MAGNETO (AND MULTI-)CALORIC MATERIALS FOR EFFICIENT REFRIGERATION

Oliver Gutfleisch

Functional Materials, TU Darmstadt, Germany

oliver.gutfleisch@tu-darmstadt.de

- Cooling - a global challenge
- MCE and AMR
- Material attributes, references Gd and LaFeSi, SOPT vs FOPT
- The materials library and demonstrators
- Conceptual extension to multicalorics
- Disentangling and utilizing the different degrees of freedom

Our research is embedded in…

- **Material criticality in a net-zero CO_2 emissions (NZE) scenario**
  - **Finiteness of strategic metals and resource strategy**

- **Rational design of novel magnetic materials**
  - **Mastery of hysteresis**
  - **Permanent magnets for E-mobility and wind turbines**
  - **Magneto- and Multicaloric materials for solid state refrigeration**
  - **Reduction - Substitution - Recycling**

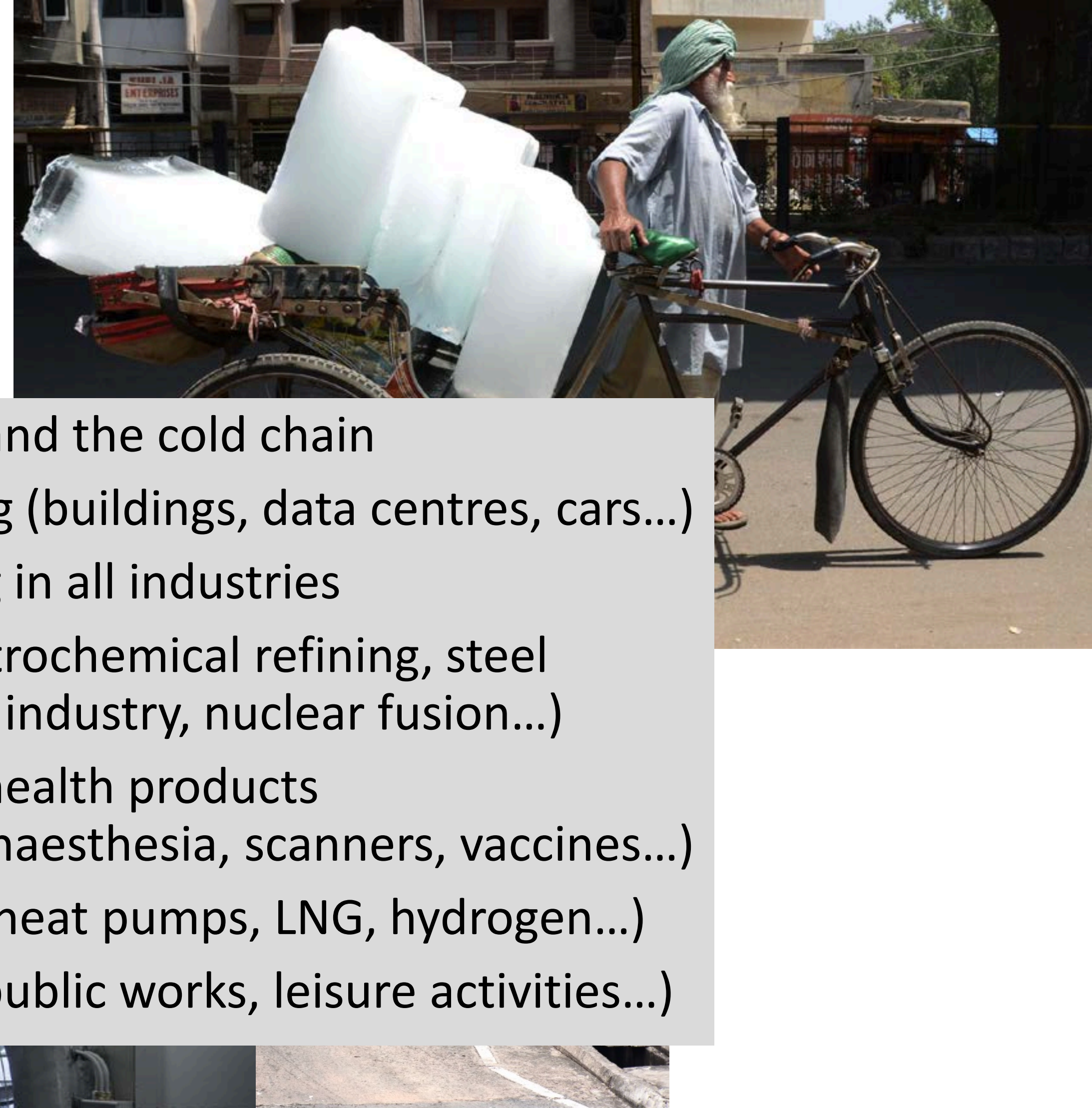
- **CRC/TRR 270 "*HoMMage*"**

Hysteresis design of magnetic materials for efficient energy conversion

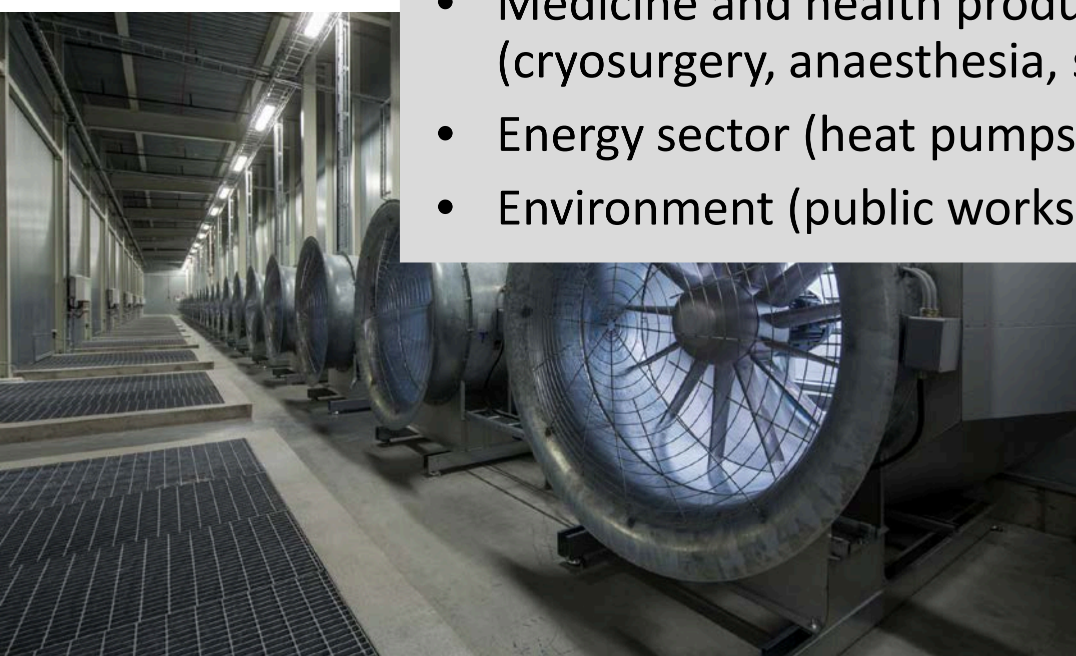
https://www.tu-darmstadt.de/sfb270

REFRIGERATION AS A GLOBAL CHALLENGE

Refrigeration is everywhere - the age of cryogenic life -



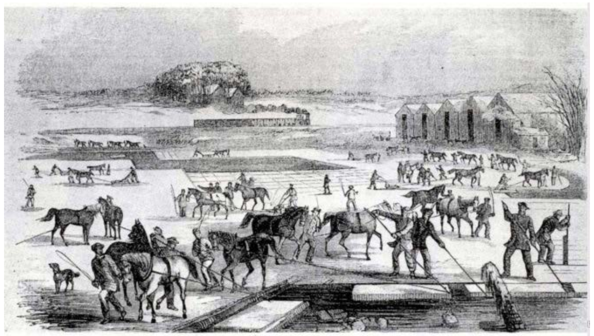
- Food industry and the cold chain
- Air conditioning (buildings, data centres, cars…)
- Process cooling in all industries
- Cryogenics (petrochemical refining, steel industry, space industry, nuclear fusion…)
- Medicine and health products (cryosurgery, anaesthesia, scanners, vaccines…)
- Energy sector (heat pumps, LNG, hydrogen…)
- Environment (public works, leisure activities…)



https://www.theguardian.com/world/2015/oct/26/india-rising-demands-cooling-hot-topic
Photograph: Narinder Nanu/AFP/Getty Images

https://www.theguardian.com/environment/2015/oct/26/cold-economy-cop21-global-warming-carbon-emissions
The Facebook data centre in northern Sweden, city of Luleå.
Photograph: David Levene/The Guardian

THE NEED TO KEEP COOL



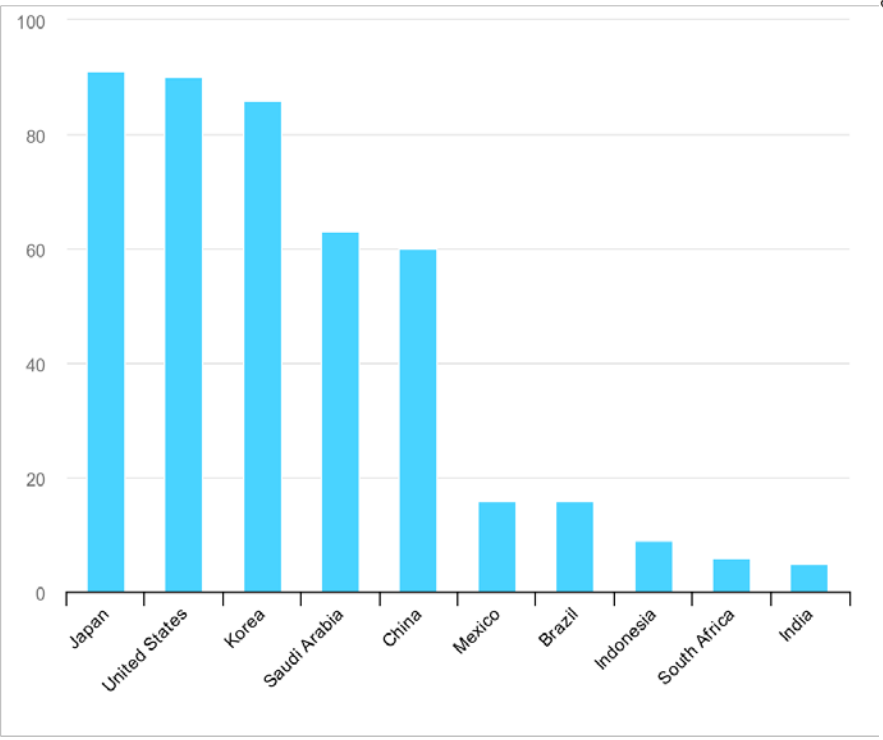
- **3 billion** refrigeration, air-conditioning and heat pump systems in operation worldwide
- **300 billion USD global** annual sales
- **12 million people** employed worldwide in the refrigeration sector
- **20% of the overall electricity** used worldwide consumed by refrigeration
- **12% of all green house gases** connected with cooling

… and a technology essentially unchanged for 120 years

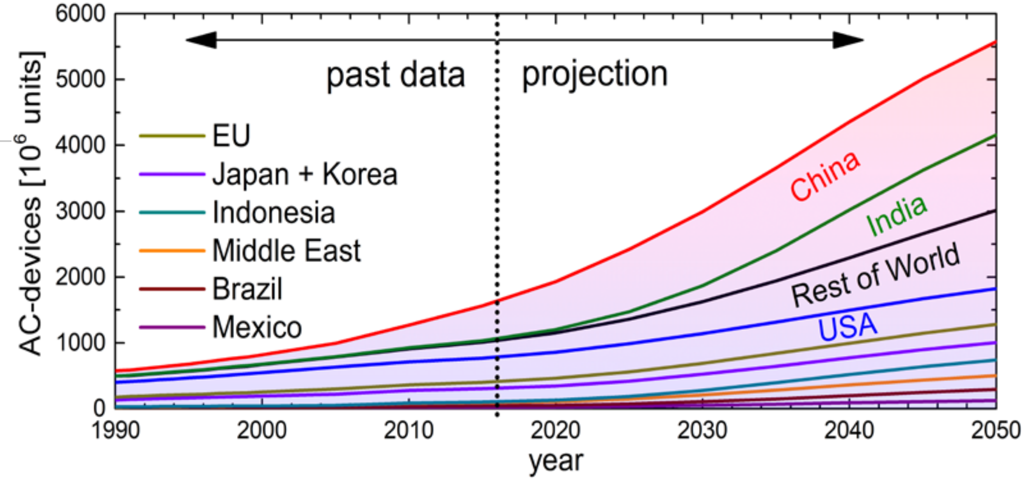
IIR 29th Informatory Note on Refrigeration Technologies 02/12/2015

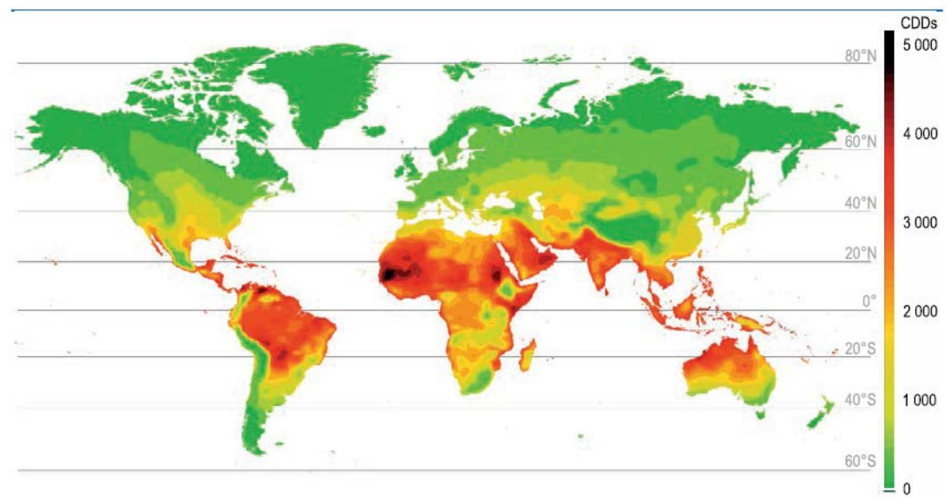
space cooling using air conditioners

Percentage of households equipped with AC in selected countries, 2018



Global air conditioner stock, 1990-2050





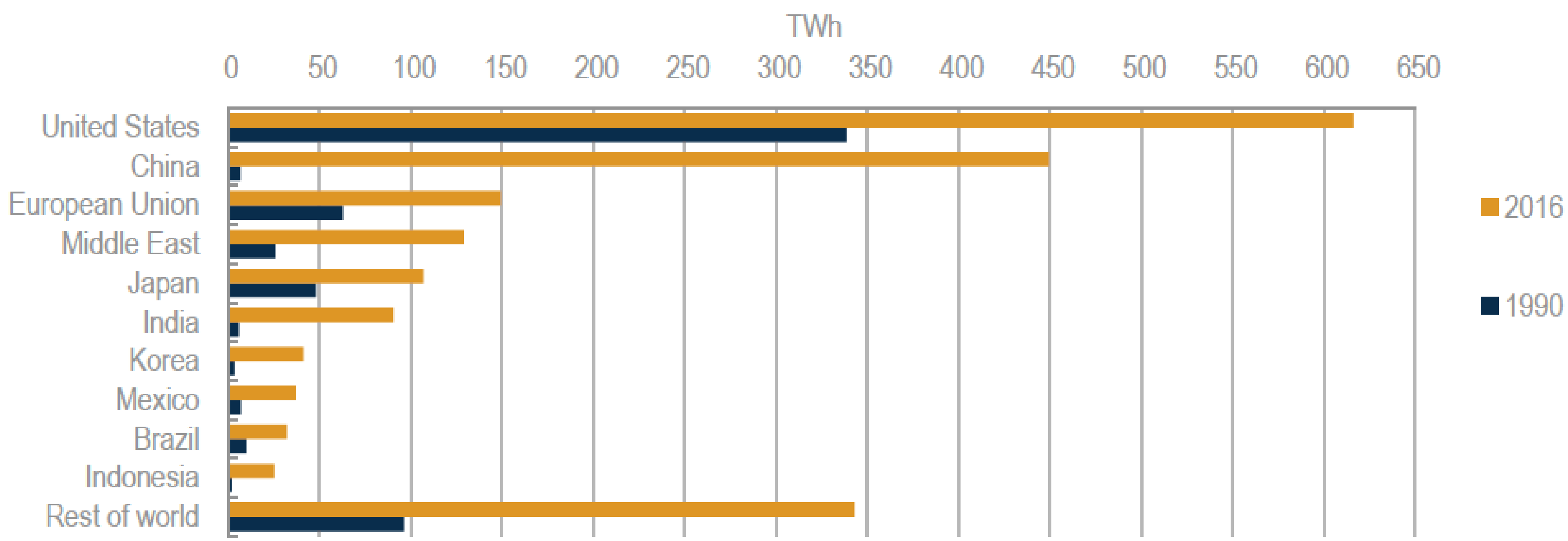
Graphs from: IEA, *The Future of Cooling (2018)*

Numbers of household versus numbers of refrigerators for Germany, USA, China and India (in million units)

The Future of Cooling

Opportunities for energy-efficient air conditioning

Figure 1.10 • Final energy consumption for space cooling by fuel and country/region



Key message • Energy use for cooling has been surging in China and other emerging economies, though it remains highest in the United States.

