lighter (85 % n-Butane, 12 % Propane, 2 % Isobutane)
45 g	Refrigerator (Isobutane)
65 g	Hair spray can (70 % Propane, 18 % n-Butane, 12 % Isobutane)
139 g	Recharging bottle for lighter (Butane/Propane)
160 g	Fog horn (Propane/Butane)
205 g	Rust remover (Dimethyl ether DME)
210 g	DeLonghi air conditioner (Care 50; R290 Propan + R170 Ethan)
308 g	McQuay split air conditioner (Care 50)
450 g	Camping gas can (Propane/Butane)
800 g	Space heating heat pump (Propane)
1,5 kg	small camping gas bottle (Propane/Butane)
11 kg	large camping gas bottle (Propane/Butane)
45 kg	Fuel tank in car (100 % Gasoline)

Korean Air Conditioning and Cooking

Hydrocarbons Phenomenon

Plug-in Chest Freezers

- Change from R404A to R290
  - → GWP reduced from 3,900 to ~ 20
  - → 10 to 15 % energy savings
- Speed controlled compressor
  - → 10 to 15 % energy savings

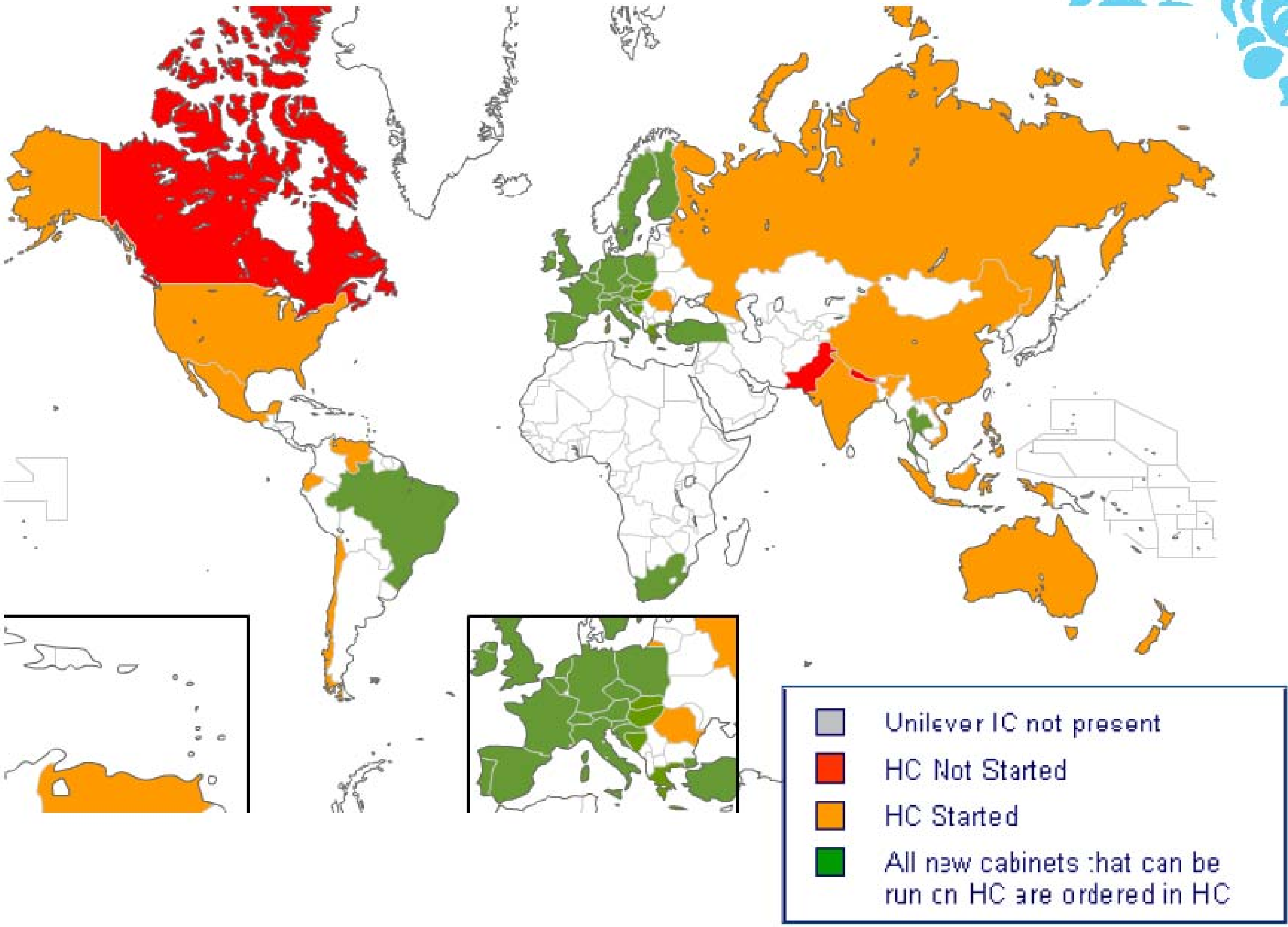
→ In total ca. 25 % lower energy consumption while simultaneously reducing direct global warming emissions close to zero

- Investment cost currently ca. 15 % higher
- Charge limitation at 150 g → maximum 1 kW cooling cap. LT
- „Build-in“ heat recovery
- Energy saving potential in summer: Additional water cooled condenser

VW Passat BlueMotion 30000 km = 3840 kg CO_2

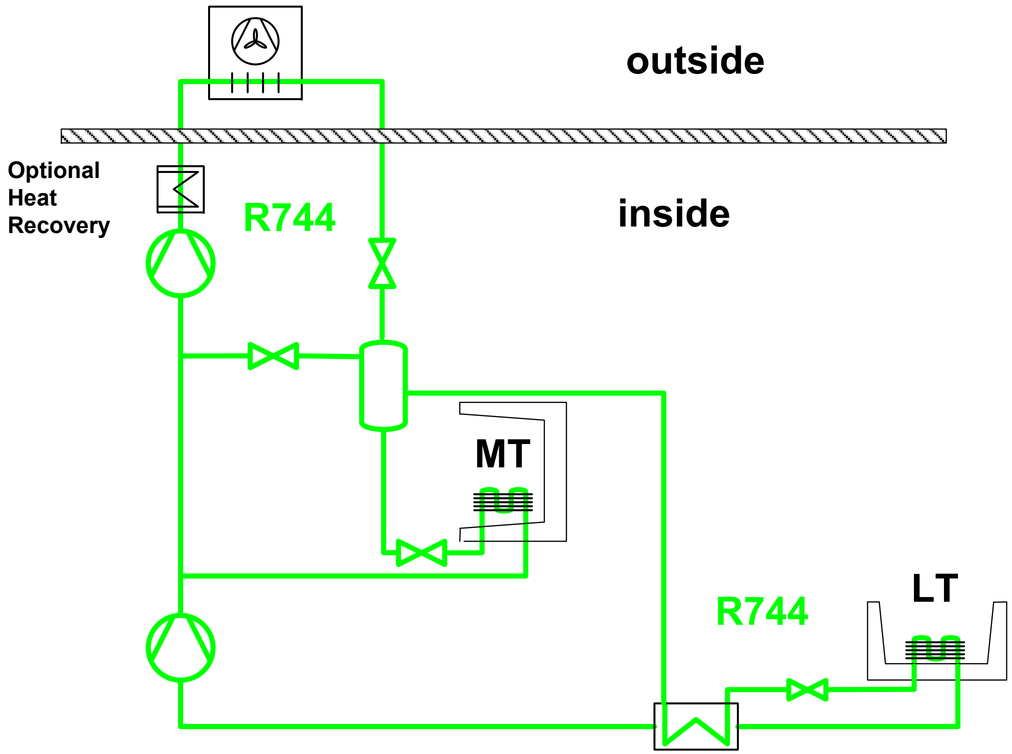
Unilever purchases only HC-cabinets – where possible

Roll-out status (early 2009)