FACING THE COLD CRUNCH

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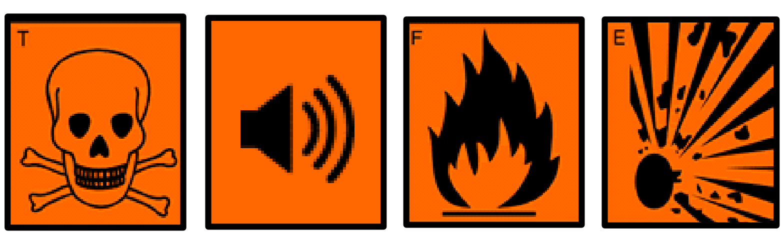
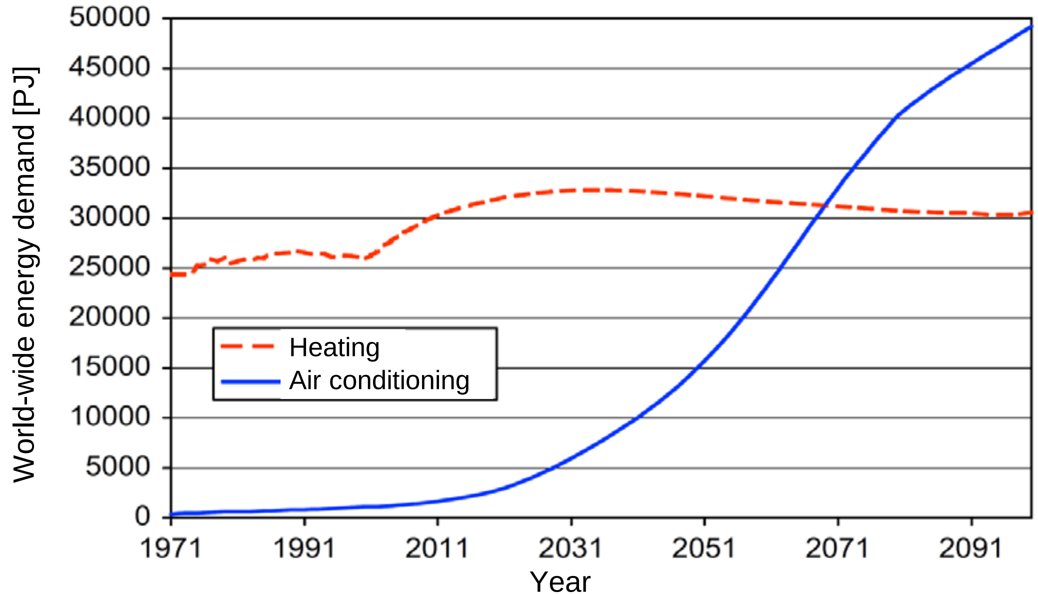
EU regulates usage of HFC´s

R22 (GWP=1725)	R134A (GWP=1430)	R404A (GWP=3922)	R410A (GWP=2088)



NH_3 (GWP=0)	CO_2 (GWP=1)	Butan (GWP=3)	Propan (GWP=3)

Adopted from M. Isaac, D. P. van Vuuren, Energy Policy 37 (2009) 507



~ 12% of total greenhouse gas emissions
~ 20% of the global electricity

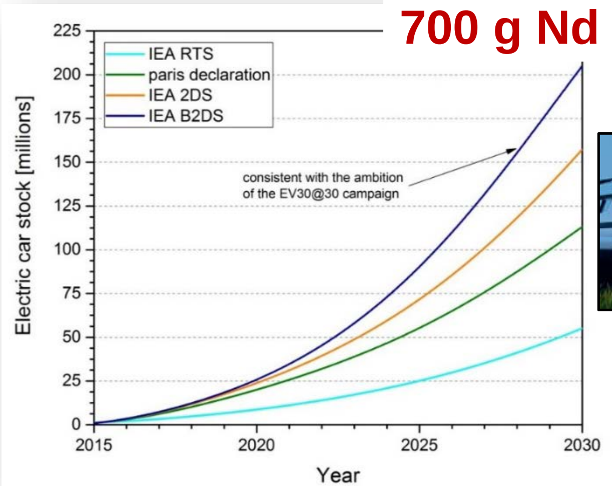
trajectory of cooling is changing dramatically BUT is not on the agenda

FUNKTIONALE MATERIALIEN

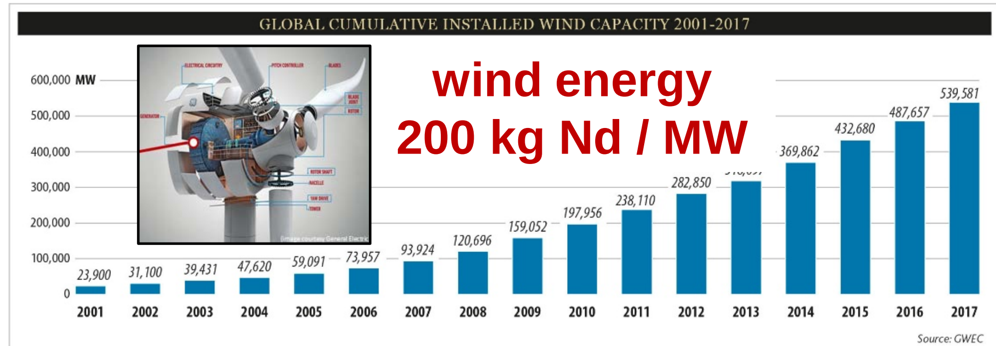
Global challenges
and the criticality of the strategic elements in magnets

https://www.iea.org/reports/energy-technology-perspectives-2017

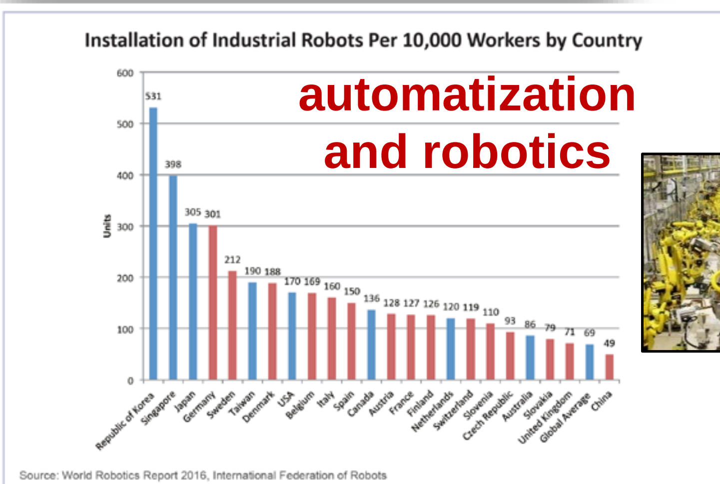
electro mobility
700 g Nd / Emotor



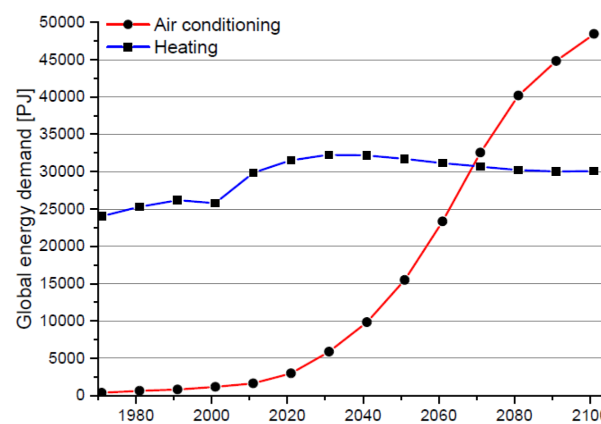
wind energy
200 kg Nd / MW



automatization
and robotics

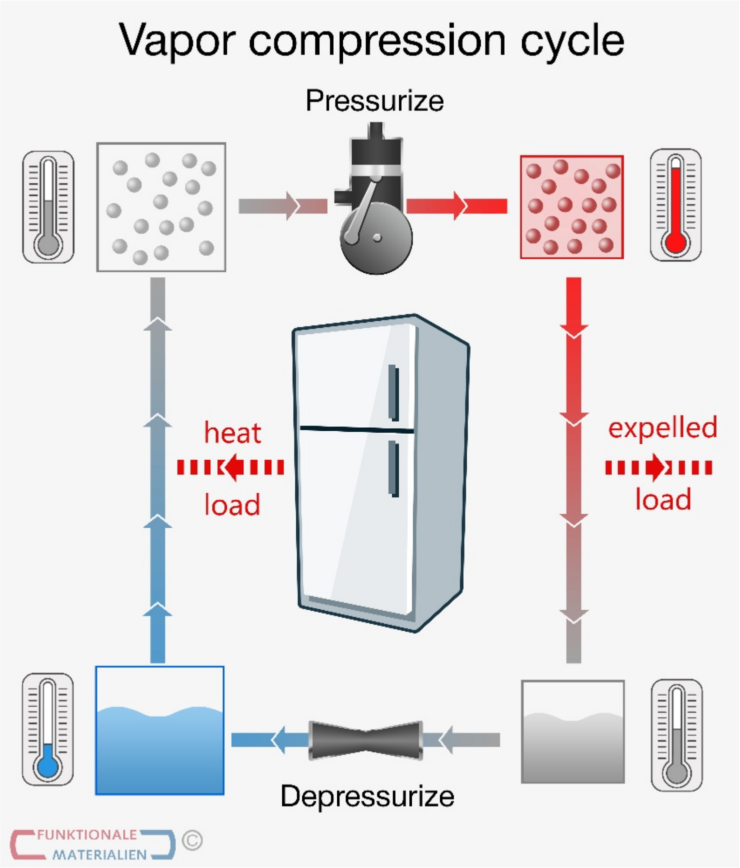


cooling
1.5 kg Nd / kW



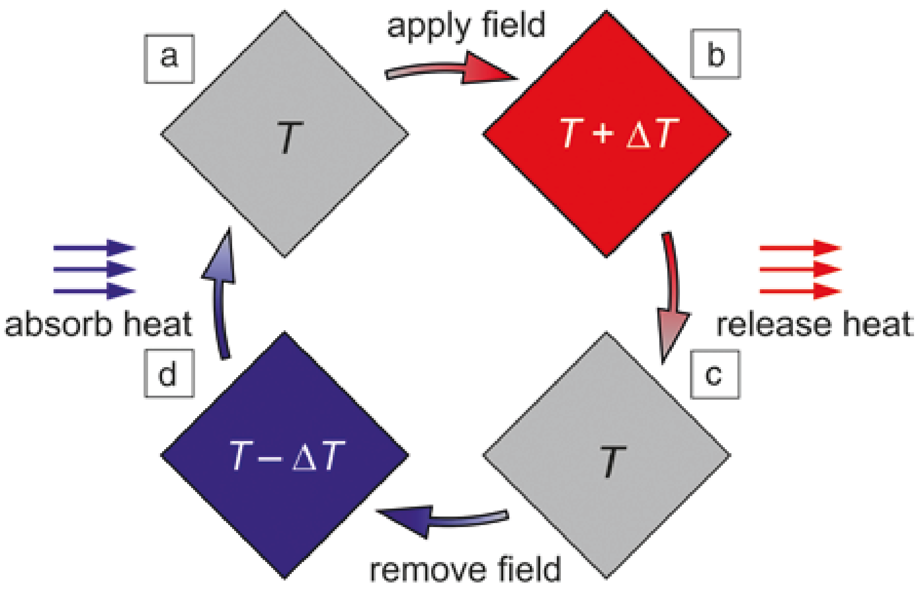
Adopted from M. Isaac, D. P. van Vuuren, Energy Policy 37 (2009) 507

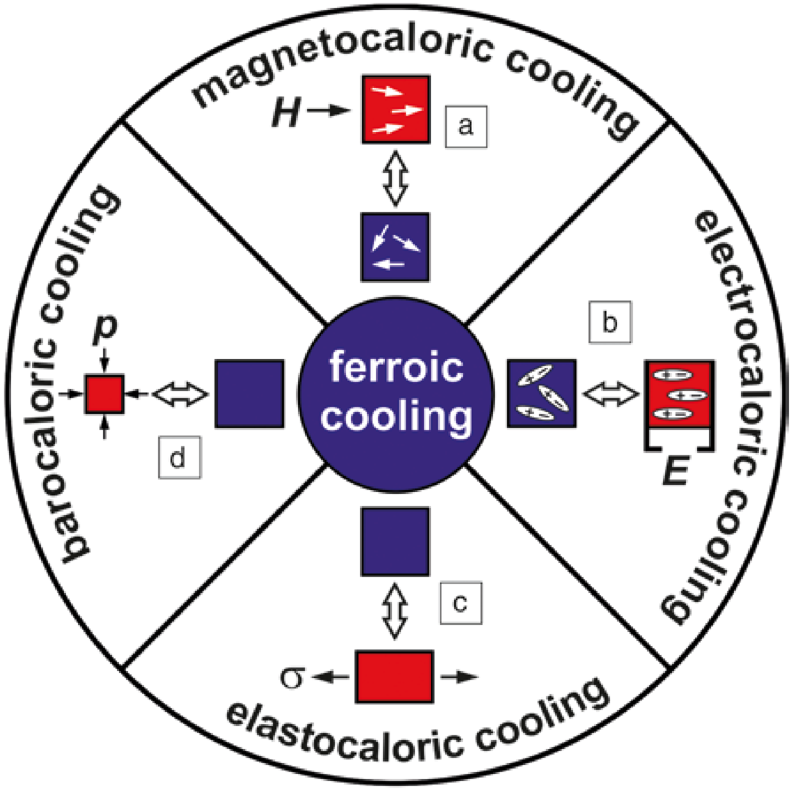
vapour compression vs caloric cooling



https://coolinnov.eu/

Caloric effects

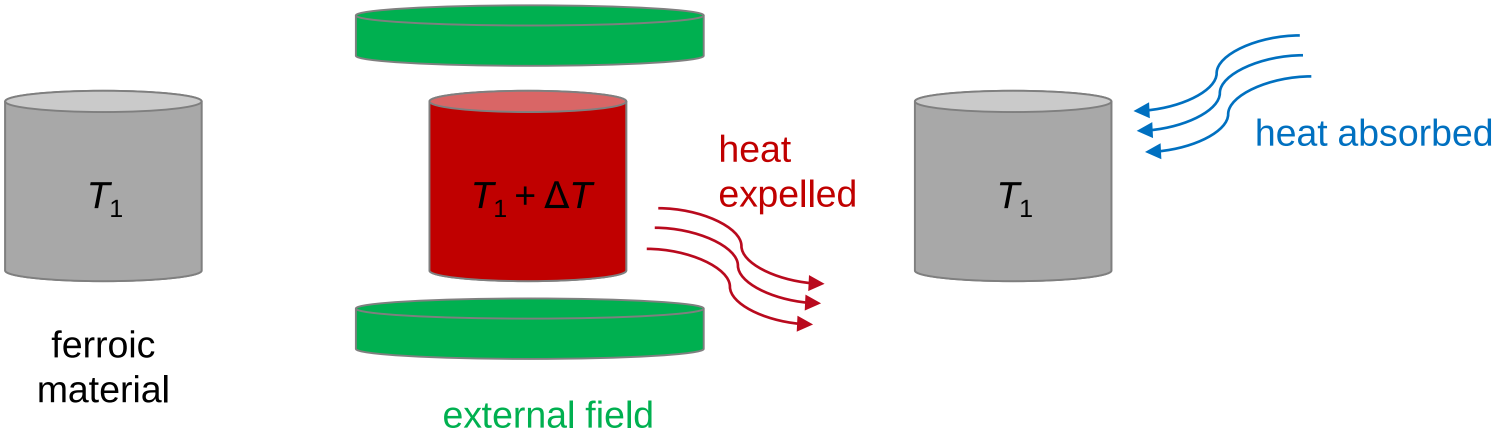


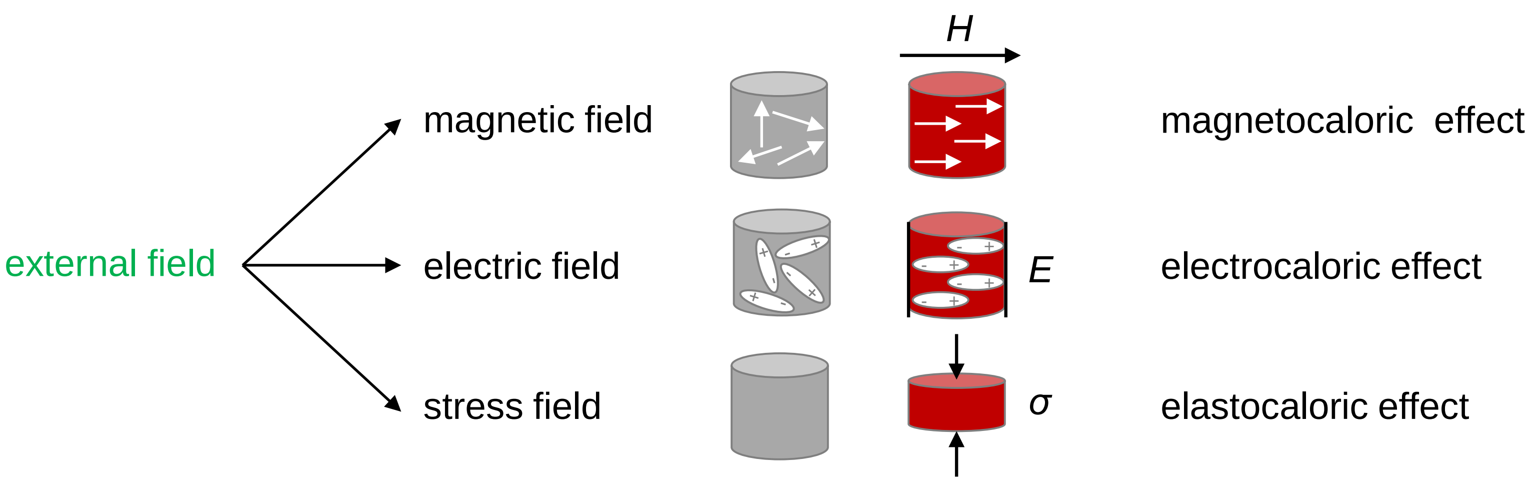


$$\Delta G = \Delta U - T\Delta S - \mu_0 H\Delta M - E\Delta P + \sigma\Delta u + p\Delta V$$

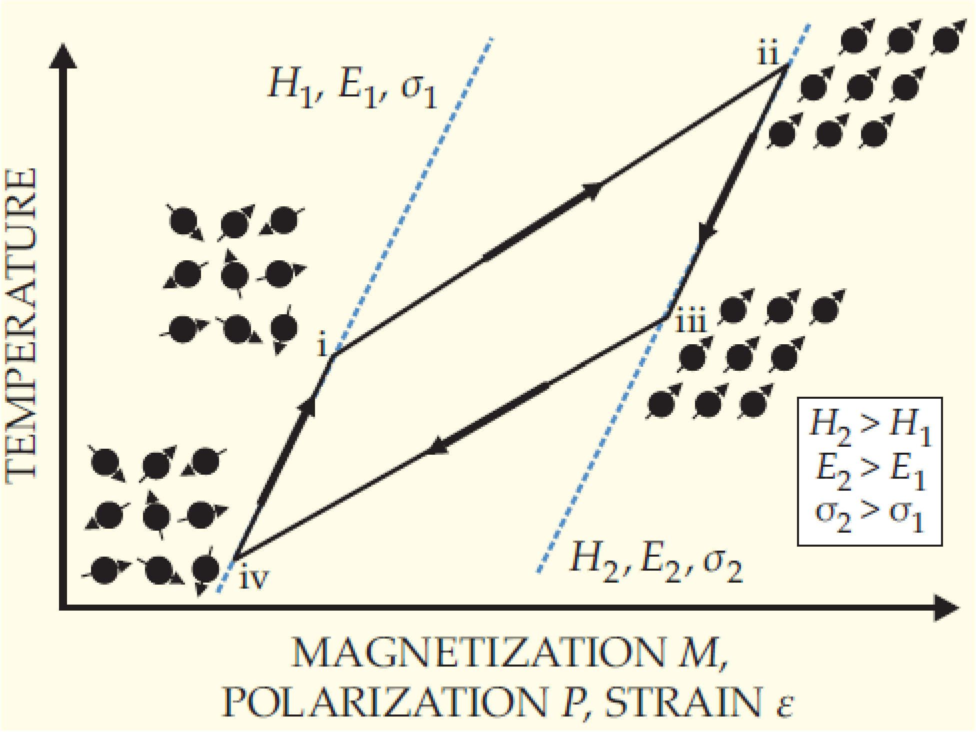
S. Fähler and V. K. Pecharsky, MRS BULLETIN 43, pp. 264-268 (2018)

Caloric effects





Temperature-state diagram of a ferroic cooling cycles



Internal degree of freedom are ordered and disordered during cycling

- variable magnetic spins (magnetocaloric)
- electric dipoles (electrocaloric)
- or structural arrangements (elastocaloric)

I. Takeuchi and K. Sandeman, 2015 , Physics Today 68, 12, 48 (2015); doi: 10.1063/PT.3.3022

FUNDAMENTALS OF THE MAGNETOCALORIC EFFECT

Why magnetic cooling?

Advantages:

- Highly efficient (in principle…)

  isentropic process: no irreversibilities of heat transfer
- No refrigerants with GWP, F-gas free, no ozone depleting substances
- Quiet, little vibrations, no compressor
- Applicable also at low temperature (gas liquefaction – H_2 economy!)
- Many temperature ranges possible
- Effect reversible → heat engines → thermomagnetic generator
- Scalable from mW to kW

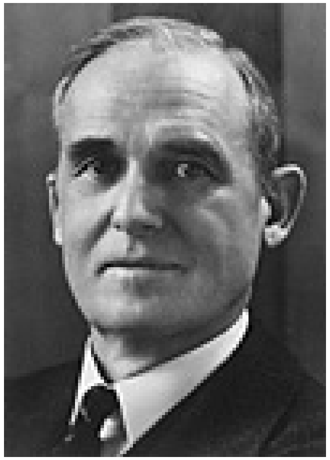
BUT mass, cost, criticality, LCA, performance of the functional magnetic materials and heat transfer, pressure drop, hysteresis and cycleability

Magnetic cooling

- The magnetocaloric effect was first described by Peter Weiss in 1917

- Adiabatic demagnetization is used to reach temperatures below 1 K

  → 1949 Nobel price in chemistry



William Francis Giauque
University of California
Berkeley, CA, USA
b. 1895
d. 1982

"for his contributions in the field of chemical thermodynamics, particularly concerning the behaviour of substances at extremely low temperatures"

W.F. Giauque, D.P. MacDougall, Phys. Rev. 43 (1933) 768

768 LETTERS TO THE EDITOR

Attainment of Temperatures Below 1° Absolute by Demagnetization of $Gd_2(SO_4)_3 \cdot 8H_2O$

We have recently carried out some preliminary experiments on the adiabatic demagnetization of $Gd_2(SO_4)_3 \cdot 8H_2O$ at the temperatures of liquid helium. As previously predicted by one of us, a large fractional lowering of the absolute temperature was obtained.

An iron-free solenoid producing a field of about 8000 gauss was used for all the measurements. The amount of $Gd_2(SO_4)_3 \cdot 8H_2O$ was 61 g. The observations were checked by many repetitions of the cooling. The temperatures were measured by means of the inductance of a coil surrounding the gadolinium sulfate. The coil was immersed in liquid helium and isolated from the gadolinium by means of an evacuated space. The thermometer was in excellent agreement with the temperature of liquid helium as indicated by its vapor pressure down to 1.5°K.

On March 19, starting at a temperature of about 3.4°K, the material cooled to 0.53°K. On April 8, starting at about 2°, a temperature of 0.34°K was reached. On April 9, starting at about 1.5°, a temperature of 0.25°K was attained.

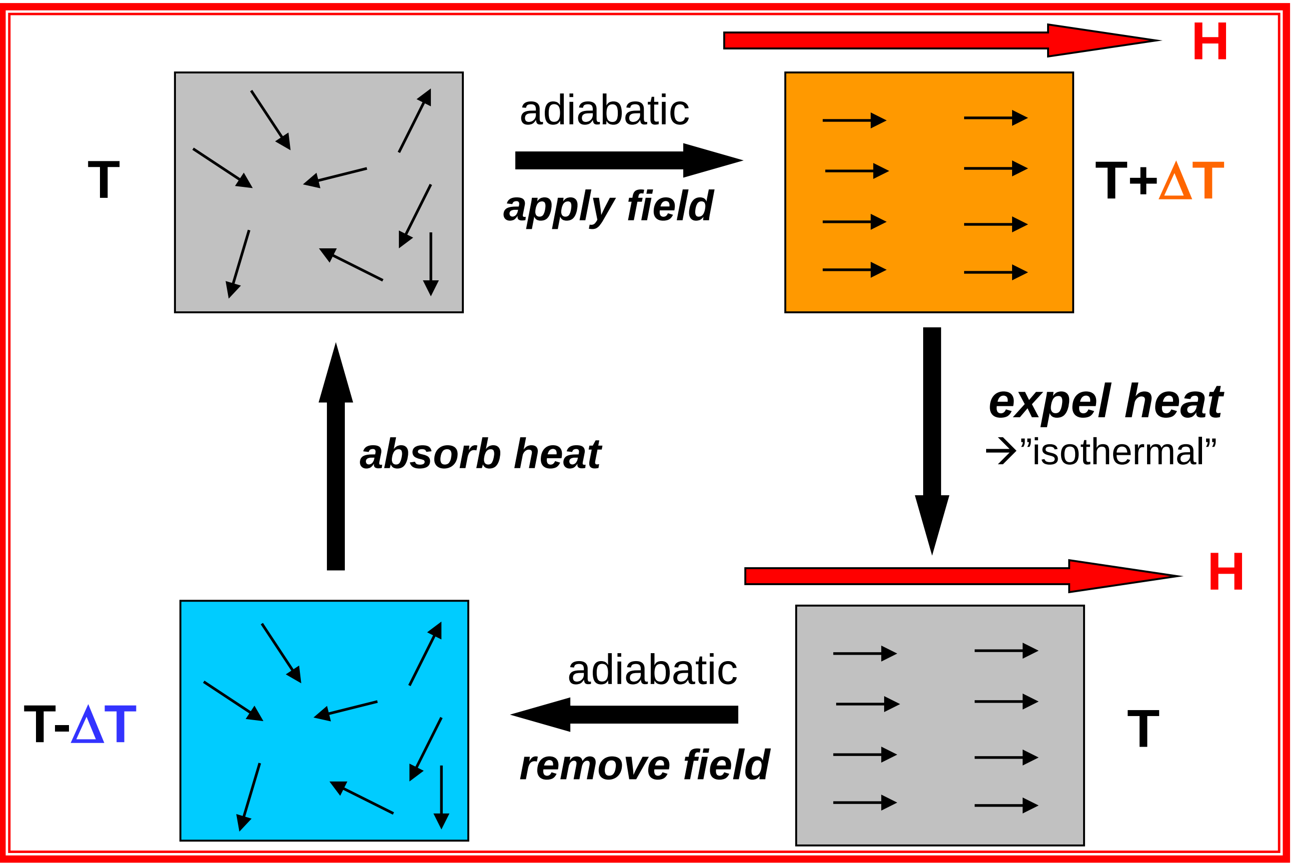
It is apparent that it will be possible to obtain much lower temperatures, especially when successive demagnetizations are utilized.

W. F. Giauque
D. P. MacDougall

Department of Chemistry,
University of California,
Berkeley, California,
April 12, 1933.

61 g of $Gd_2(SO_4)_2 8H_2O$
0.8 Tesla: 1.5 K → 0.25 K

Magnetocaloric effect



$$\Delta S_m = \int_0^H \left(\frac{\partial M}{\partial T}\right)_H dH$$

$$\Delta T = -\int_0^H \frac{T}{C_{H,p}} \left(\frac{\partial M}{\partial T}\right)_{H,p} dH$$

Large H

Large $\left(\frac{\partial M}{\partial T}\right)_H$

Small $C_{H,p}$

} **Large MCE**

- **Maxwell equation applies to equilibrium thermodynamics**
- **coupled magnetostructural transitions, related latent heat, hysteresis**
- $\Delta S_{iso} = \Delta S_{mag} + \Delta S_{lat} + \Delta S_{el}$

CONTRIBUTIONS TO TOTAL ENTROPY

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In an **adiabatic process**, the total entropy-change Δs_{tot} is zero, so that

$$\Delta s_{tot} = \Delta s_{lat} + \Delta s_{mag} + \Delta s_{el} = 0$$

Since within a thermodynamic state Δs_{el} vanishes,
applying a magnetic field to a magnetic material causes s_{mag} to decrease ($\Delta s_{mag} < 0$) and s_{lat} to increase ($\Delta s_{lat} > 0$), so that the material warms.

This is the conventional magnetocaloric effect, the principle which is employed to attain very low temperatures using PM salts.

A unified terminology of magnetocalorics

https://www.beuth.de/de/technische-regel/din-spec-91373/288638546

June 201

DIN SPEC 91373

ICS 01.040.17; 01.040.27; 17.220.99; 27.200

Magnetocal
Terminolog
Text in Engl

Magnetokalori
Termino
Text Eng

Magnéto
Termino
Texte en anglais

3.1.2 Material properties

3.1.2.1
specific isotherm
Δs_T

3.1.1 Basic ter

3.1.3 Applic

3.1.1.6
first-order
transition in

3.1.2.2
adiabatic tempe
ΔT

3.1.3.5
thermomagnetic ge

3

3.1.1.9
dilati
magn

3.1.2.11
magnetoc
ΔT_{hyst}

3.1.3.7
active magnetic rege
AMR

3.1.4.1
refrigerant

3.1.1.14
critical point
composition of
phase transition

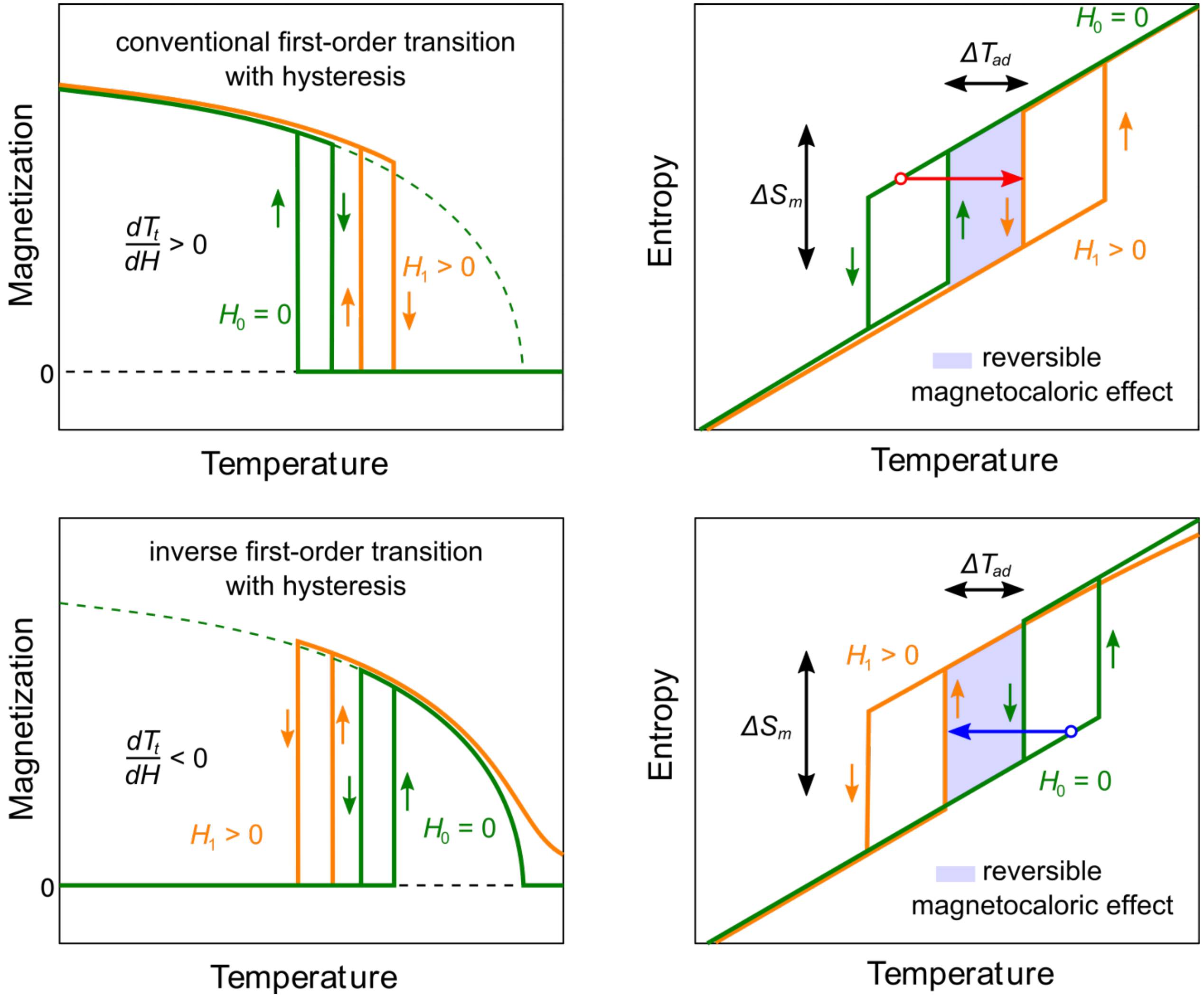
3.1.3.8
refrigeration cap
quantity of heat th

3.1.4.2
specific magnetocaloric

in press

Contents

Classification of MCE materials



→ Thermal hysteresis reduces the reversibility of the magnetocaloric effect

→ Shift of transition temperature in magnetic fields is the driving force of MCE

Phil. Trans. R. Soc. A (2016)
Energy Technology (2018)
Nature Communications (2018)

Disentangling the Microscopic Contributions to the Entropy Change

Energy Technol. **2018**, *6*, 1397–1428

$$\left|\Delta T_{ad}^{max}\right| = T\left|\Delta S_{T}^{max}\right|/C_{p} \qquad S = S_{el} + S_{mag} + S_{lat}$$

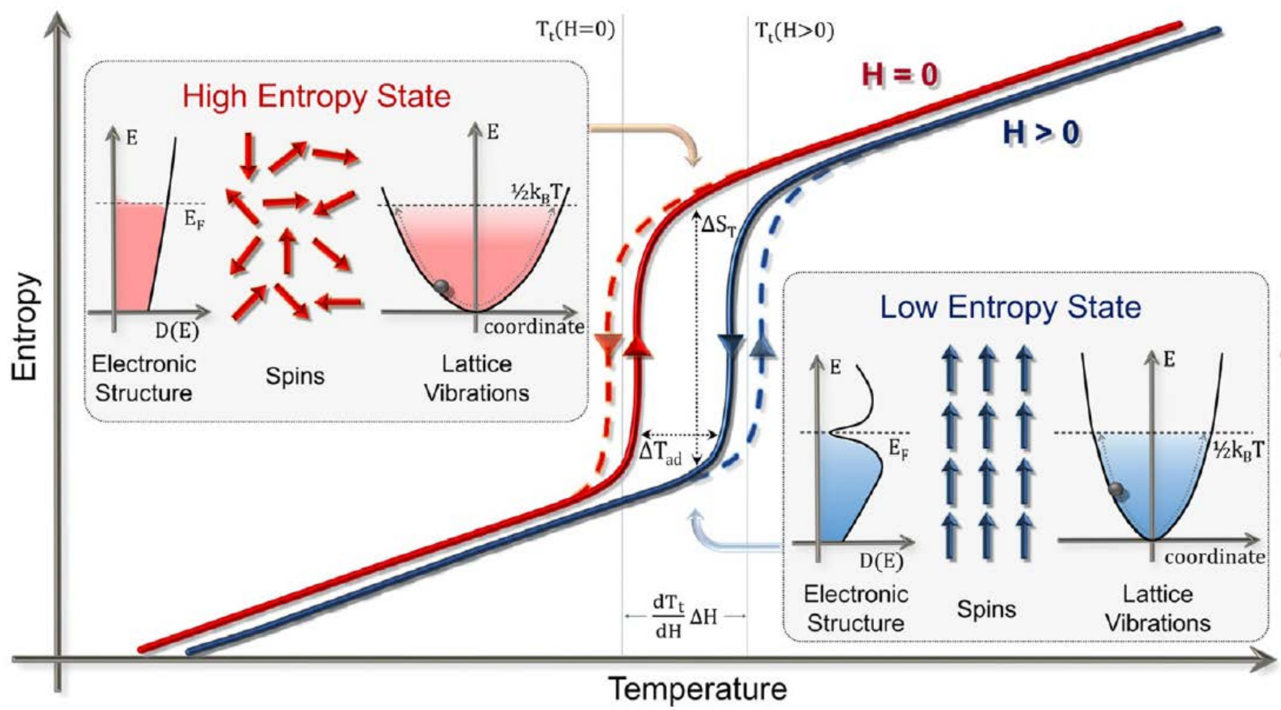
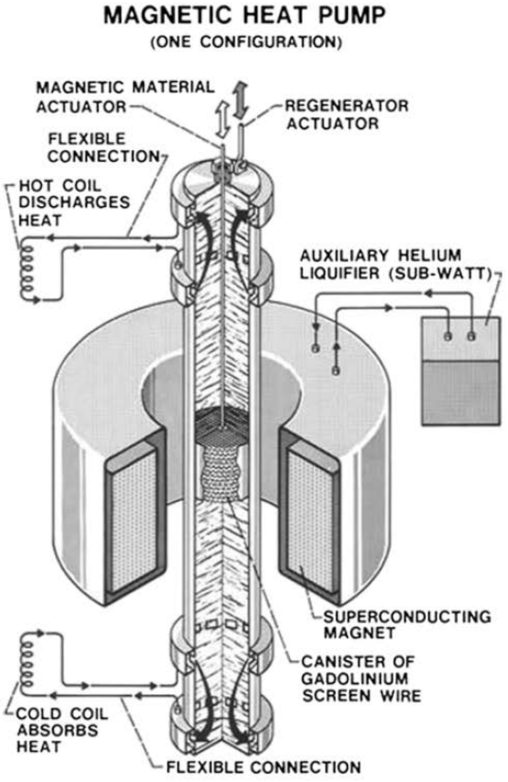
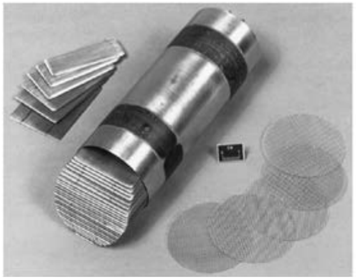


Figure 1. Schematic T–S diagram illustrating the magnetocaloric effect at a first-order transition. Application of a magnetic field H shifts the transformation temperature T_t to higher values. Applying the magnetic field isothermally in the intermediate temperature range between $T_t(H=0)$ and $T_t(H>0)$ leads to a decrease of ΔS_T in the total entropy, whereas an adiabatic field release decreases the temperature by ΔT_{ad}, which can be used for heat transport or cooling. Thermal hysteresis, indicated by the dashed lines, causes heat dissipation and reduces the maximum possible ΔT_{ad} in a cycling setup. The boxes depict basic characteristics of the respective high- and low-entropy states of the three relevant degrees of freedom. For the electronic entropy, these are, respectively, a high or low density of states at the Fermi level $D(E_F)$, for the magnetic entropy orientational disorder or order of the atomic moments, and for the lattice entropy, the presence of on-average softer or stiffer vibration.

Brown´s magnetic refrigerator (1976)





Gd Plates 1 mm thick (1 mole)

T_C = 294 K

Regenerator: 80% H_2O -20% C_2H_5OH

ΔH = 70 kOe

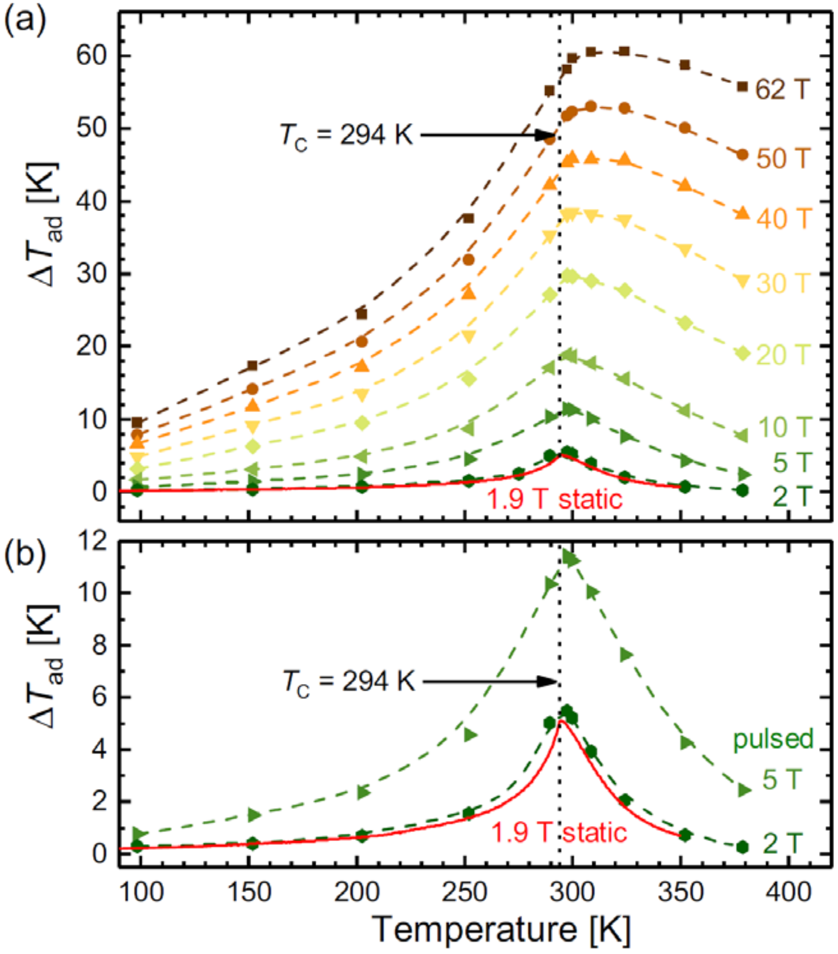
50 cycles

T_{hot} = 319 K
T_{cold} = 272 K } Δ_T = 47 K

ΔT_{ad} of Gd = 16 K at 294 K (T_C)

Magnetic heat pumping near room temperature
Brown, G.V., 1976, J. Appl. Phys. 47, 3673–3680.