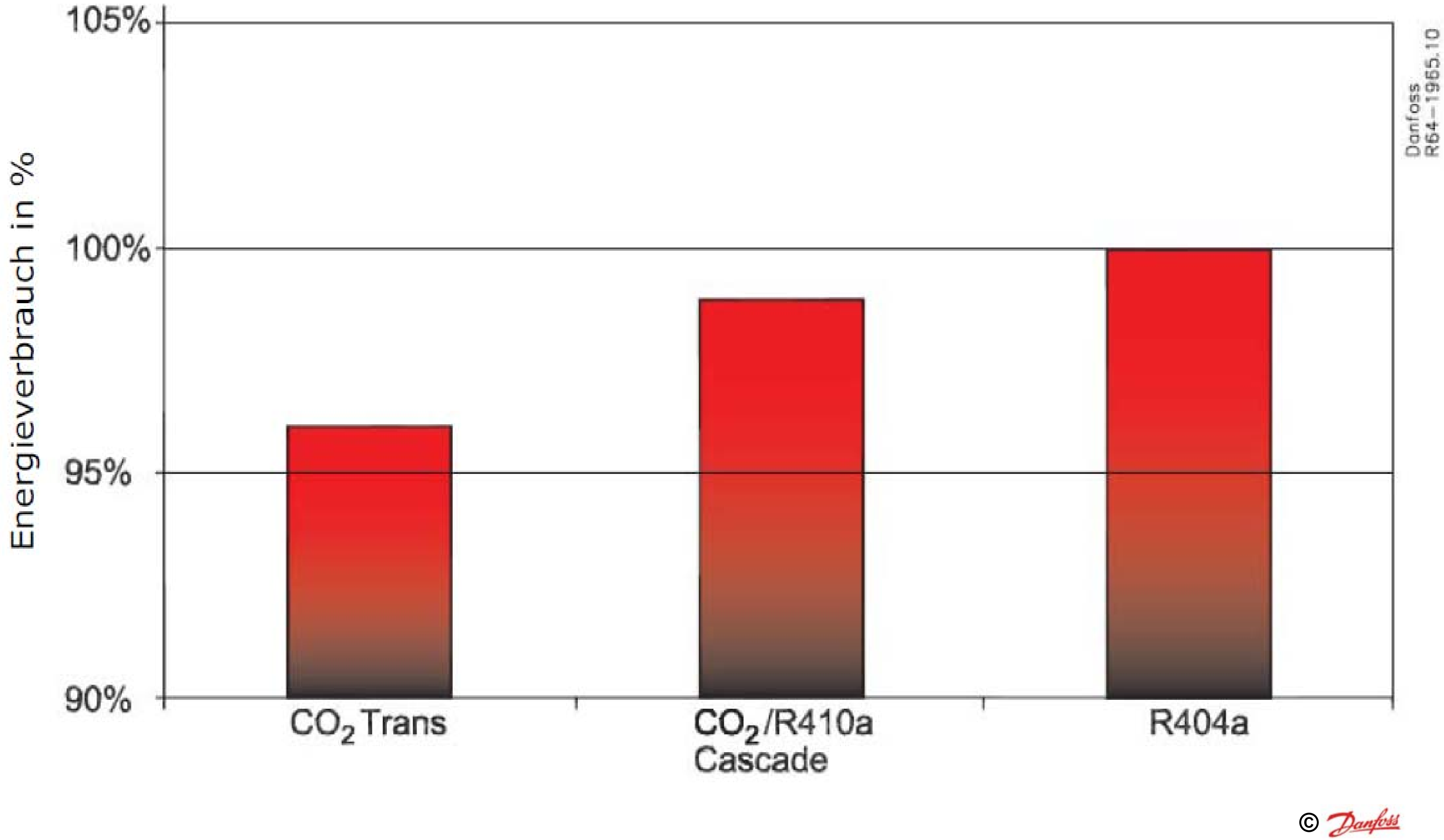
Rene van Gerwen: Hydrocarbon refrigeration in the retail industry – the practical experience of Unilever. Atmosphere 2010

Central CO_2-Supermarket refrigeration system

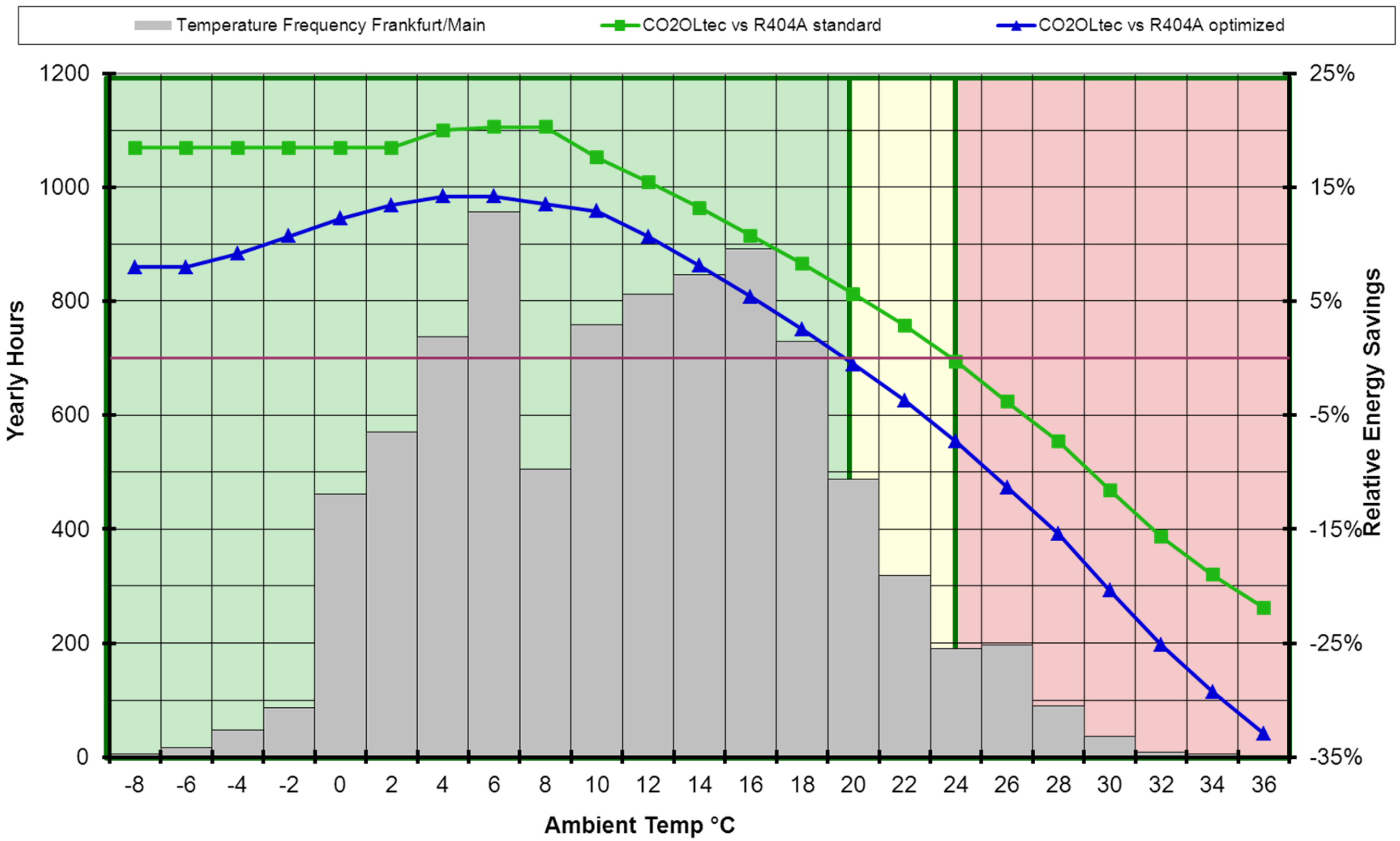


- More than 1000 transcritical centralized systems built until August 2011
- Energy efficiency good in cold and moderate climate, i.e. north of Switzerland
- Energy efficiency lower than standard R404A system in warm climate
- Initial cost up to 50 % higher than standard R404A system
- CO_2 requires special knowledge due to high pressures – up to 120 bar in outdoor coil
- Indoor part of system can be kept below 40 bar operating pressure
- Take care of excessive pressures during longer stand still period