Adiabatic temperature change of gadolinium



*PRB **99**, 134429 (2019)*

Active Magnetic Regenerator (AMR)

AMR first proposed by J.A. Barclay,1982

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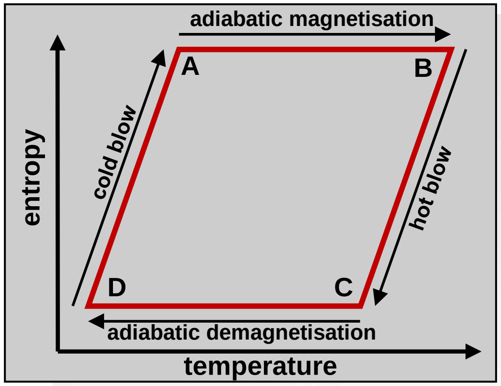

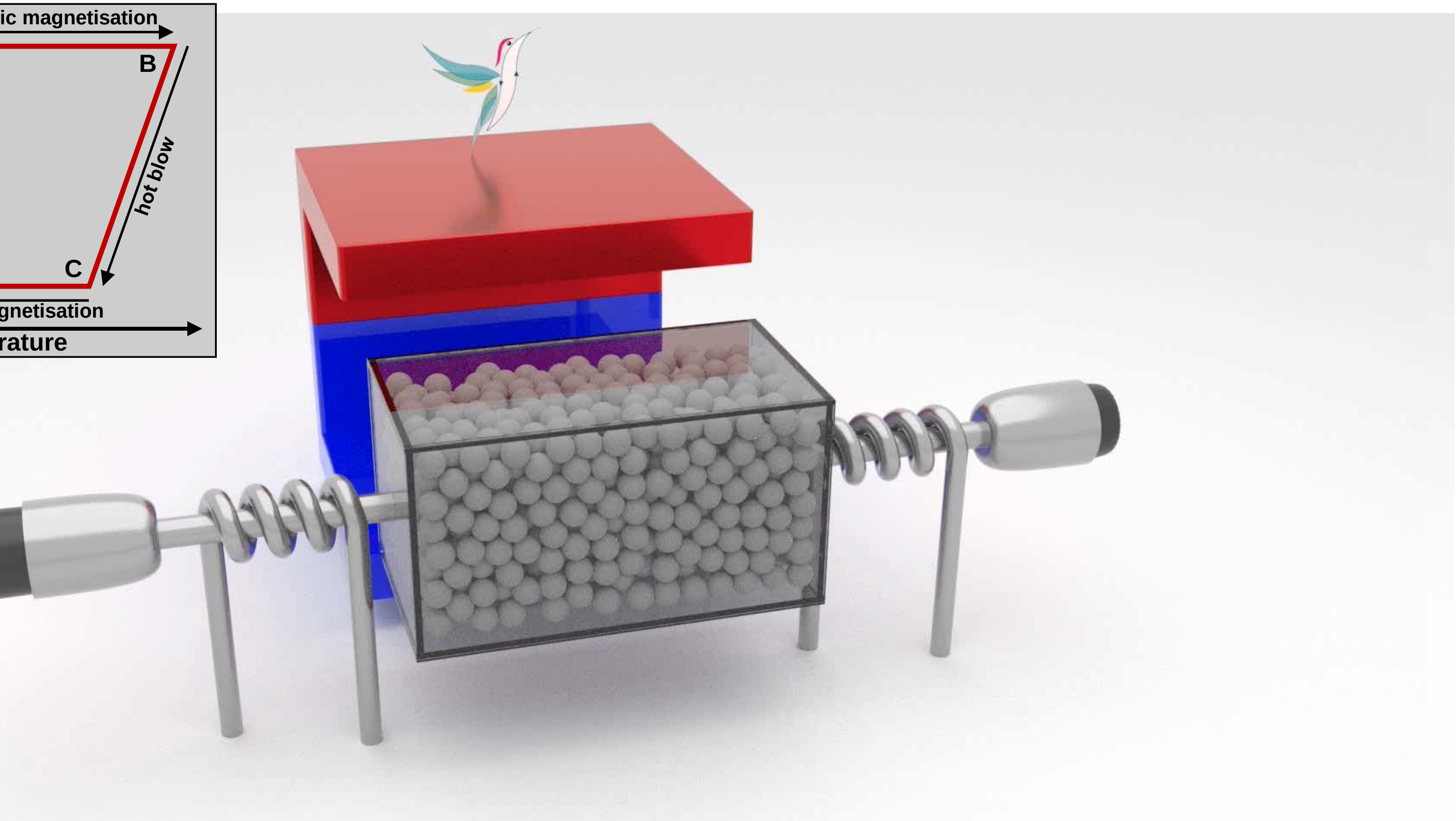

by Tino Gottschall

DIN SPEC 91373:2018-06

3.1.3.7
active magnetic regenerator
AMR
device in which the magnetocaloric material does double duty both as refrigerant and as a thermal regenerator and where each distinct part of the regenerator performs individual thermodynamic cycles which are linked by a moving heat exchange fluid

MATERIALS

Magnetic refrigerant attributes

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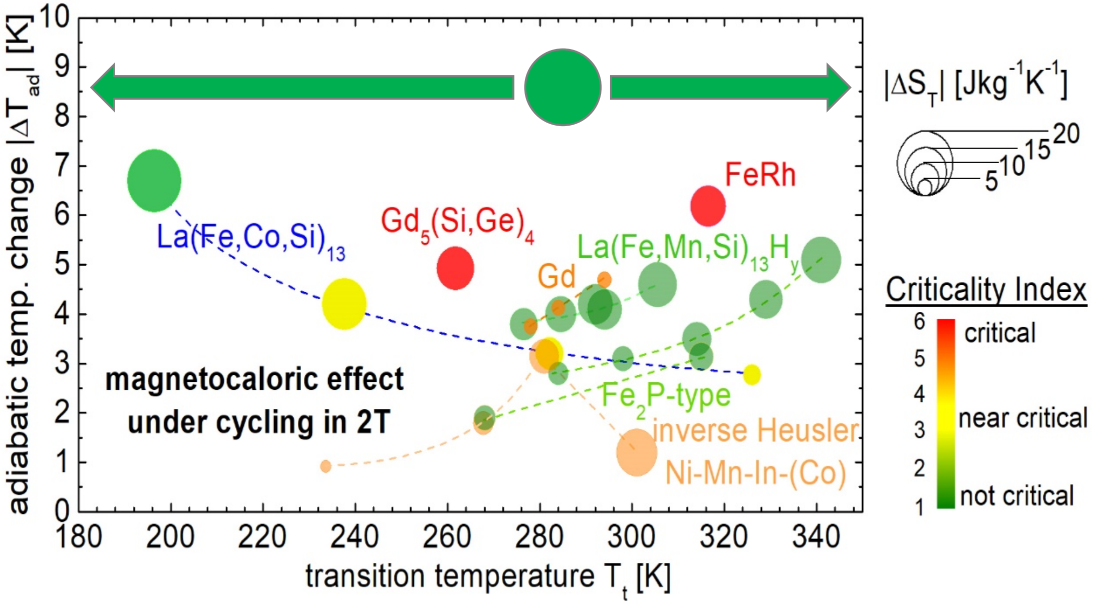
- large temperature change ΔT_{ad}
- large magnetic entropy change ΔS_m
- minimize hysteresis for max. reversibility
- easy tunable T_t
- high thermal and low electrical conductivities
- easy to produce / to shape
- fatigue and corrosion resistant
- environmental friendly, non-toxic
- criticality / supply risk / cost

Impact on mass of PM

FUNKTIONALE MATERIALIEN

Sustainable bulk magnetic materials at their physical limits

Magnetocalorics

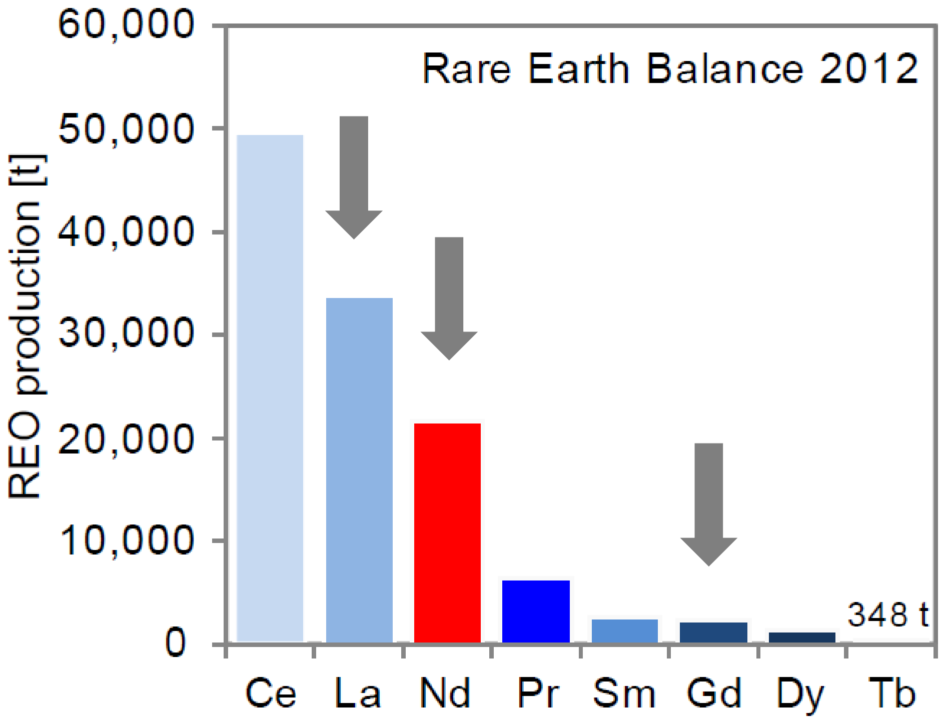


→ **“new” magnets with secondary functionalities such as complex geometry by (nano-) additive manufacturing, local vs. effective anisotropy and exchange, mechanical, thermal and electrical properties**

Making a cool choice - The materials library of magnetic refrigeration, Progress Report in Adv. Energy Mat. 2019

Rare earth balance

Utilisation of earth abundant rare earths



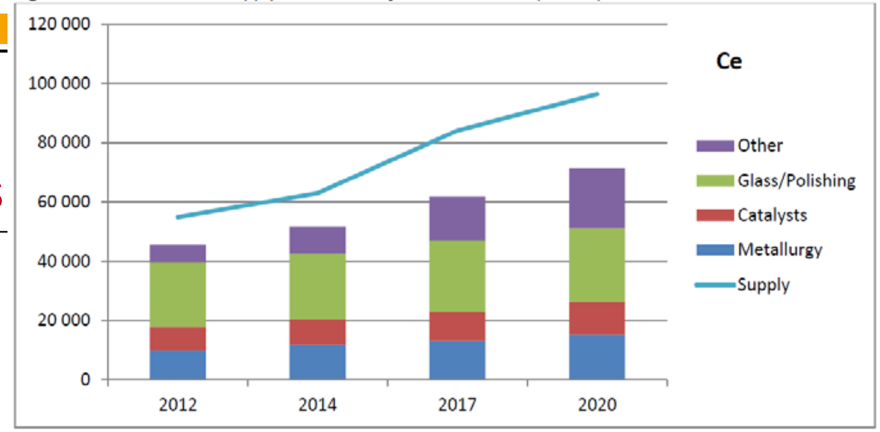
Production 2020:
every kg Nd yields 1.5 kg La and 2.5 kg Ce

Prices (US$/kg)
Nd 60, Ce 7, Sm 7, Gd 55, Dy 350, Tb 550

EU 2015: Critical raw materials for the EU

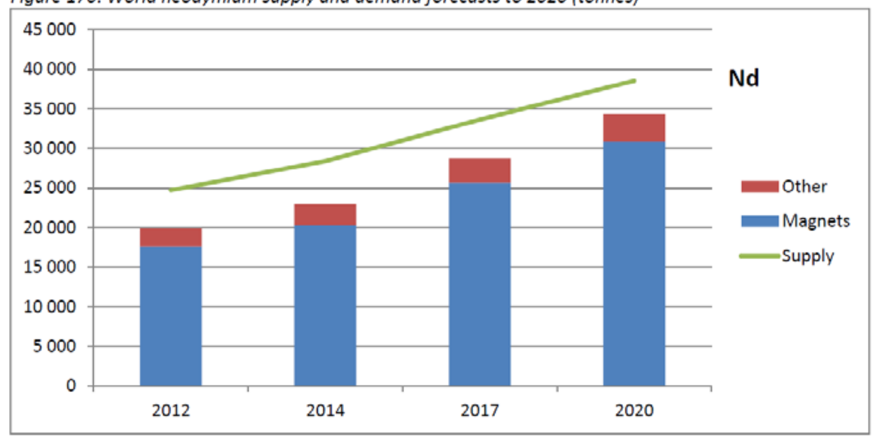
Gauss and Gutfleisch, The resource basis of magnetic refrigeration, J. of Industrial Ecology, 2016.
prices: mineralprices.com as of 25 April 2018

Figure 164: World cerium supply and demand forecasts to 2020 (tonnes)



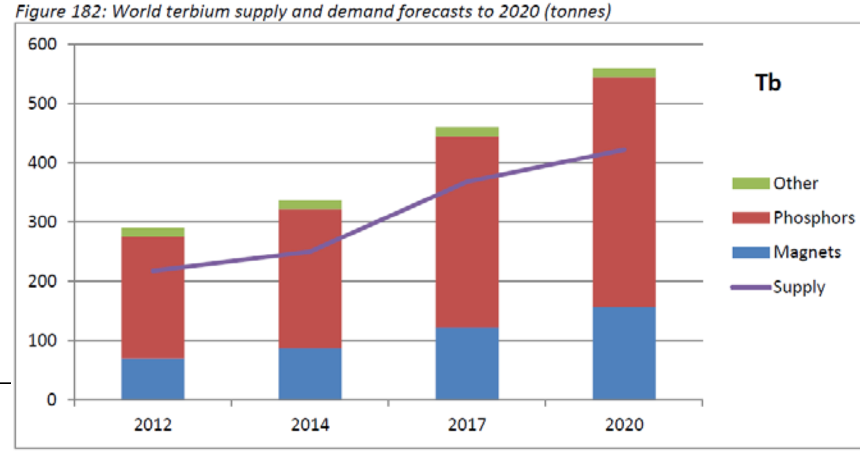
Sources: Roskill, IMCOA and Technology Metal Research Reports and Presentations (2012-2013)

Figure 170: World neodymium supply and demand forecasts to 2020 (tonnes)



Sources: Roskill, IMCOA and Technology Metal Research Reports and Presentations (2012-2013)

Figure 182: World terbium supply and demand forecasts to 2020 (tonnes)



Sources: Roskill, IMCOA and Technology Metal Research Reports and Presentations (2012-2013)

LaFeSi – towards an ideal magnetocaloric material

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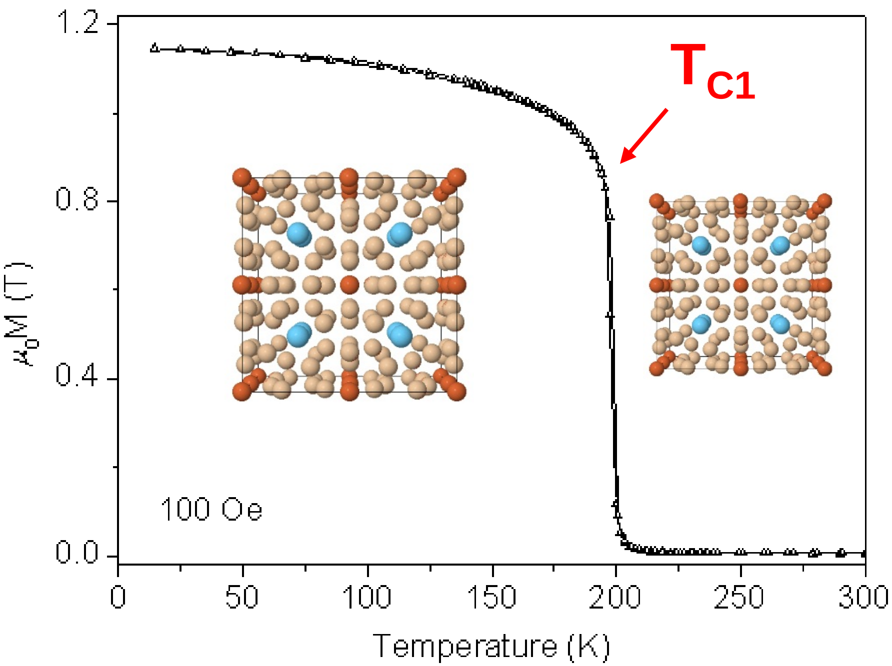
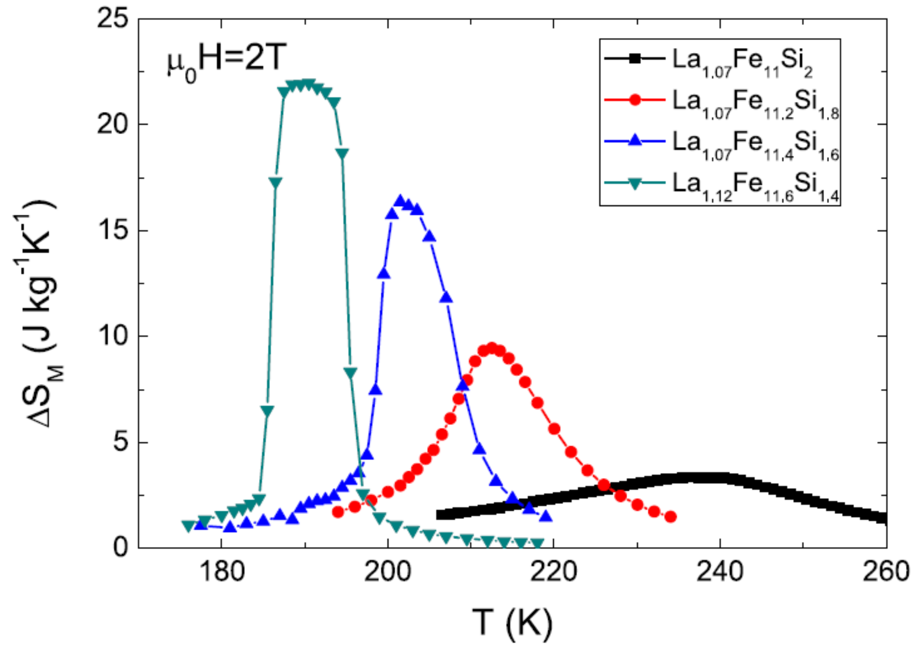
Phase Transition in $LaFe_{11.6}Si_{1.4}$



Acta Mat. 59 (2011) 3602
Scripta Mat. 67 (2012) 584
J. Appl. Phys. 115 (2014) 17A941
J. Phys. D: Appl. Phys. 50 (2017) 414004

FOPT → SOPT
Series of $LaFe_{13-x}Si_x$

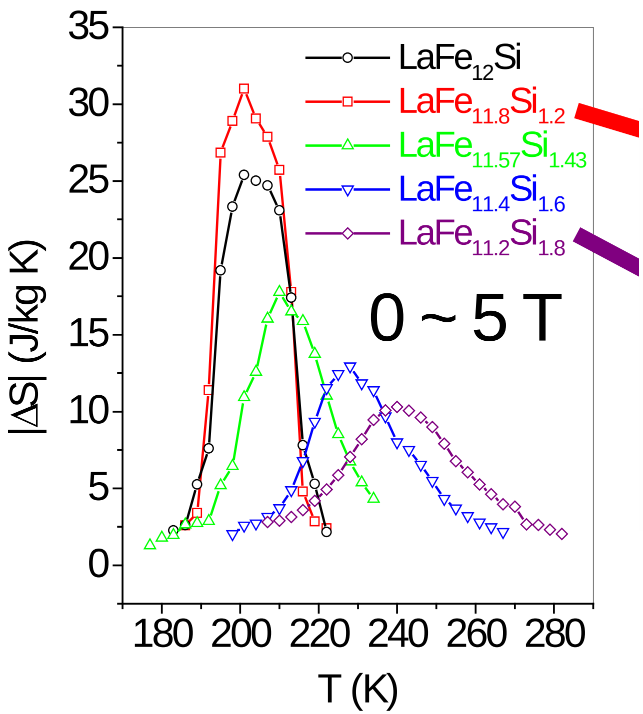


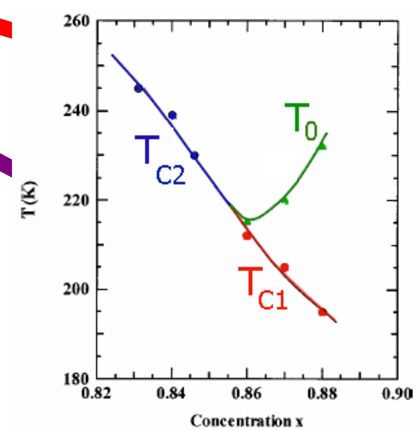
→ quantitative criterion for determining the order of magnetic phase transitions

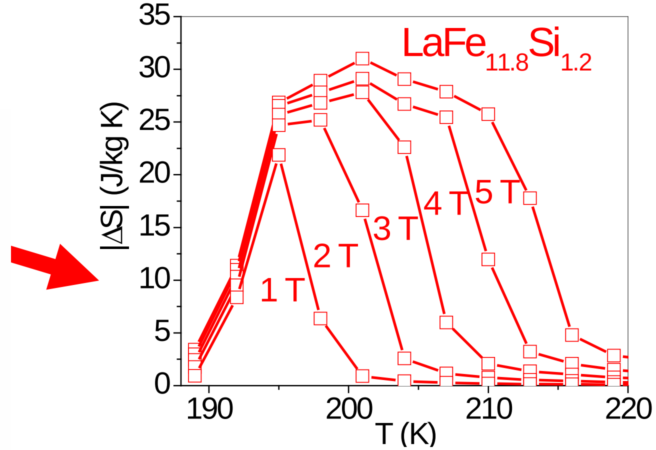
Nature Communications (2018) 9:2680

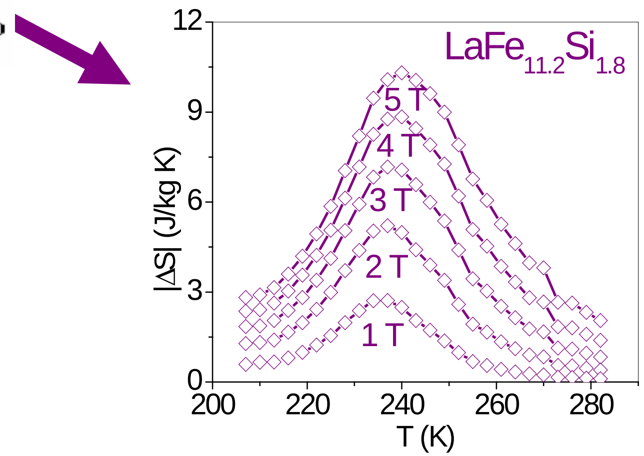
FUNKTIONALE MATERIALIEN

SHIFT OF TRANSITION TEMPERATURE









- Transition of 1st order advantageous for application in small magnetic fields
- Transition of 2nd order shows broad operating range

J. Appl. Phys. 97 (2005) 10M305

LaFeSi – towards an ideal magnetocaloric material

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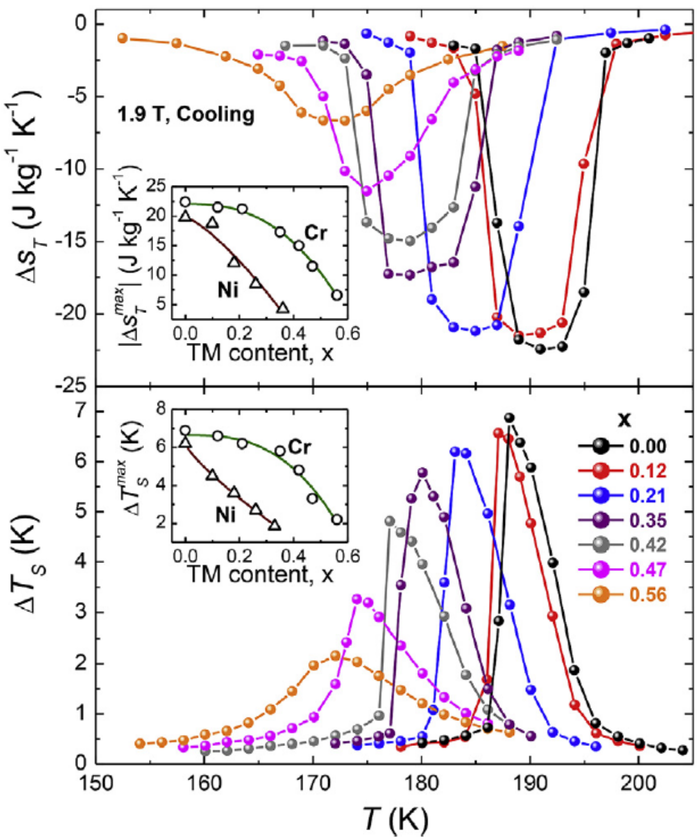
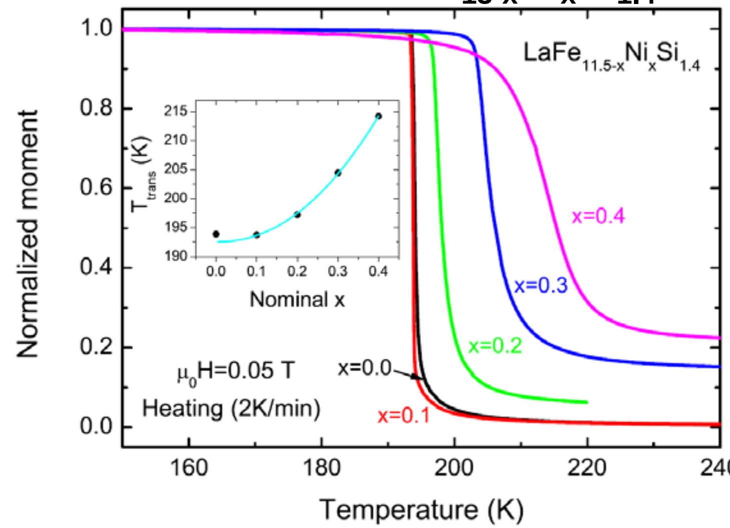
FOPT → SOPT
Series of $LaFe_{13-x}Cr_xSi_{1.4}$

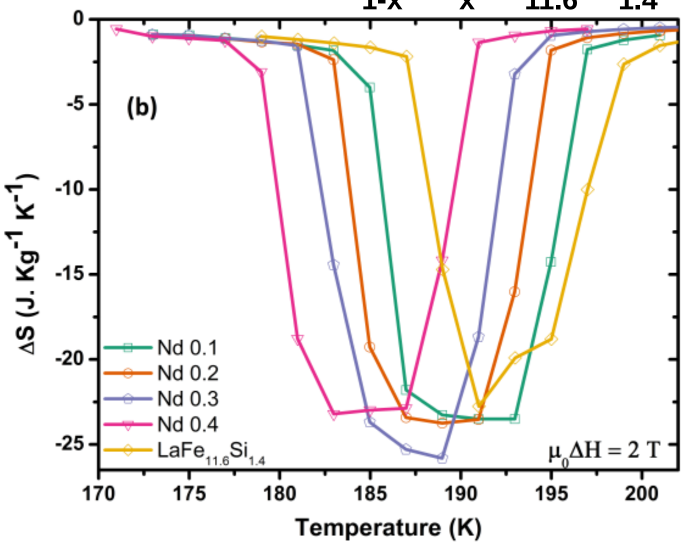


Acta Materialia 175 (2019) 406
Acta Materialia 160 (2018) 137
J. Phys. D: Appl. Phys. 54 (2021) 225001

Series of $LaFe_{13-x}Ni_xSi_{1.4}$



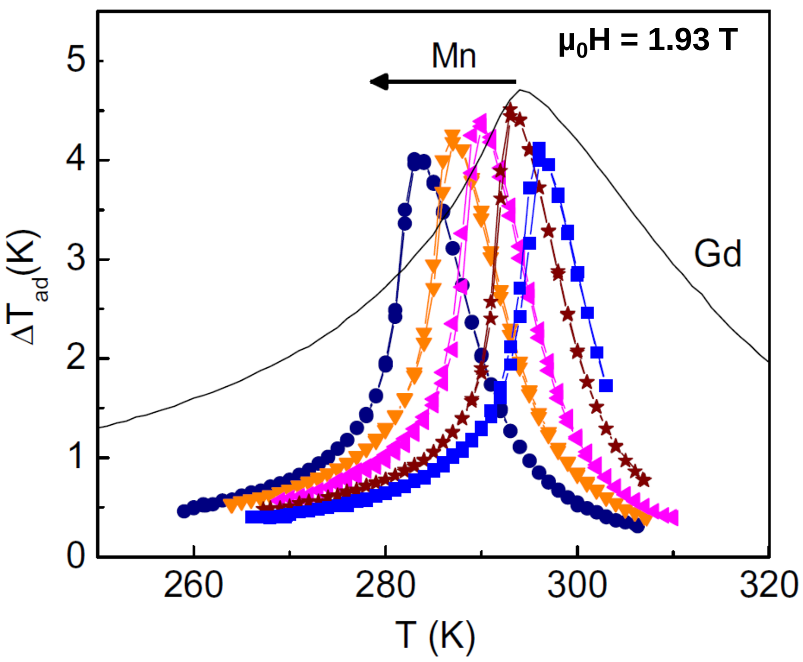
Series of $La_{1-x}Nd_xFe_{11.6}Si_{1.4}$



LaFeSi – a substitute for Gd

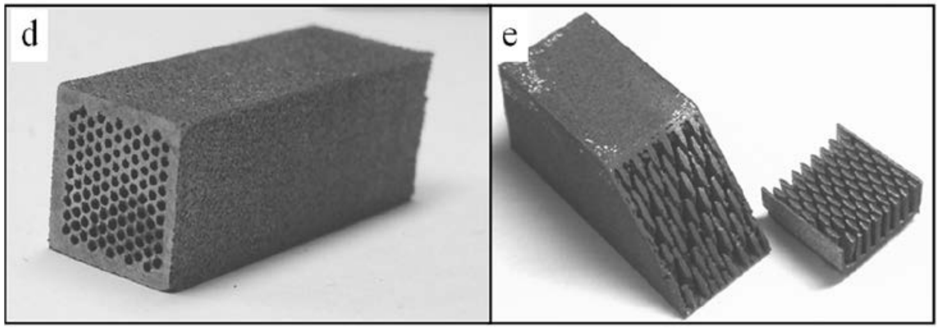
The making of …

ΔT_{ad} of $La(FeMnSi)_{13}H_{1.53}$



Acta Mat. 59 (2011) 3602
Scripta Mat. 67 (2012) 584
J. Appl. Phys. 115 (2014) 17A941

Acta Materialia 125 (2017) 506

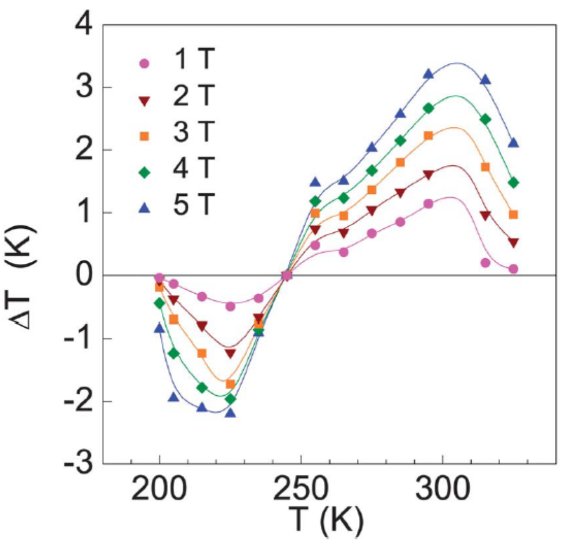


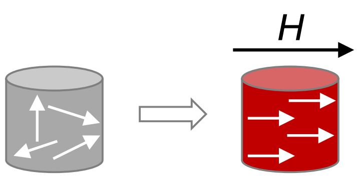
JAP 114 (2013)

Temperature changes in caloric materials

TECHNISCHE UNIVERSITÄT DARMSTADT

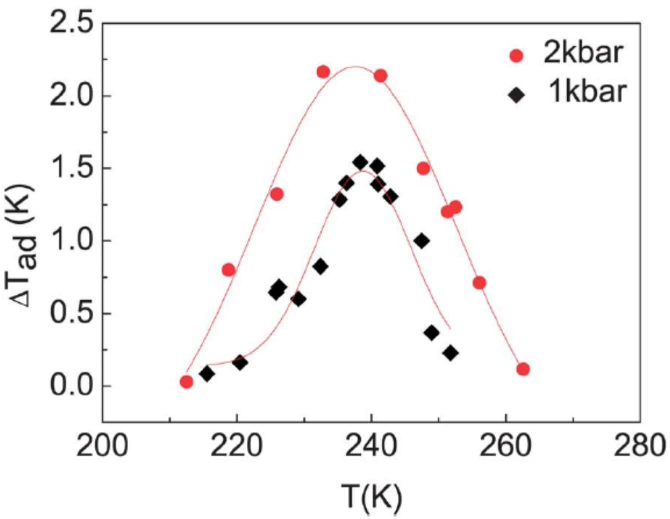
magnetocaloric
$Ni_{50}Mn_{34}In_{16}$

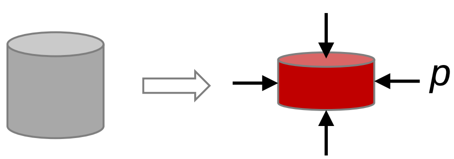




S. Aksoy, et al.,
Appl. Phys. Lett., 2007, 91, 241916

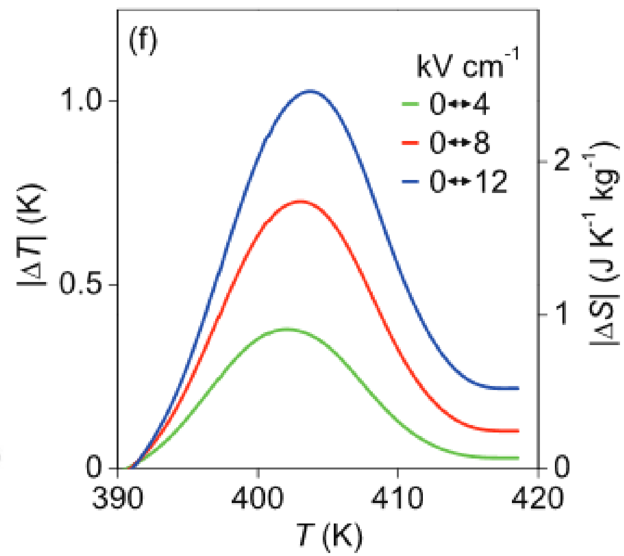
baro-/elastocaloric
$LaFe_{11.33}Co_{0.47}Si_{1.2}$

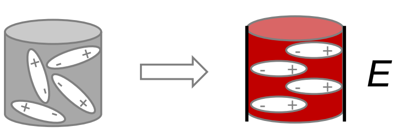




L. Mañosa, et al.,
Nat. Commun., 2011, 2, 595

electrocaloric
$BaTiO_3$



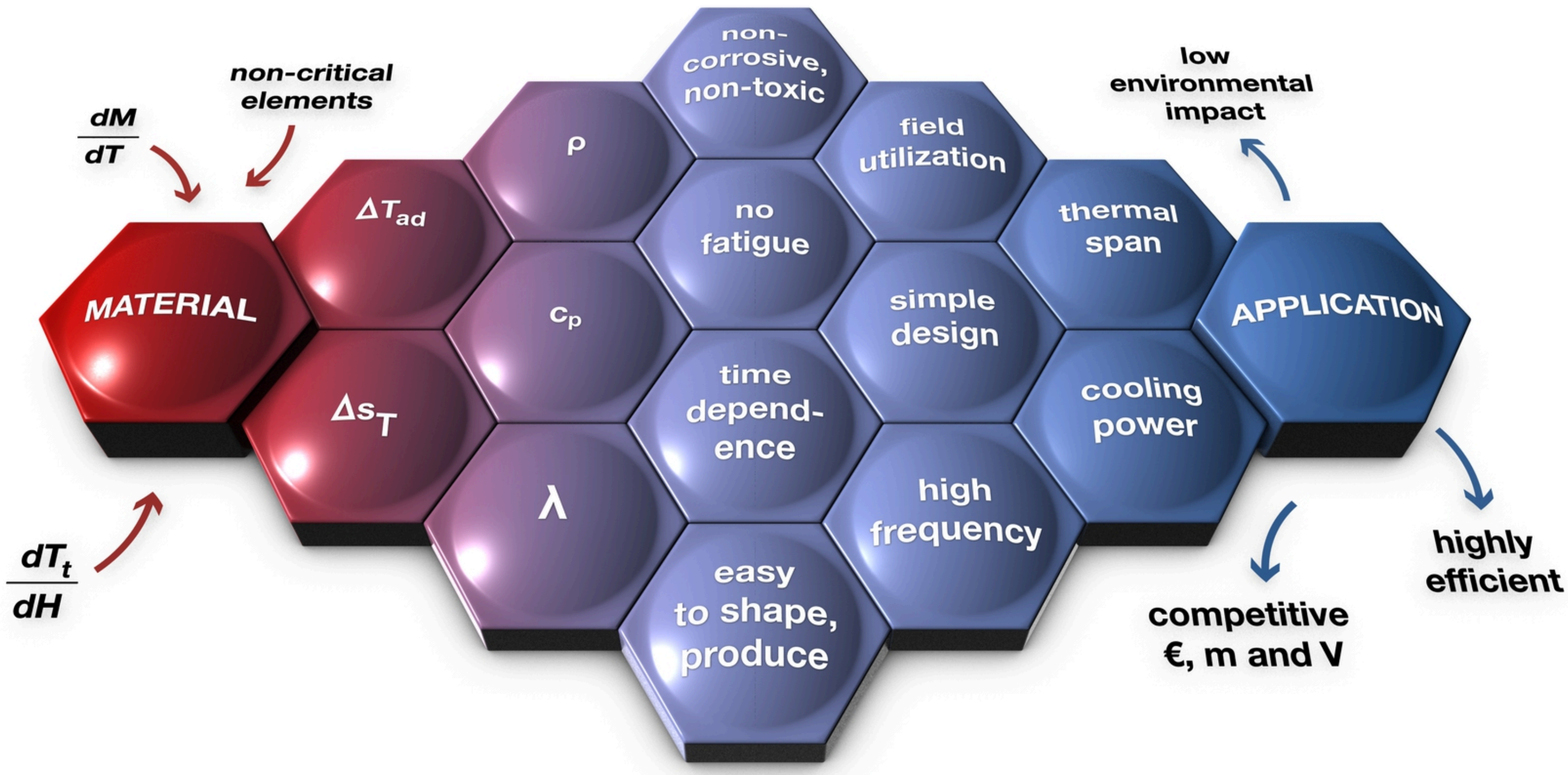


X. Moya et al.,
Adv. Mater. 2013, 25, 1360–1365

FUNKTIONALE MATERIALIEN

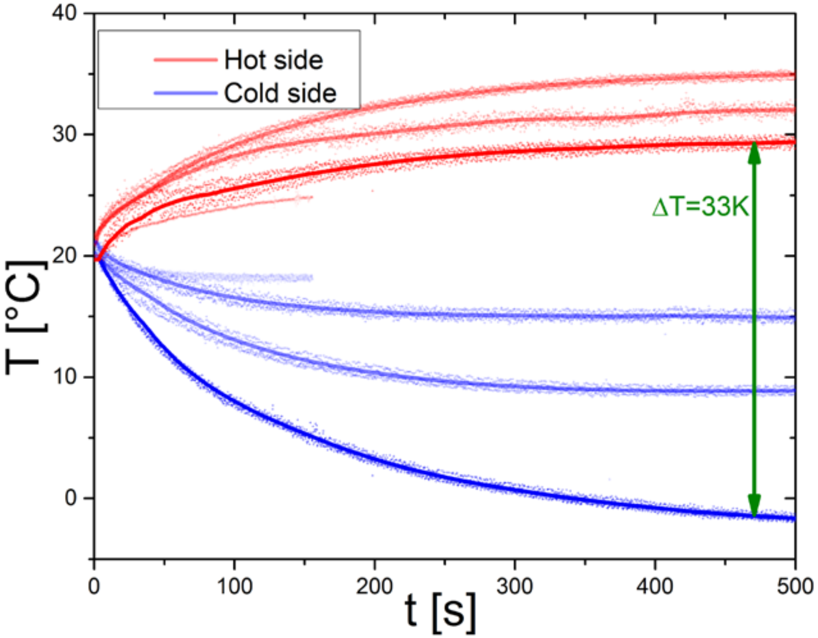
DEMONSTRATORS AND DEVICES

Roadmap to magnetic refrigeration:
from materials to devices

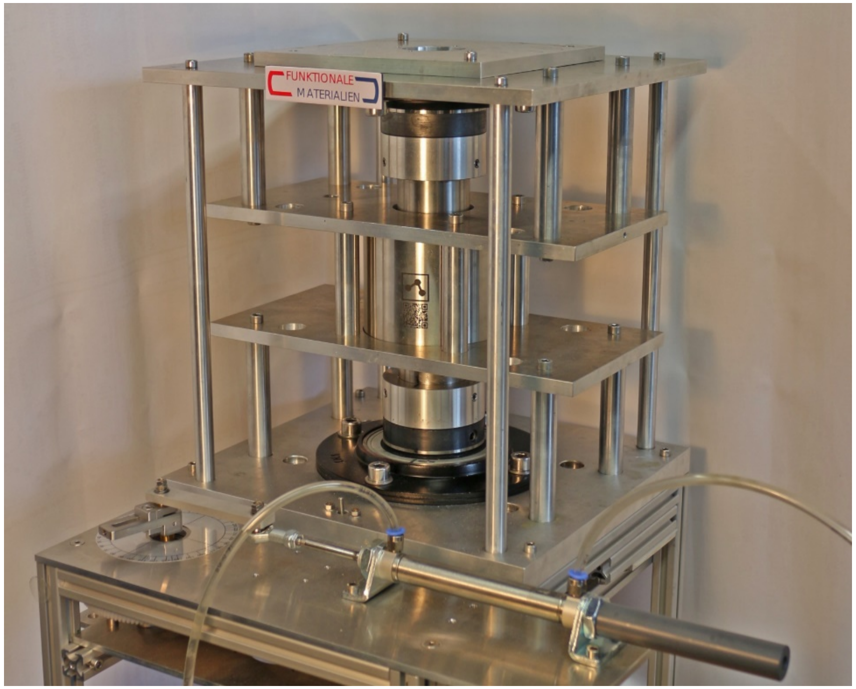


Making a cool choice - The materials library of magnetic refrigeration, Progress Report in Adv. Energy Mat. 2019