Measurements on 3 danish supermarkets



COMPARISON WITH R404A SYSTEMS

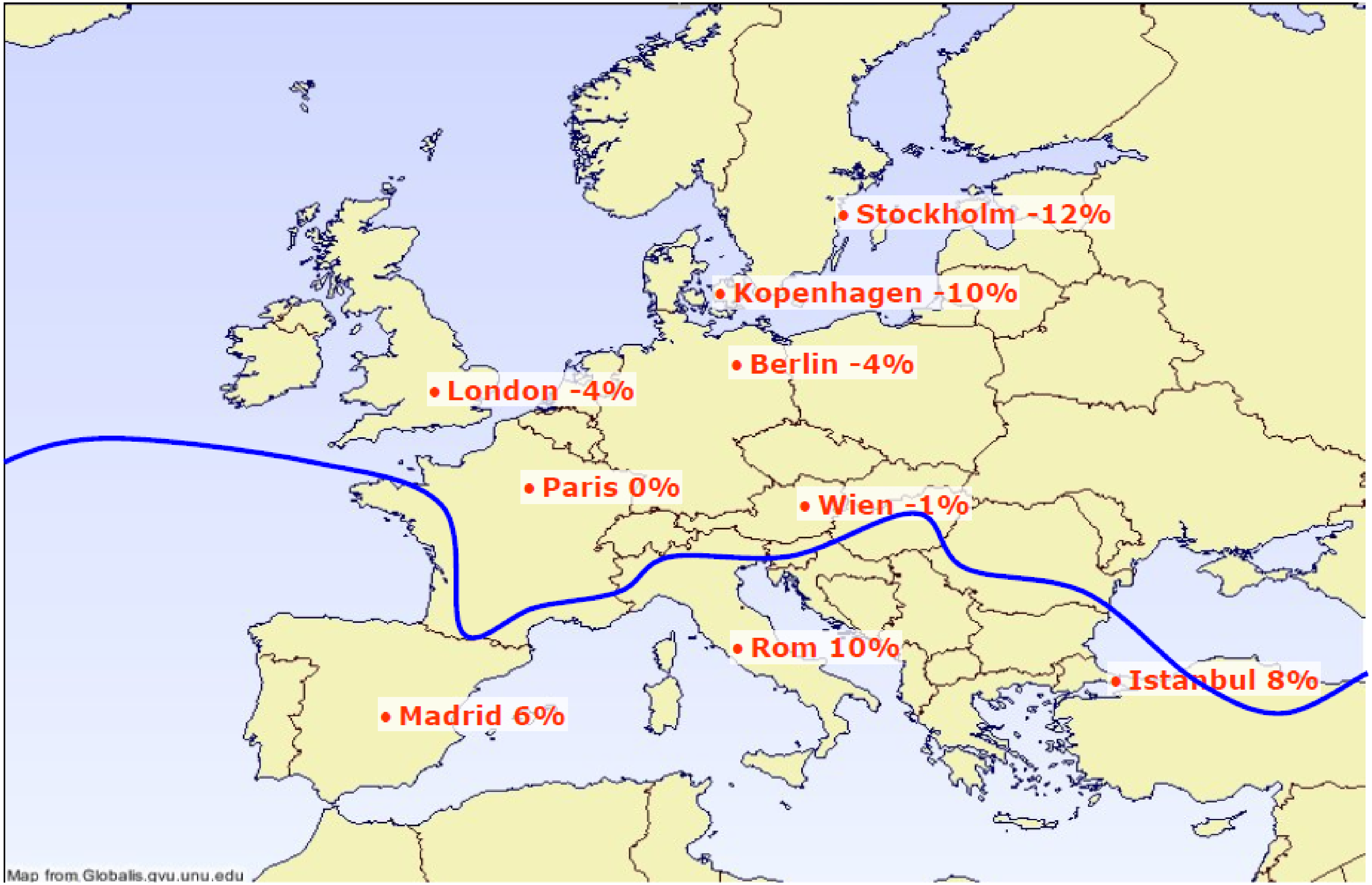


CO_2 systems show good results for ambient temperatures up to 20-24°C

Finckh, O.; Schrey, R.; Wozny, M.: Energy and Efficiency Comparison Between Standardized HFC and CO_2 Transcritical Systems for Supermarket Applications. 23rd IIR Congress of Refrigeration, Prague, 2011

Energy consumption of R744 transcritical vs. R404A

http://www.ipu.dk Pack calculation II



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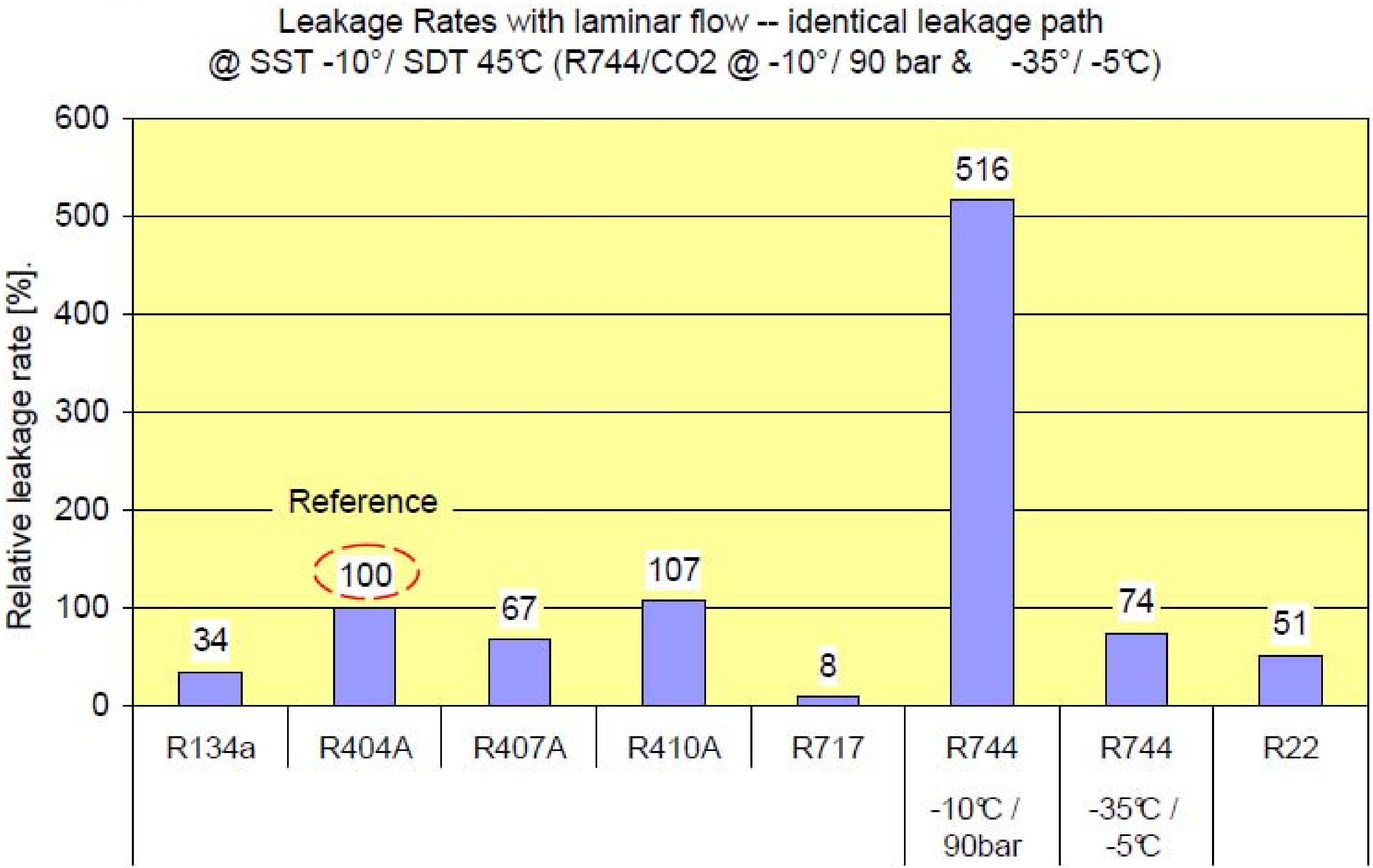
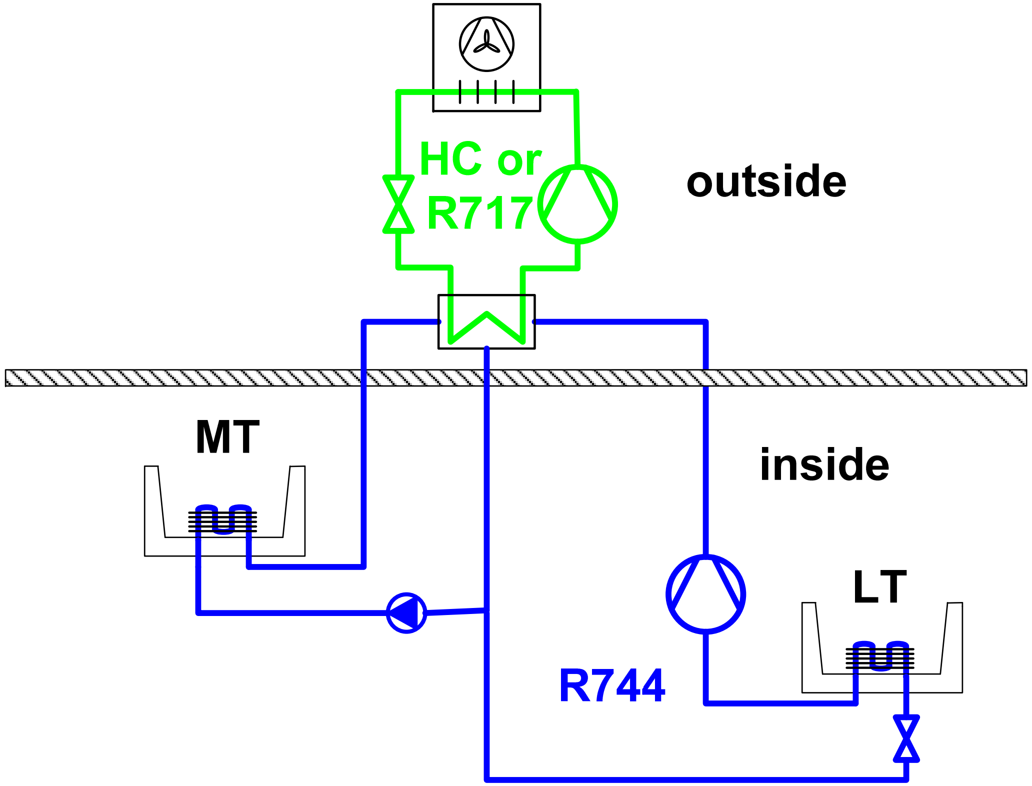
Assessment of Refrigerants – Comparison of Leakage Rates

BITZER GROUP OF COMPANIES



Central Multiplex System with CO_2

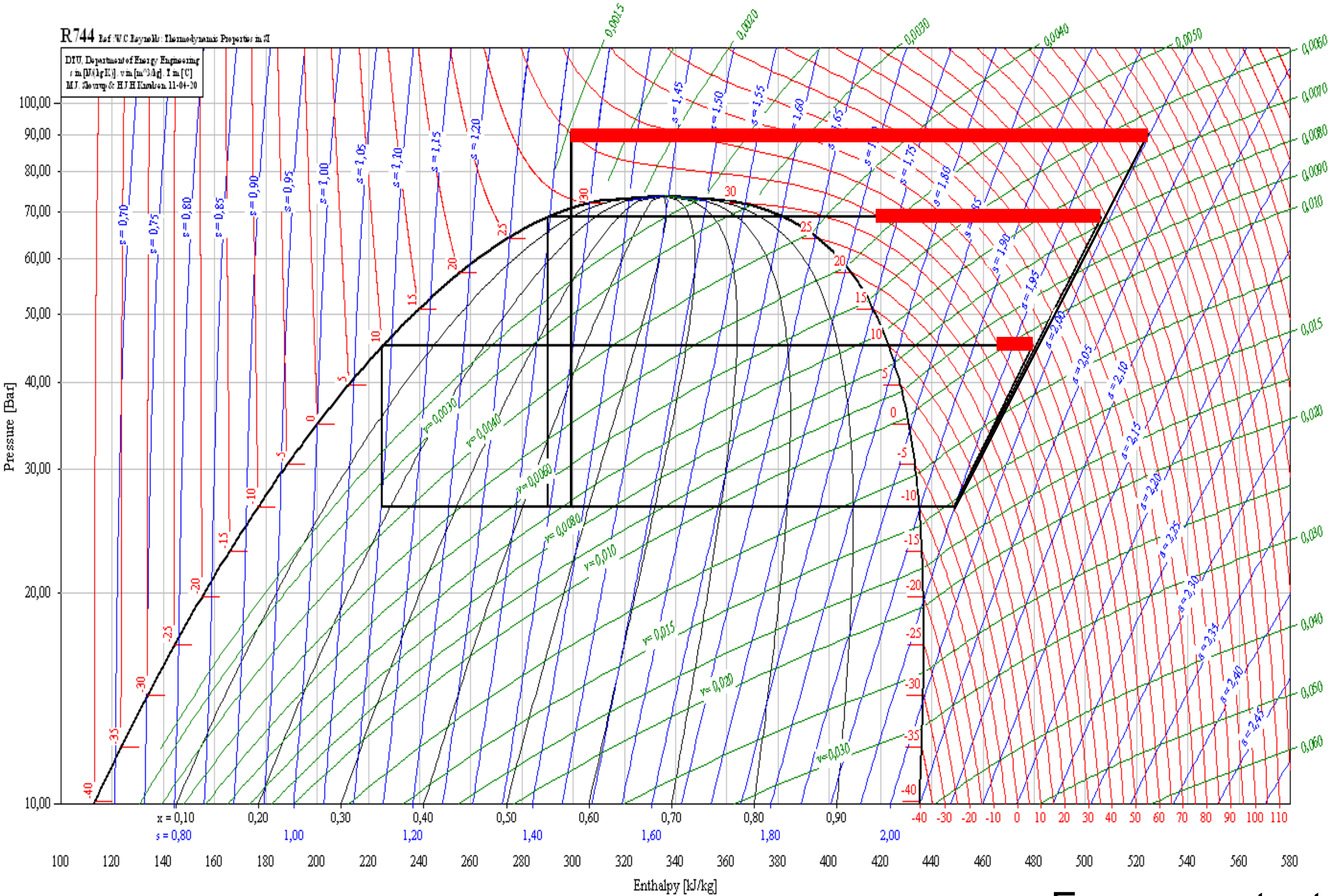


- Energy efficient application of CO_2-system for MT and LT – both work sub-critical
- All components available; R744 pressure below 40 bar
- Factory built HC or R717 system as upper stage with reduced charge
- Daikin (J & E Hall) showed such system (HC as upper stage) on Euroshop 2008
- At least one supermarket with R717 in The Netherlands in Bunschoten

Heat recovery at CO_2-refrigeration systems

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

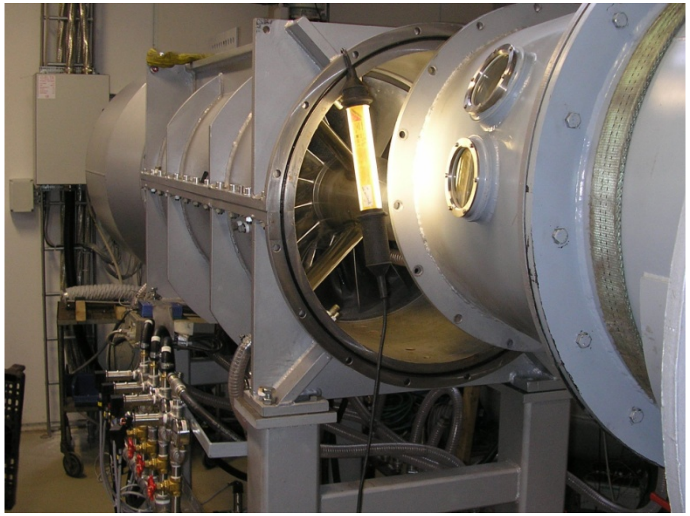
Pressure



Energy content

Water (R718) as refrigerant

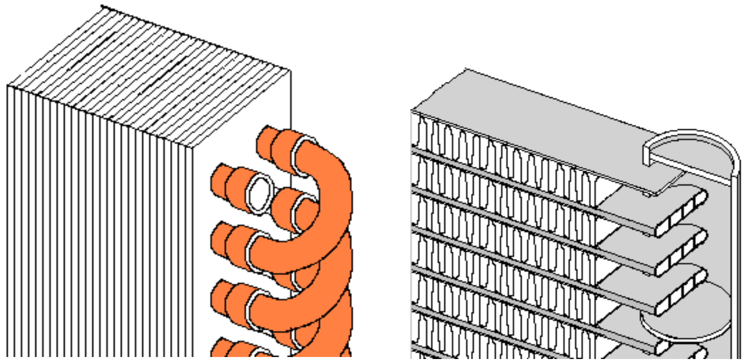
- Not flammable, not poisonous
- System pressures in vacuum,
  e.g. 10 °C → 12,3 mbar and
  35 °C → 56,3 mbar
- Pressure losses have to be eliminated in all components !!!
- Large vapor volume flow
- Separate developments at
  - IDE
  - ILK / Cofely
  - Consortium of DTI /KOBE Steel / TEPCO / Chubo Electr. Power Comp. / Kansai Electr. Power Comp. / Central Research Institute of Electric Power Industry / Johnson Controls
    → 10 to 15 % lower energy consumption as HFC-system
- Plants exist e.g. at VW Manufaktur in Dresden and LEGO in Denmark