From materials to devices



$\Delta\mu_0 H$:	1.1 T
Mass of magnet:	3.9 kg
Active Volume:	63.6 cm³
Frequency:	up to 5 Hz
Fluid:	water
Temperature span:	26 K
Gd mass:	76 g
Sphere diameter:	250-355 µm



Improvements compared to 1st generation:

- Use of **recycled** $Nd_2Fe_{14}B$
- Less permanent magnet mass
- 124% higher active volume
- 18% higher magnetic field change
- 50% lower torque → smaller motor
- Less heating of magnets
- 50% higher maximum thermal span

From materials to devices

TECHNISCHE UNIVERSITÄT DARMSTADT

Reprint from MagNews, the UK Magnetics Society magazine http://ukmagsoc.org

A green magnetic cooling device built using upcycled NdFeB magnets

Dimitri Benke[1], Jonas Wortmann[1], Marc Pabst[1], Tino Gottschall[1], Iliya Radulov[1], Konstantin Skokov[1], Oliver Gutfleisch[1, 2]
Davide Prosperi[3], Alex Bevan[3], Stephen Dove[3], Gojmir Furlan[3], Catalina Tudor[3], Peter Afiuny[3], Miha Zakotnik[3]
1 Material Science, Functional Materials, Technische Universität Darmstadt, Germany
2 Fraunhofer Project Group Materials Recycling and Resource Strategies IWKS Hanau, Germany
3 Urban Mining Company, USA

FULL PAPER

Energy Technology
Generation, Conversion, Storage, Distributio
www.entechnol.d

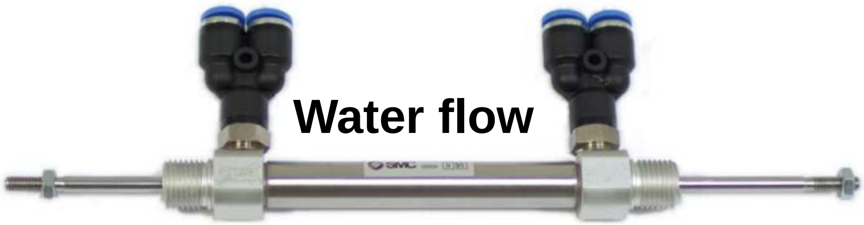
Check fo updates

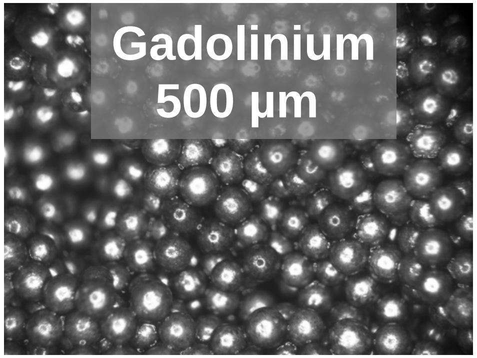
Magnetic Refrigeration with Recycled Permanent Magnets and Free Rare-Earth Magnetocaloric La–Fe–Si

Dimitri Benke, Maximilian Fries, Marius Specht, Jonas Wortmann, Marc Pabst, Tino Gottschall, Iliya Radulov, Konstantin Skokov, Alex Ivor Bevan, Davide Prosperi, Catalina Oana Tudor, Peter Afiuny, Miha Zakotnik, and Oliver Gutfleisch*

A “simple” demonstrator for education

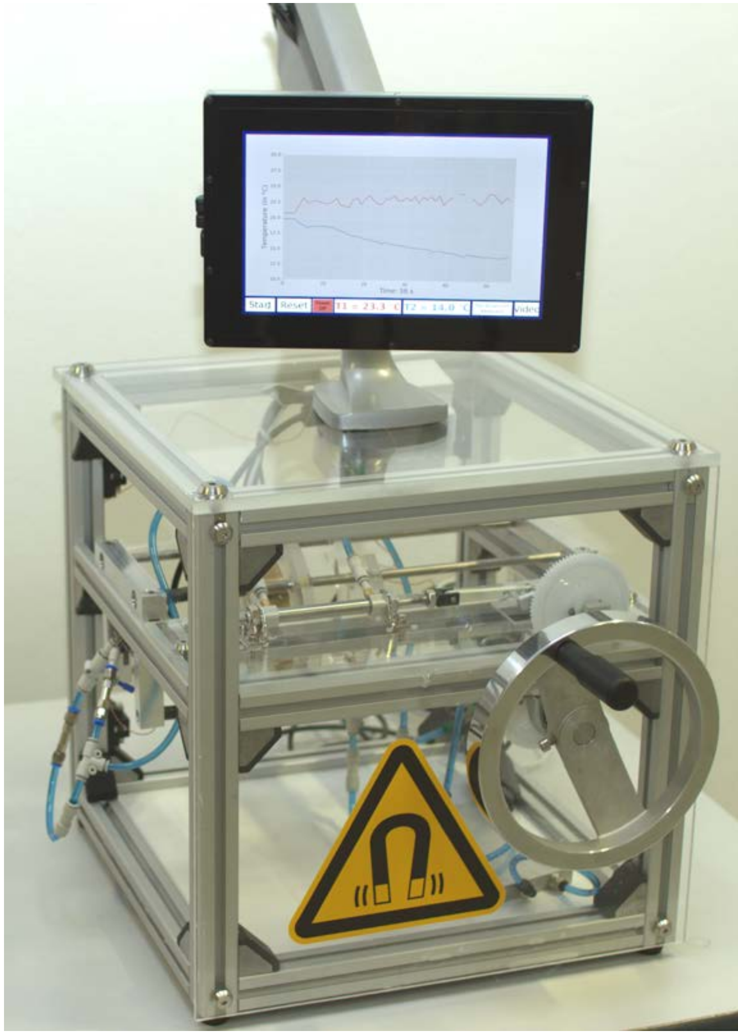
TECHNISCHE UNIVERSITÄT DARMSTADT



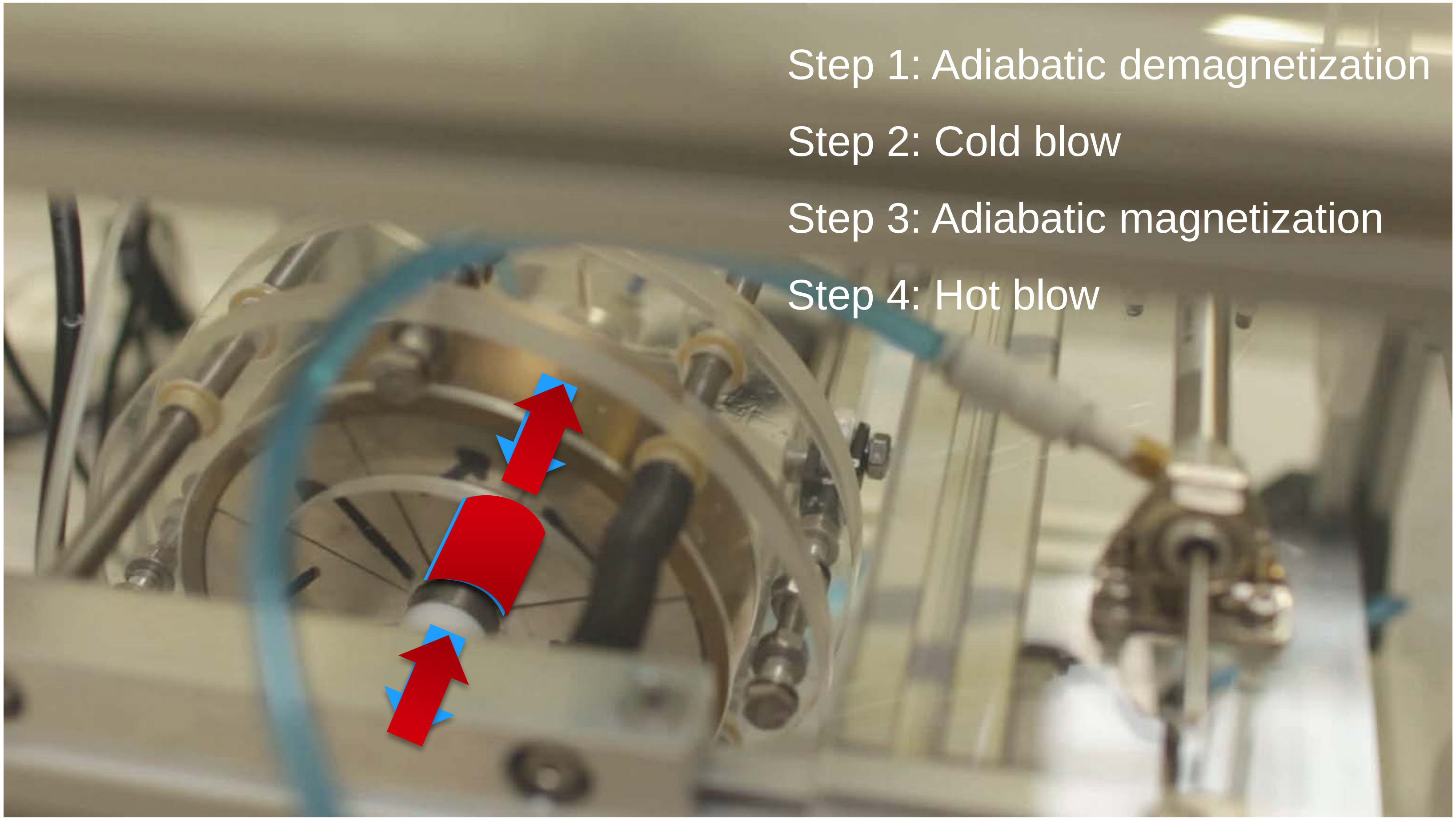


MAGNOTHERM SOLUTIONS

visit magnotherm-solutions.com
for more information,
designed by T. Gottschall at HZDR

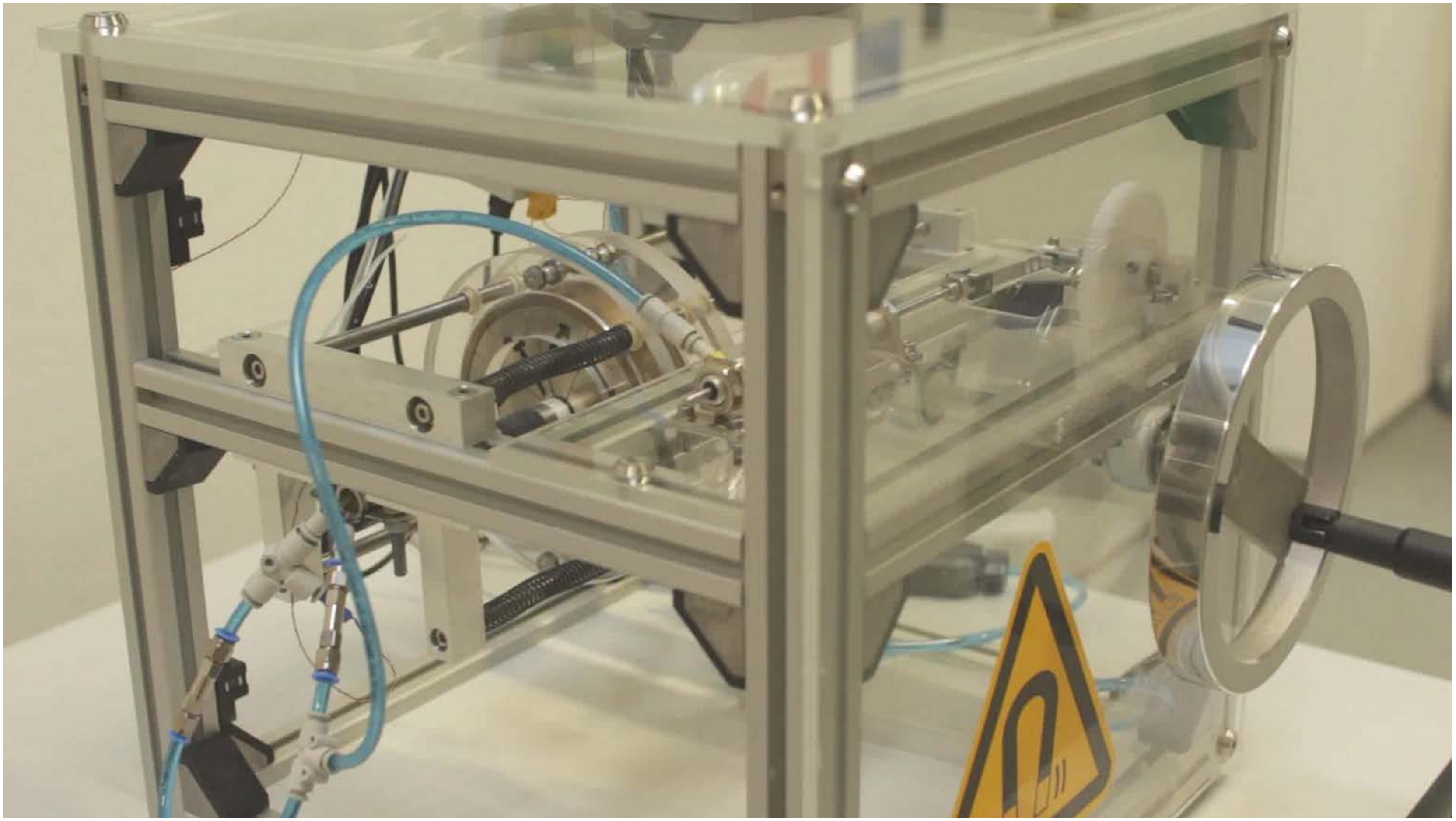


A "simple" demonstrator for education



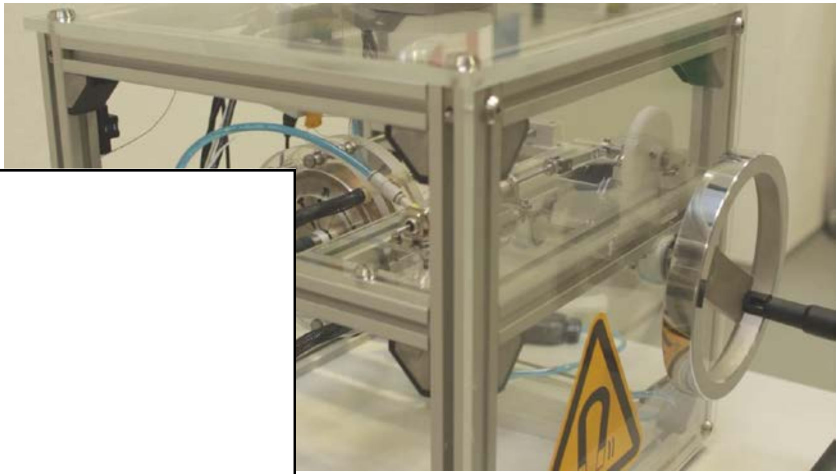
visit magnotherm-solutions.com for more information, designed by T. Gottschall at HZDR

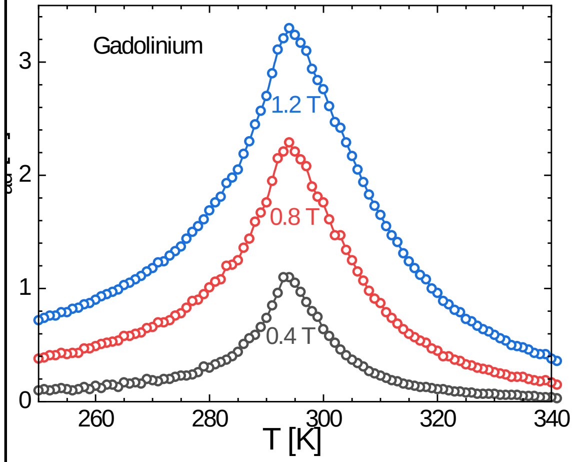
A “simple” demonstrator for education



visit magnotherm-solutions.com for more information, designed by T. Gottschall at HZDR

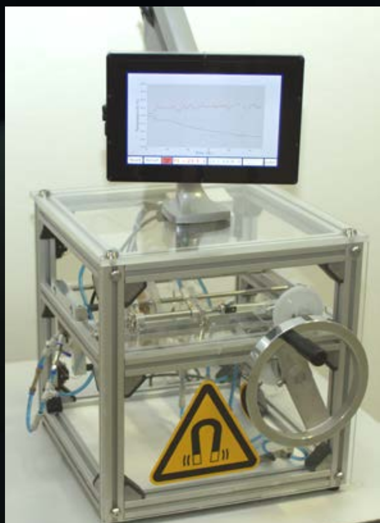
A “simple” demonstrator for education





erm-solutions.com for more information,
designed by T. Gottschall at HZDR

“Providing the cleanest and most sophisticated cooling and heating solutions for everybody to reduce climate impact and costs.”