© Danish Technological Institute

Reducing refrigerant charge by using

Minichannel Condensers



	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 %

/DANFOSS SANHUA/

… at the cost of higher refrigerant side pressure drop

Summary reducing direct emissions

- HFC can be replaced by natural refrigerants with no or low GWP in many applications at moderat additional cost
- In countries with adequate laws, e.g. Denmark, Norway and Sweden, many HFC-free or HFC-reduced systems are built with good energy efficiency
- Refrigerant charges can be greatly reduced applying up to date technology

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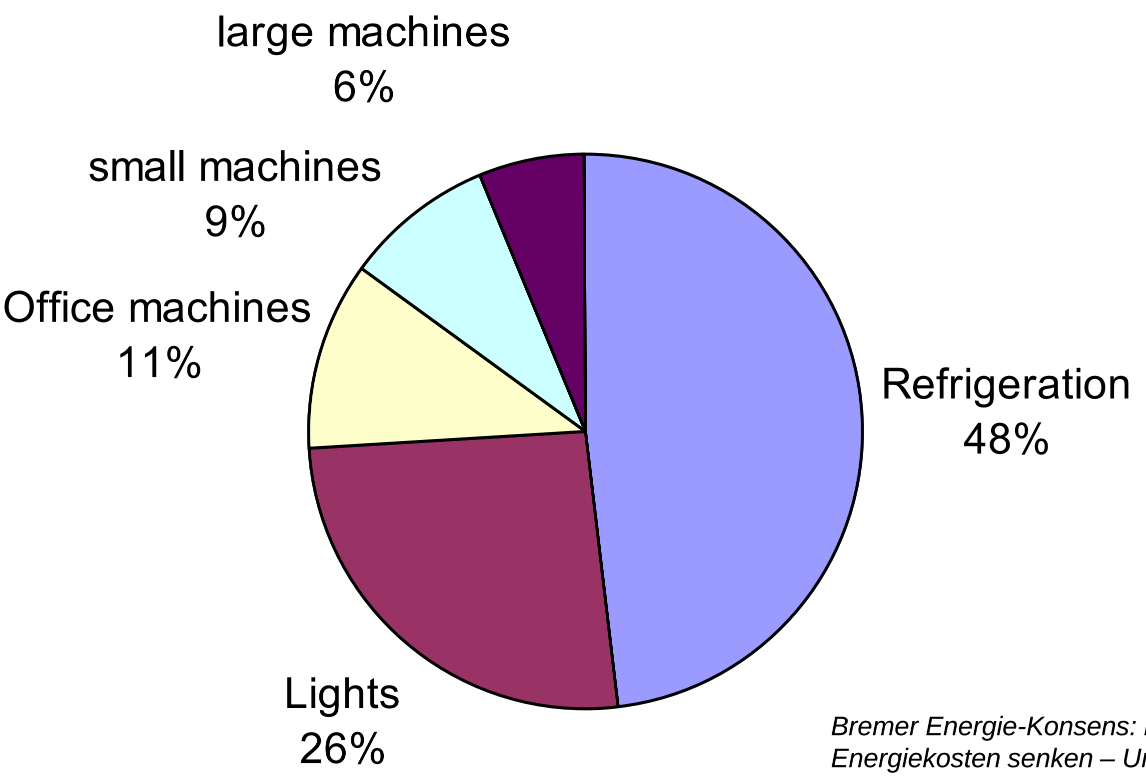
Reduce Energy Consumption

Consumption of Electricity in a typical Supermarket



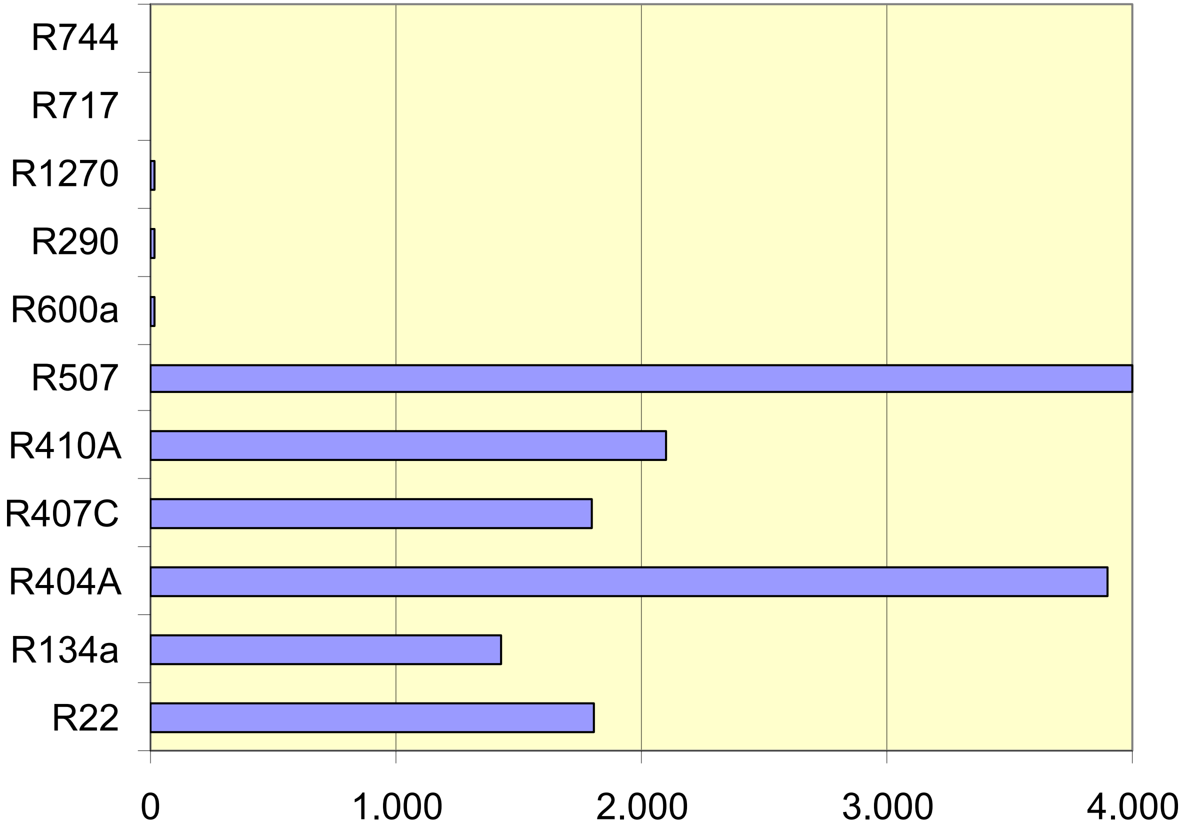
Bremer Energie-Konsens: Lebensmittelhandel aktuell – Energiekosten senken – Umwelt schonen. Ein praktischer Leitfaden für die effiziente Nutzung von Kühlmöbeln. www.energiekonsens.de, 5. Januar 2007

… in addition use of fossil fuel for space heating and hot water

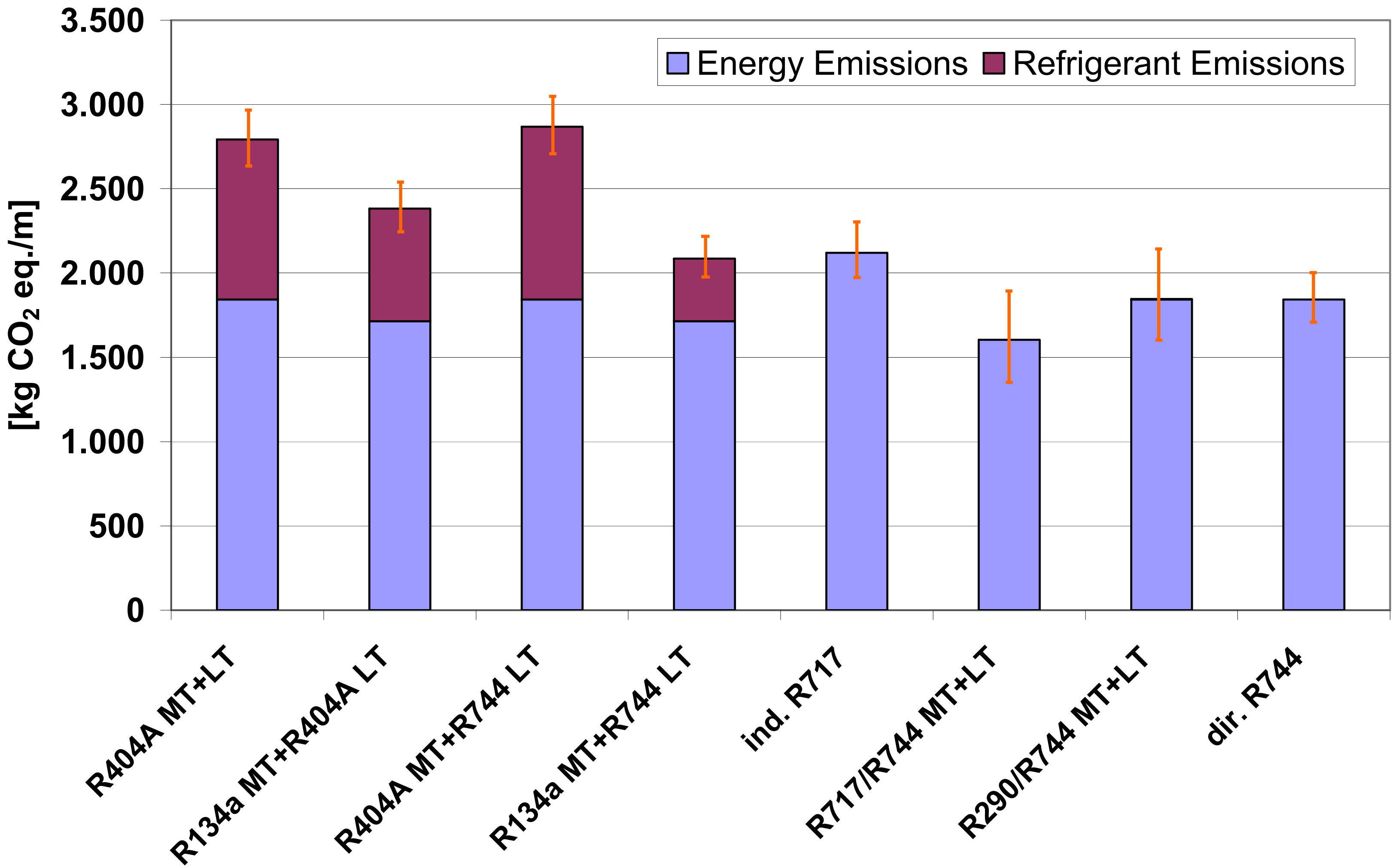
TEWI – Total Equivalent Warming Potential

Combining direct and indirect greenhouse gas emissions

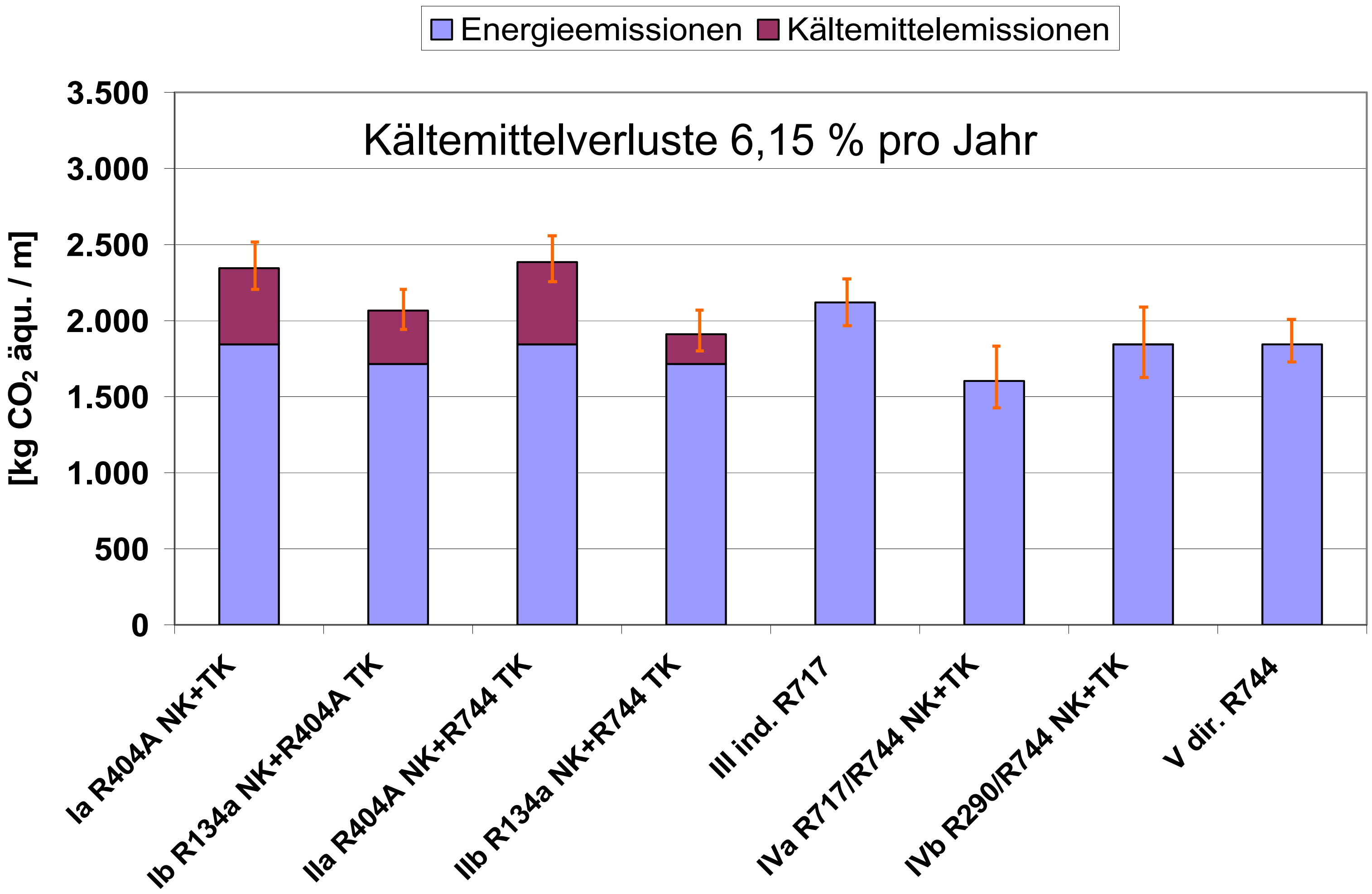
$$TEWI = GWP * L * n + GWP * m * (1 - \alpha_R) + n * E_a * \beta$$



TEWI Results Supermarket (HFC: 11.7 % loss p. yr)