MS30 demonstrator

MAGNOTHERM®

Next Generation Cooling

MS300 Prototype

- **1 kilowatt**
- **-1°C <> 28°C**
- **available in Q4 2021**

MS90 demonstrator

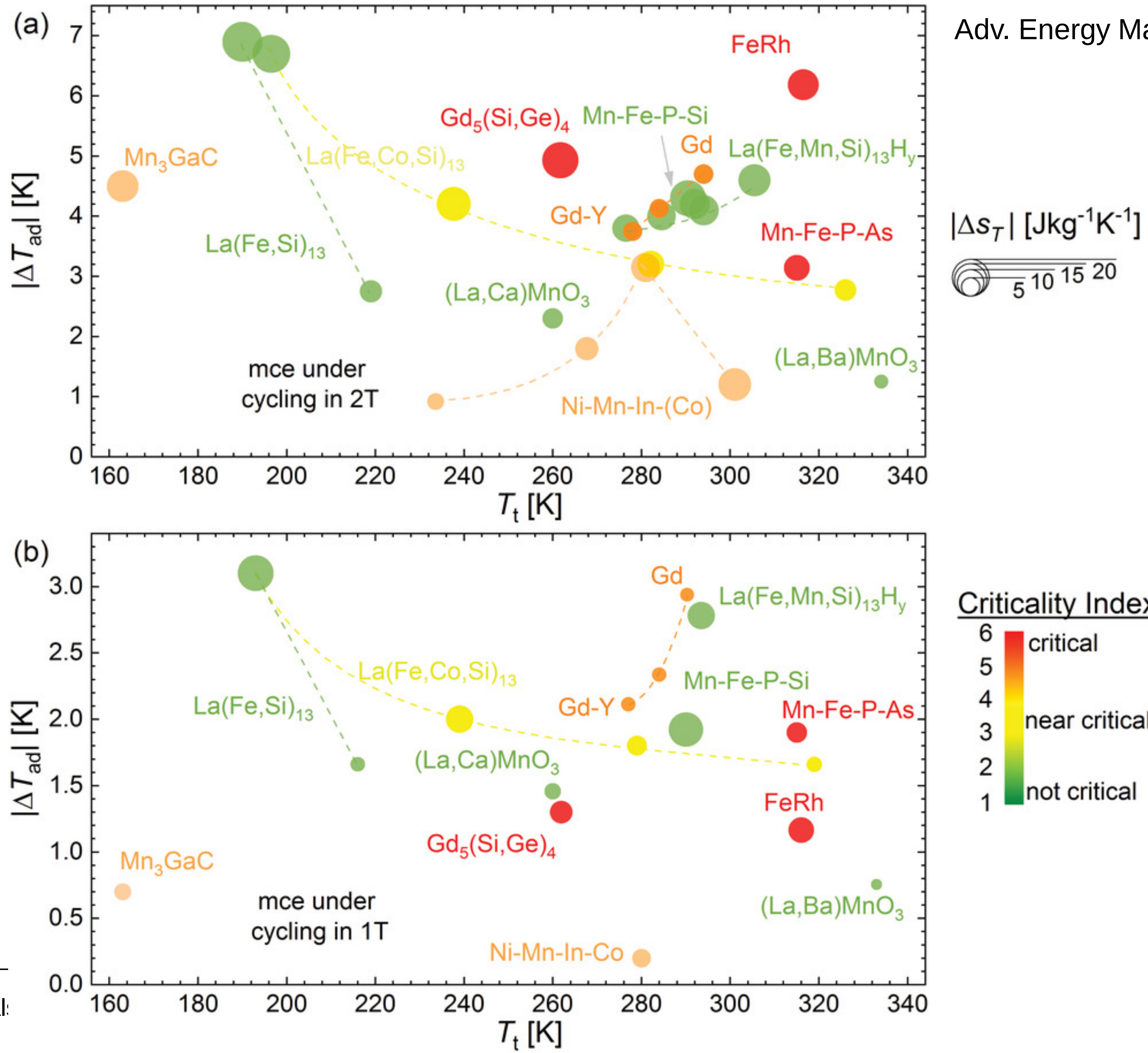
info@magnotherm.com

www.magnotherm.com

HEUSLER SYSTEMS

Making a Cool Choice: The Materials Library of Magnetic Refrigeration

Adv. Energy Mater. 2019, 1901322

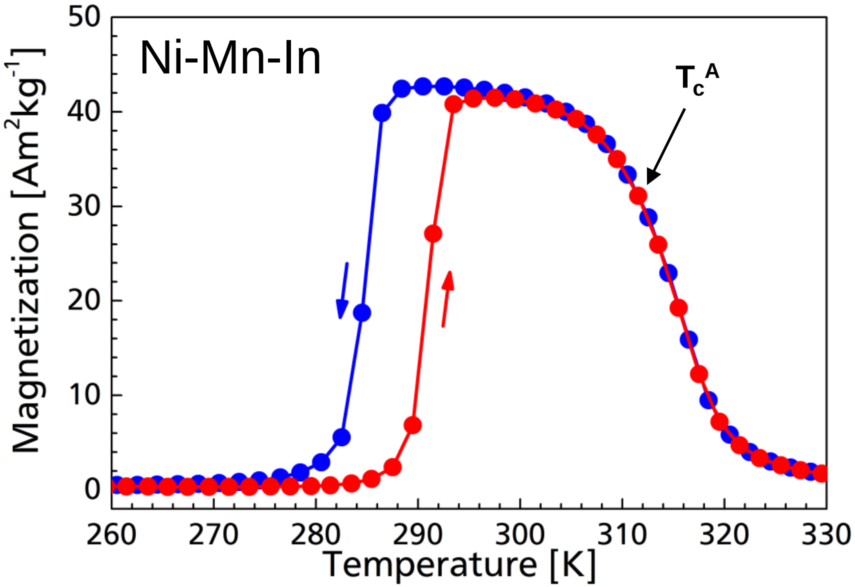


FUNKTIONALE MATERIALIEN

another substitute: Heusler compounds

- High-temperature phase
- High magnetization

Austenite B2



Martensite $L2_1$

Low-temperature phase
Low magnetization

Appl. Phys. Lett. 106 (2015) 021901

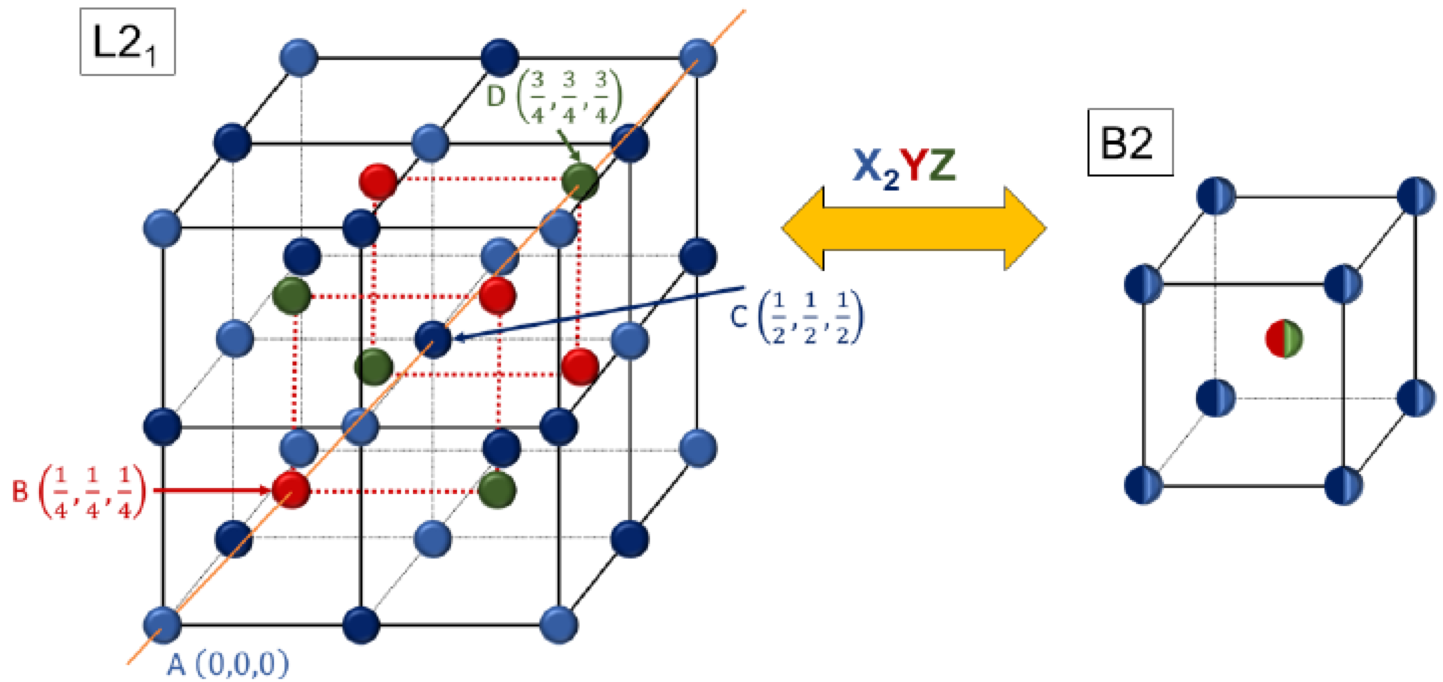


Figure 2.6: Heusler (L2$_1$) structure and B2 disorder for X_2YZ compounds. The shown representation of L2$_1$ is shifted by ($\frac{1}{4}$, $\frac{1}{4}$, $\frac{1}{4}$) compared to the classic representation of the $Fm\bar{3}m$ unit cell.

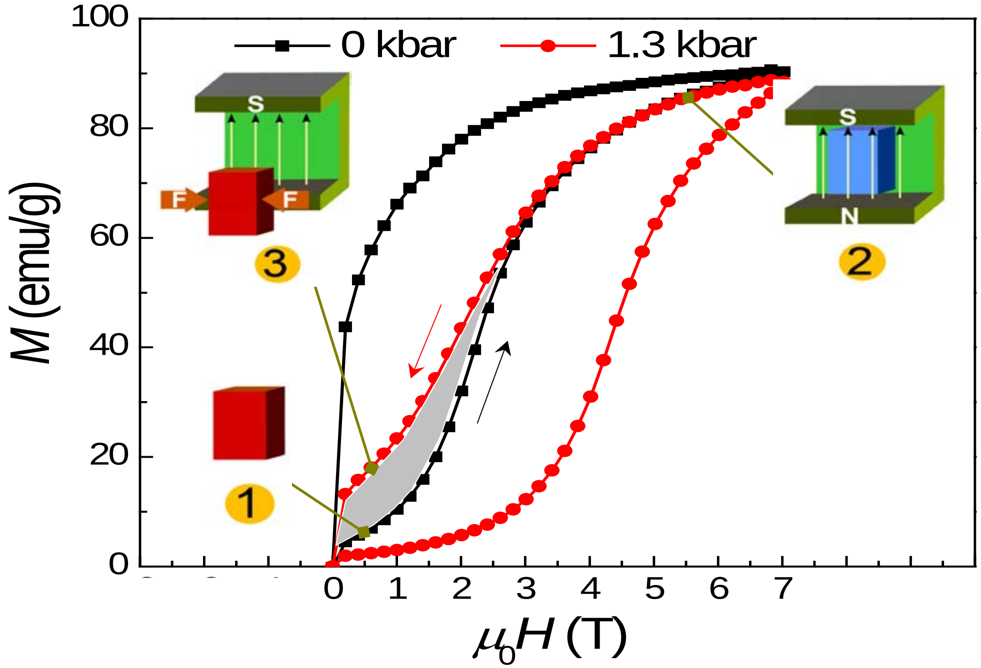
PhD Thesis 2020, A. Taubel, TU Darmstadt

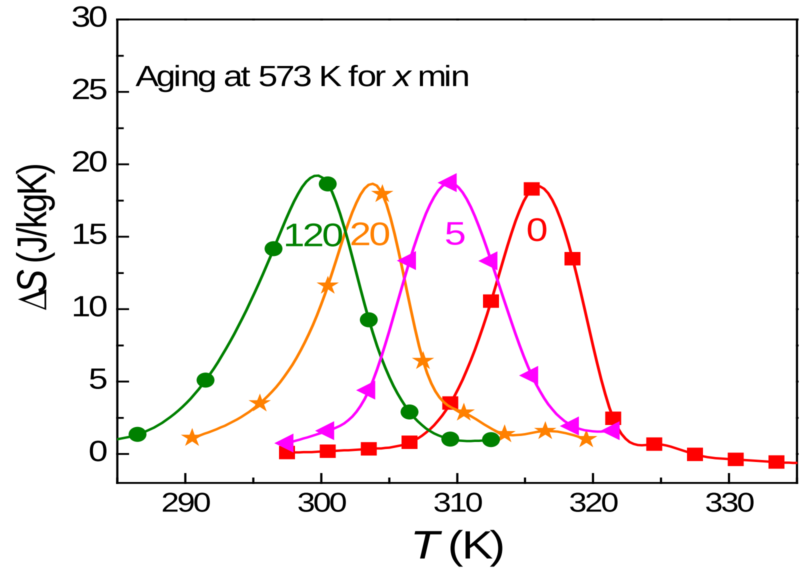
rearrangement of structural variants (H, T, p, σ)

Physical Review Materials 4 (2020) 111401

MULTICALORICS

Controlling reversibility in NiMnInCo

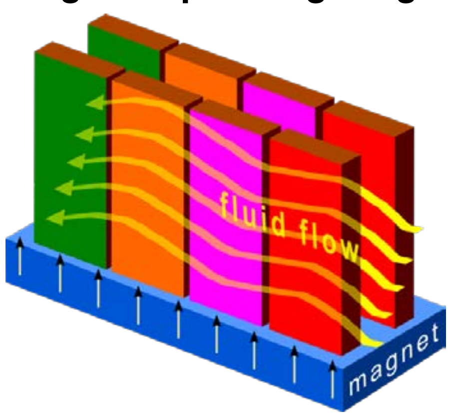




- **Adjusting the transition temperature**
- **Increasing the operating range**

Large thermal irreversibility can be overcome by the combination of magnetic and mechanical forces

Nature Mater. 11 (2012) 620



Comparison of barocaloric effects

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$$\frac{dT_t}{d\sigma}$$

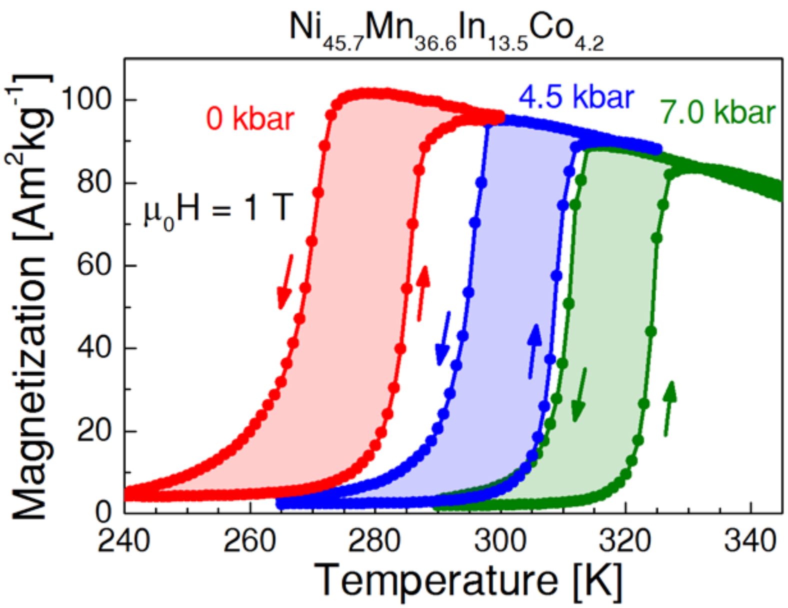
Heusler alloys
Inverse MCE
Conventional barocaloric

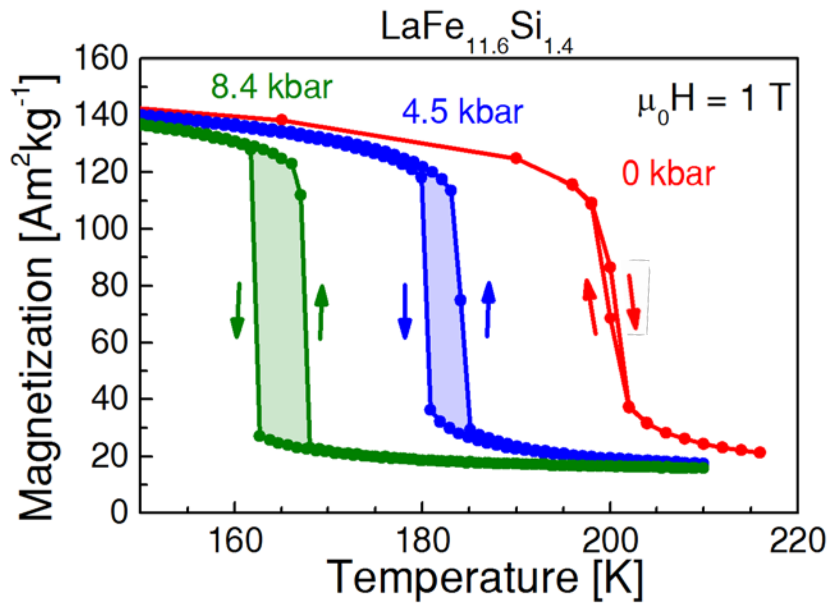
La(Fe,Si)$_{13}$
Conventional MCE
Inverse barocaloric

ΔV

Appl. Phys. Lett. 106 (2015) 021901
Phys. Rev. Applied 5 (2016) 024013

J. Appl. Phys. 115 (2014) 17A941
J. Magn. Magn. Mater. 396 (2015) 228

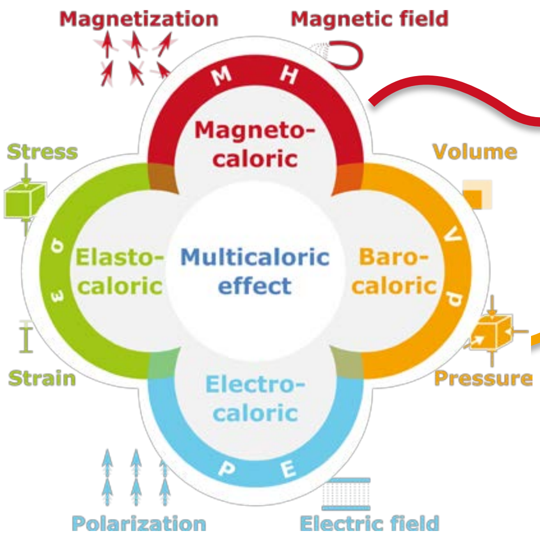


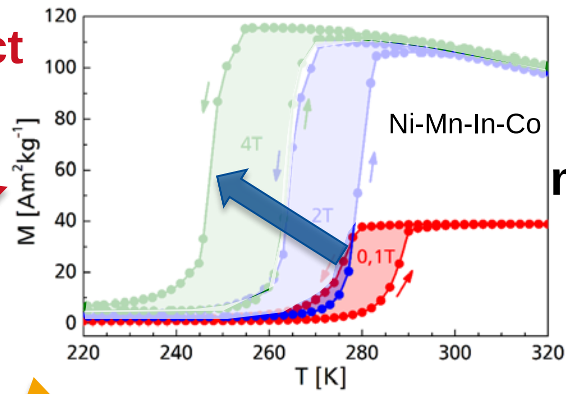


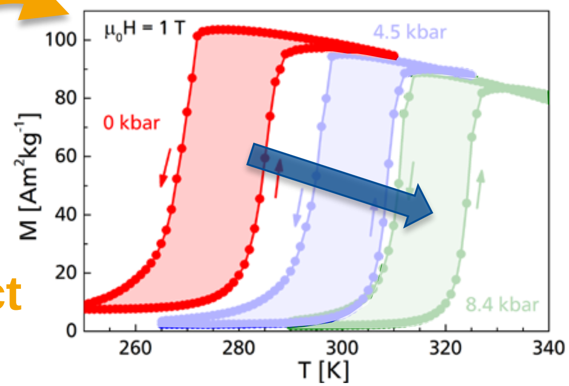
FUNKTIONALE MATERIALIEN

Multicaloric effect

Inverse magnetocaloric effect







Conventional barocaloric effect

materials with first-order **magneto-structural transition**

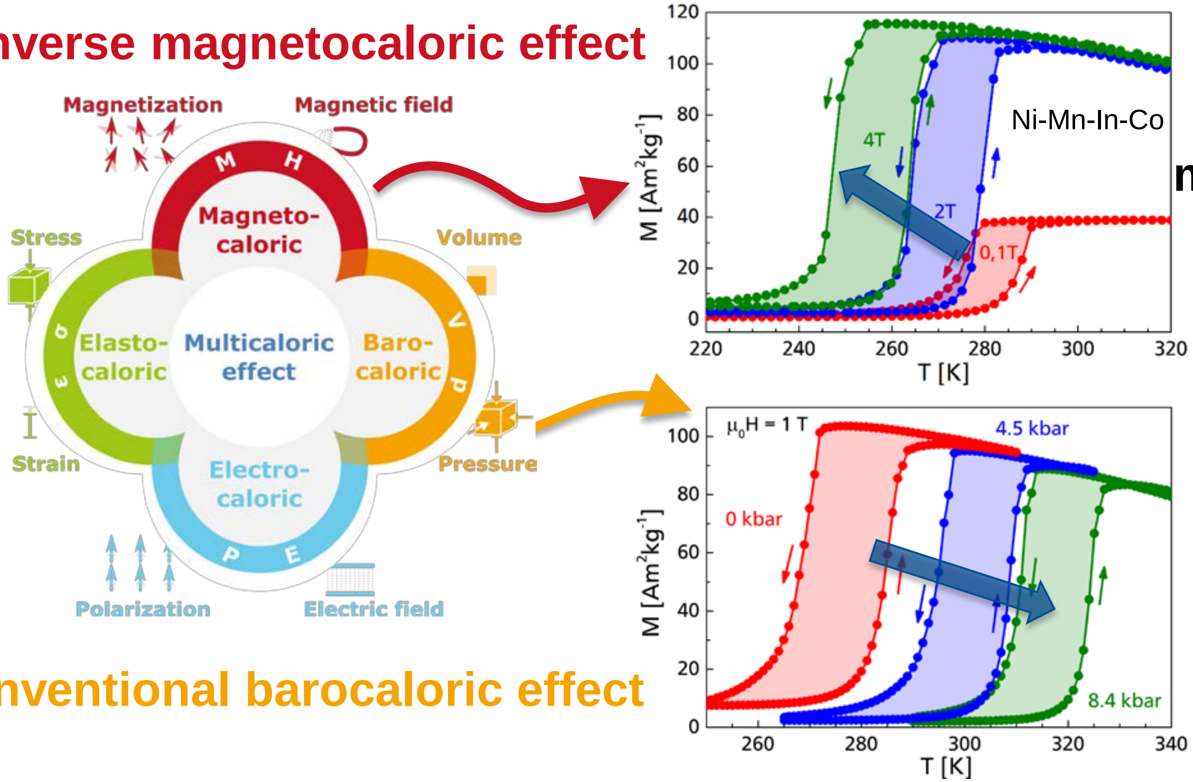
Large magnetocaloric effect

Phys. Rev. B 93, 184431 (2016).