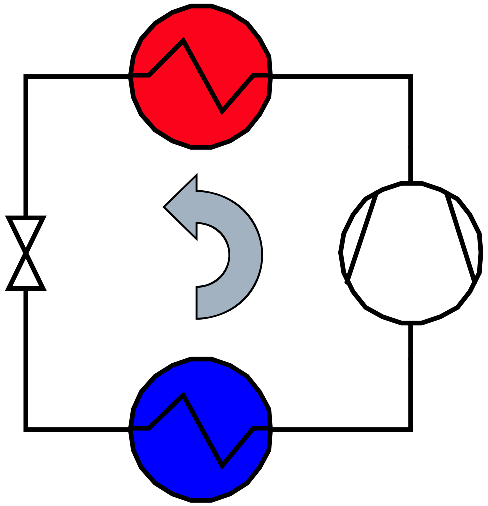
TEWI-Calculation Supermarket

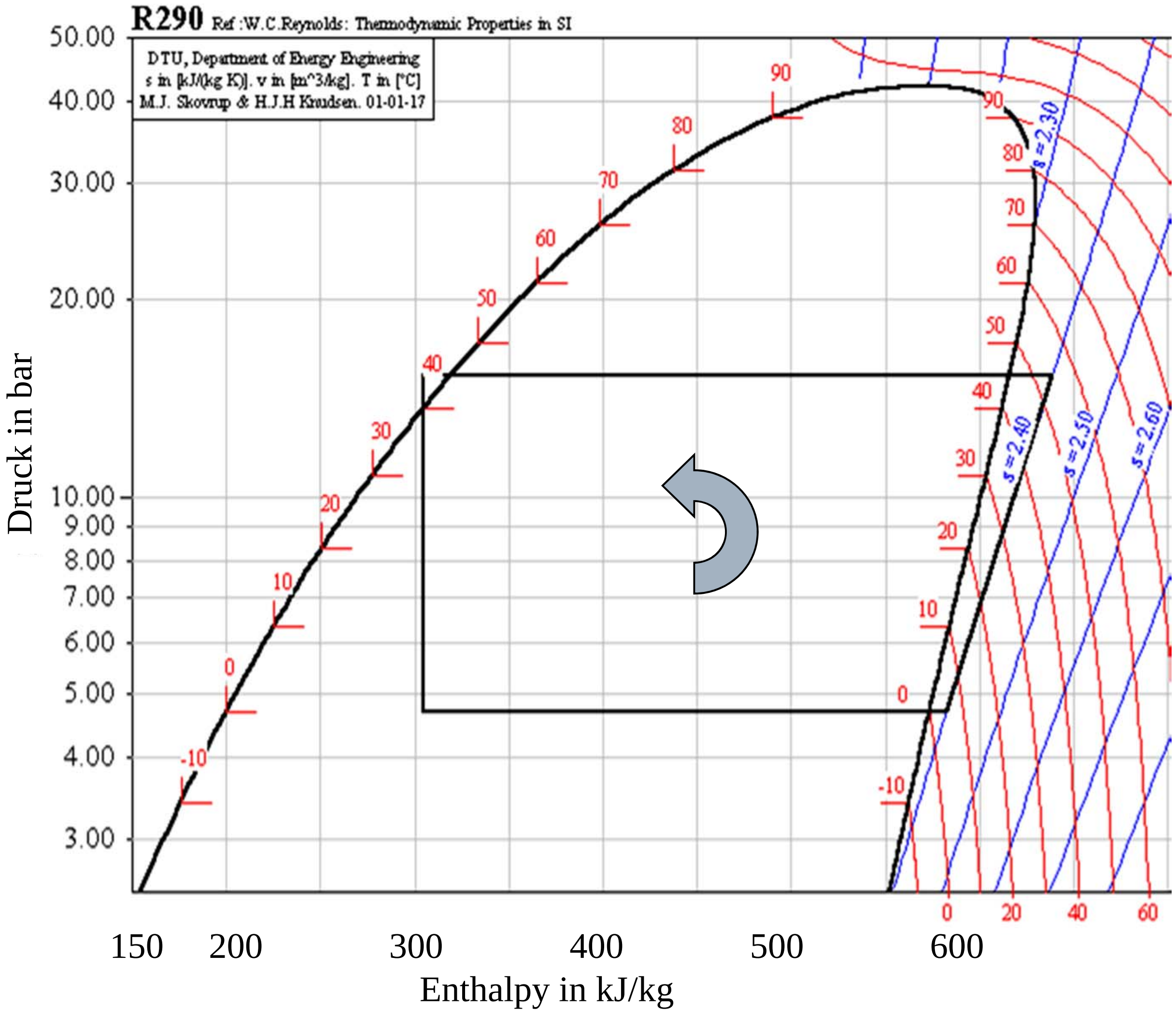


J.-M. Rhiemeier, J. Harnisch, C. Ters, M. Kauffeld und A. Leisewitz: Vergleichende Bewertung der Klimarelevanz von Kälteanlagen und -geräten für den Supermarkt. Förderkennzeichen (UFOPLAN) 206 44 300 (2008)

Thermodynamics of energy savings

… in refrigeration systems



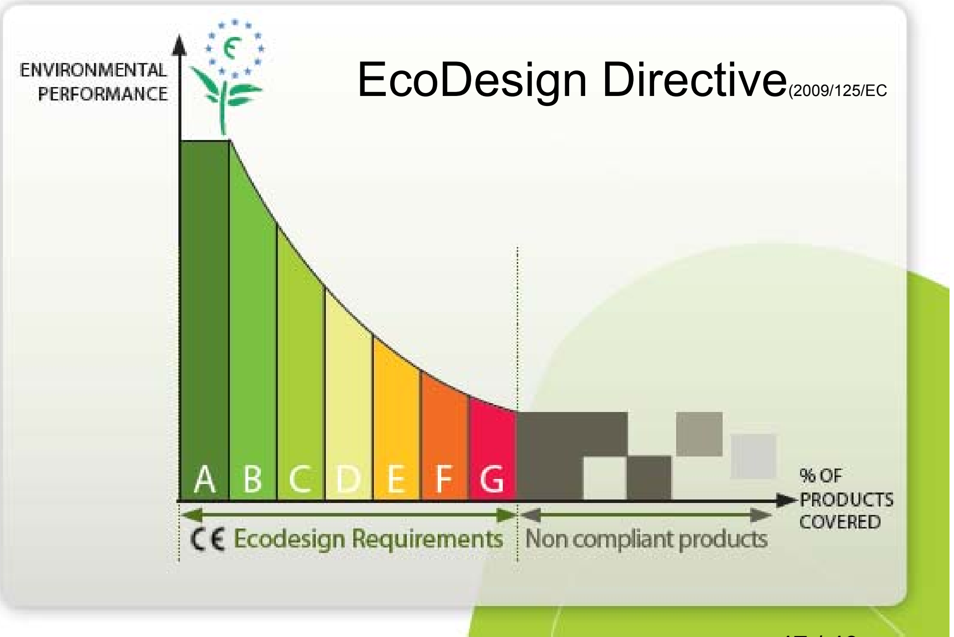


c.o.p. of Carnot-process:

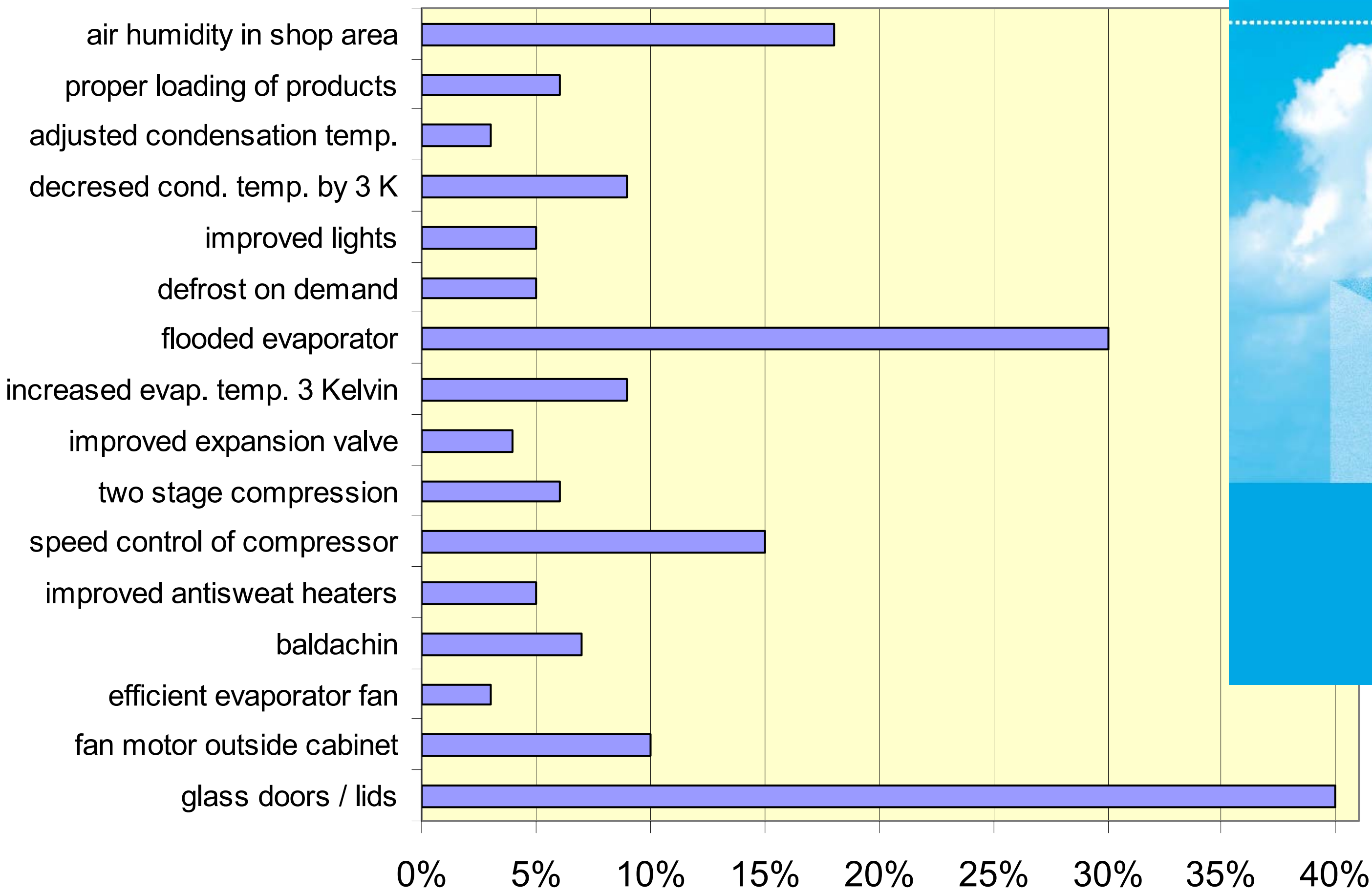
$$\varepsilon_{K\ Carnot} = \frac{T_k}{T_w - T_k}$$

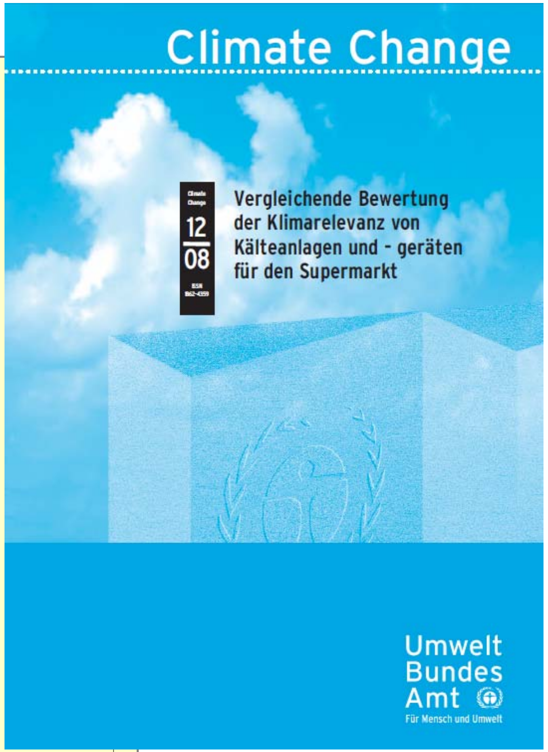
Reduce Energy Consumption

- ☐ Evaporator / condenser
- ☐ Refrigerated cabinet/room
- ☐ Refrigeration System
- ☐ Refrigeration Cycle
- ☐ Expansion valve
- ☐ Compressor



Potential of selected measures





www.umweltdaten.de/publikationen/fpdf-l/3624.pdf

… many of them can be combined, e. g. most of the above applied in one system → 80 % reduced energy consumption

Renewable Energy

- Heat recovery
  - Ventilation system
  - Refrigeration system
- Soil heat
- Ground water
- Biomass
- Wind energy
- Solar energy
  - Photovoltaic
  - Solar heating
  - Solar cooling
  - Solar lighting

Wärmerückgewinnung mit CO_2-Wärmepumpe bei McDonald's in Vejle, DK

Natürliche Beleuchtung durch spezielle Oberlichter bei ALDI Süd in Rastatt

Hybrid Solar Beleuchtung (HSL) bei Wal-Mart in Texas

Solare Vorwärmung der Zuluft bei Wal-Mart in Colorado

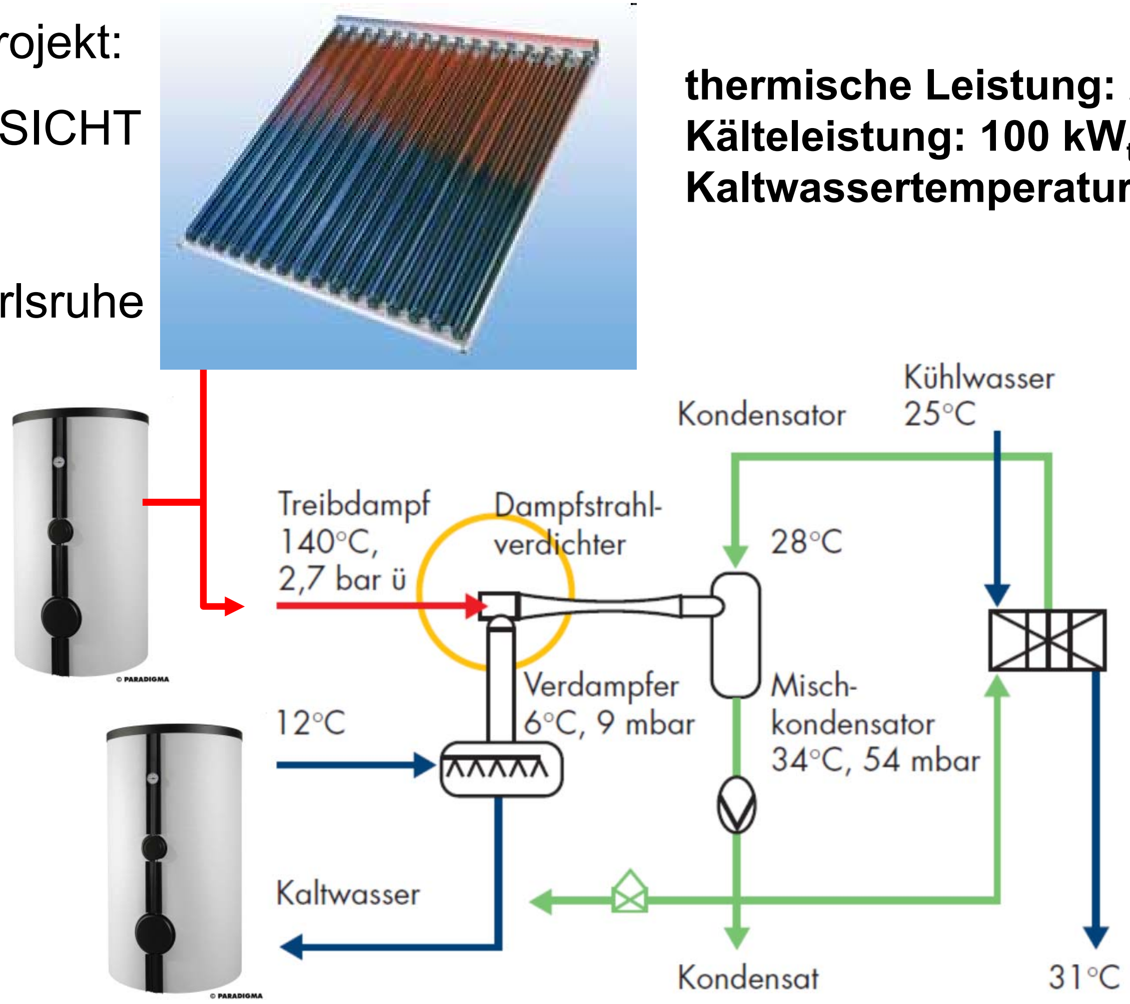
Quellen: McDonald's Juni 2004, ALDI Süd Filiale 2010, Wal-Mart Fotos aus ASHRAE-Journal 9 + 10 2007

Solar-thermal R718-steam ejector air conditioner

BMBF-Verbundprojekt:

- Fraunhofer UMSICHT
- GEA Jetpumps
- Ritter Solar
- Hochschule Karlsruhe

thermische Leistung: 200 kW_{th}
Kälteleistung: 100 kW_{th} (DSKM)
Kaltwassertemperatur von 6 °C



Summary reducing indirect emissions

- Refrigeration systems offer energy savings potentials well beyond 50 % at acceptable cost
- Utilization of renewable energy is also increasing for refrigeration systems
- Tri-generation (combined heat, cold and power production) offers ways for using warm/hot waste heat even during summer time

Outlook for refrigeration in the 21. century

No refrigerant emissions,

low energy consumption,

integrated thermal energy storage,

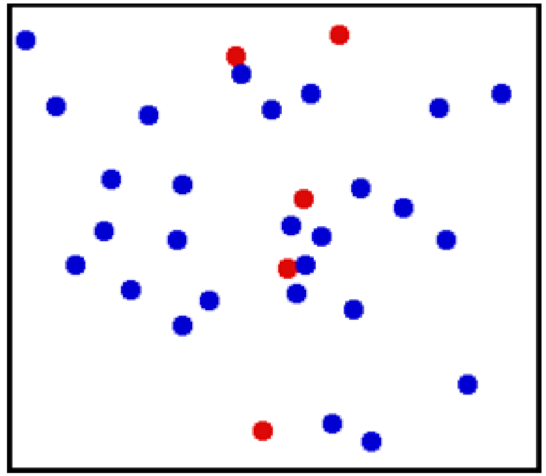
excellent reliability,

high safety and

high product quality.

→ creative engineers needed
with guts for going after new ideas

Vision: reversed microwave oven



Comments, Questions ?

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