Adv. Funct. Mater. 27, 1606735 (2017).

Multicaloric effect

Inverse magnetocaloric effect



Conventional barocaloric effect

materials with first-order **magneto-structural transition**

Large magnetocaloric effect

Thermal hysteresis reduces cyclic performance for individual caloric effects

→ **Combination of 2 stimuli**

Phys. Rev. B 93, 184431 (2016).

Adv. Funct. Mater. 27, 1606735 (2017).

From minimising to exploiting hysteresis

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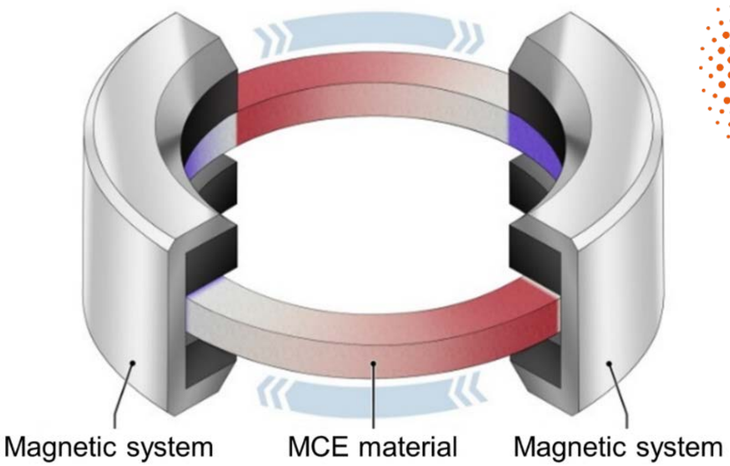
Conventional AMR

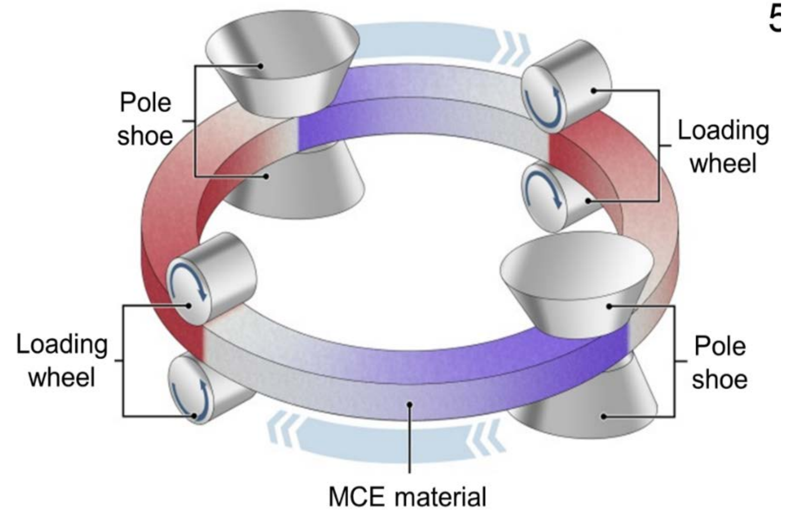
- feasible technique but large amounts of permanent magnets needed

ERC Advanced Grant
"Cool Innov"

Using Hysteresis

- drastic reduction of Nd-Fe-B magnets
- higher field strengths possible and needed
- materials with large hysteresis and susceptible to multiple stimuli





Nature Materials 2018; German Patent 10 2016 110 385.3

Different degrees of freedom in multifunctional materials

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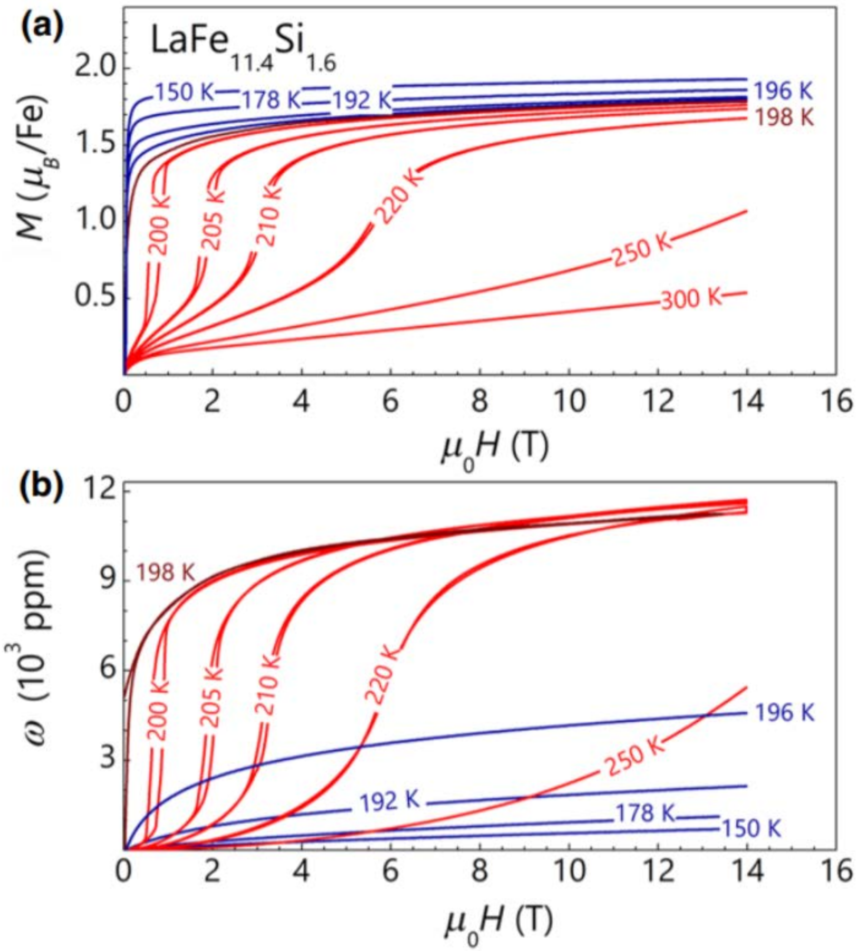
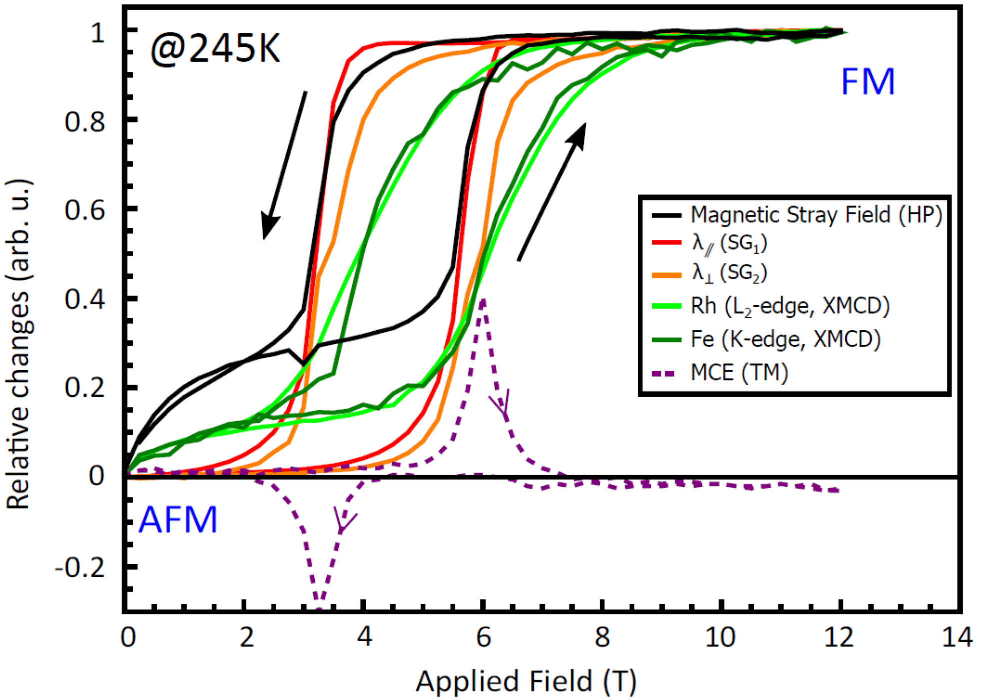
→ interplay between their structural, magnetic, and electronic subsystems





ULMAG – "ULtimate MAGnetic characterization" a novel experimental setup at beamline ID12 at ESRF, see A. Aubert et al. at this conf.

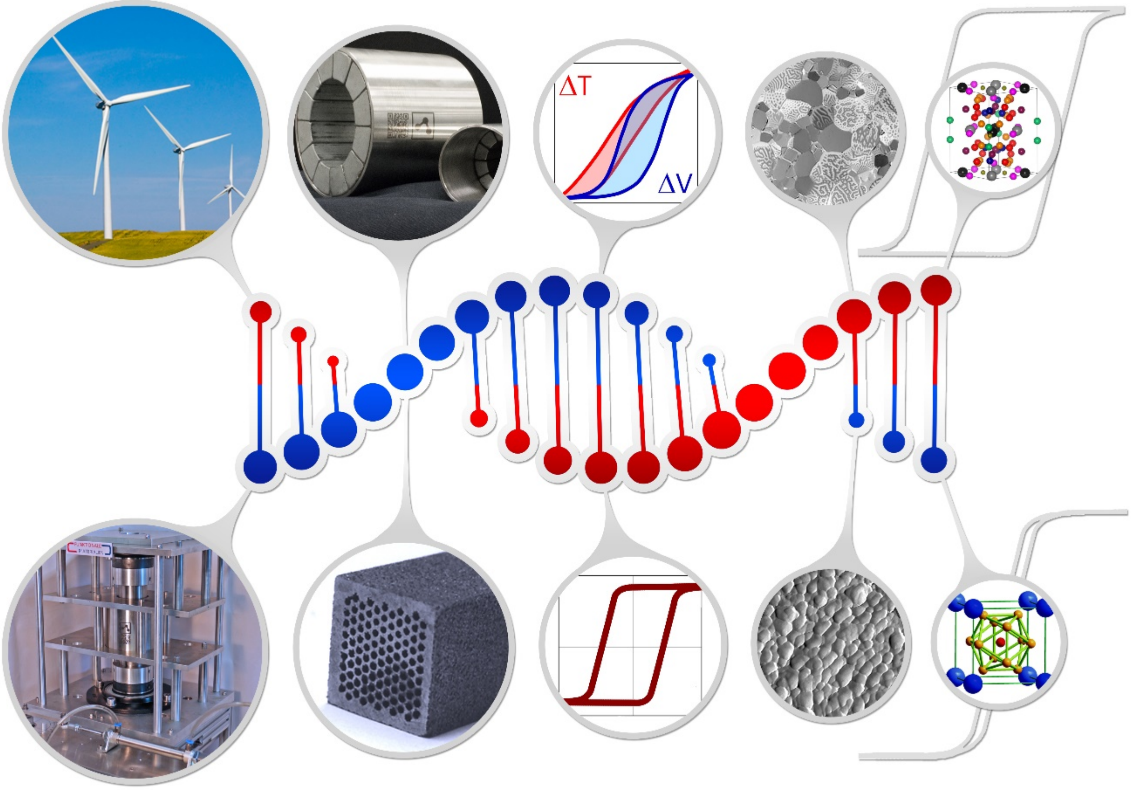
FUNKTIONALE MATERIALIEN

CRC 270: decipher the DNA of hysteresis
in permanent magnets and magnetocalorics

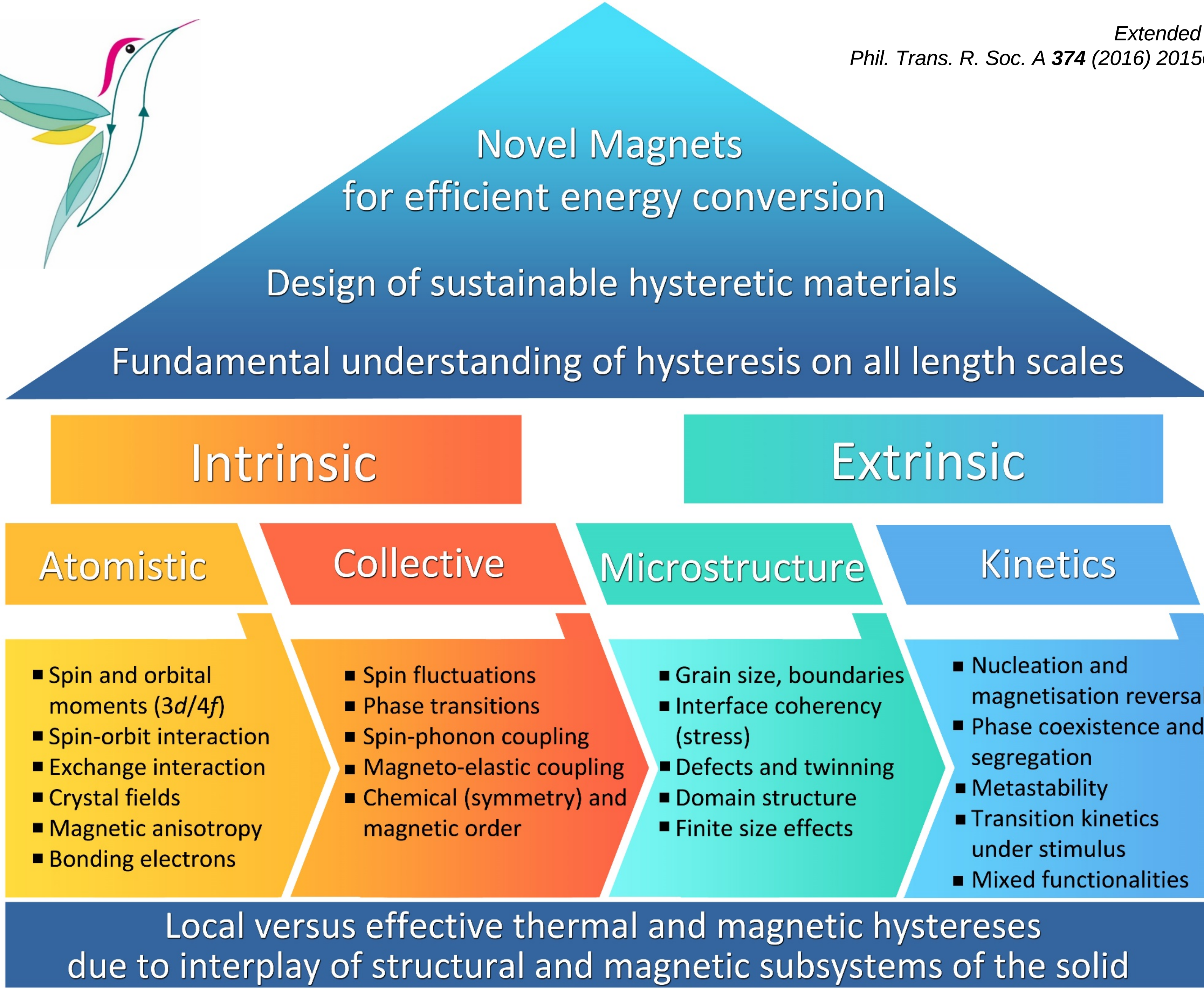
Maximum Hysteresis for Permanent Magnets
→ **Spin-orbit coupling**

electron, lattice, and spin degrees of freedom

Minimum Hysteresis for Magnetocalorics
→ **Spin-phonon coupling**



Extended from
Phil. Trans. R. Soc. A ***374*** *(2016) 20150308*

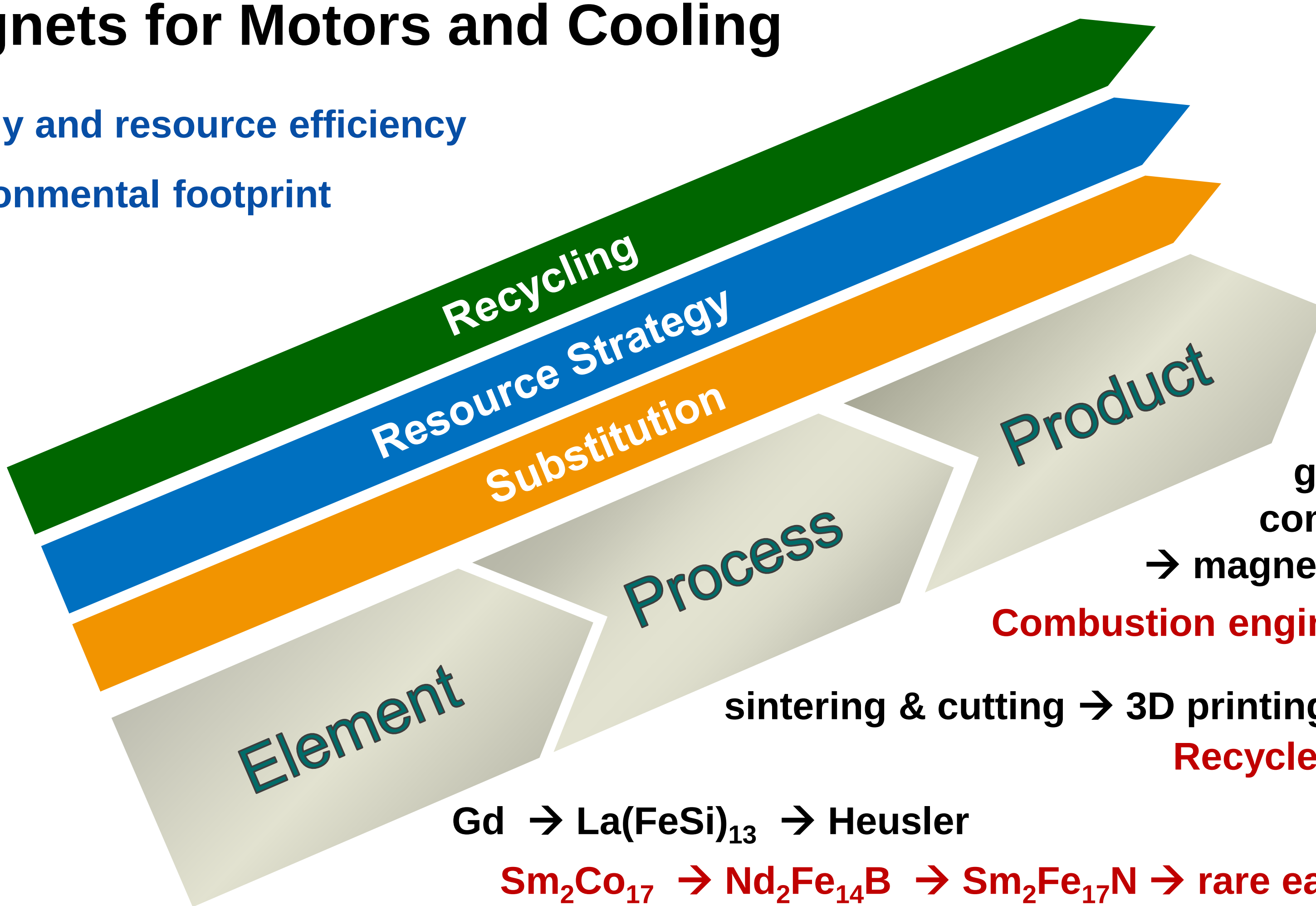


Efficient utilisation and substitution on different levels

Magnets for Motors and Cooling

Energy and resource efficiency

Environmental footprint



gas vapour compression → magnetic cooling

Combustion engine → Emotor

sintering & cutting → 3D printing or extrusion

Recycled magnets

Gd → La(FeSi)$_{13}$ → Heusler

Sm_2Co_{17} → $Nd_2Fe_{14}B$ → $Sm_2Fe_{17}N$ → rare earth free

Conclusions

- **next generation cooling could be magnetic**
- **to come: multi-stimuli calorics (H, T, p, σ)**
- **magnetocalorics for liquefaction of natural gas and hydrogen**

- **big demands for high performance GREEN PMs, thus REEs, in E-mobility, wind turbines, magnetic refrigeration are still to come**
- **currently no equivalent substitutes for Nd-Fe-B magnets in many applications; a new RE free PM would be technologically disruptive**
- **we have enough REEs!**
  RE balance: utilization of free rare earths La and Ce
- **environmental indicators of a product would be drastically improved if recycled REPMs were used → magnetic refrigeration**

- **hysteresis design will enable new magnetic materials for efficient energy conversion at their physical limits and new secondary functionalities**

CRC/TRR 270

Acknowledgements

- University Duisburg-Essen
- CNRS Grenoble
- NIMS Tsukuba
- Universities of Barcelona, Seville, Parma
- Ames National Lab.
- HZDR and IFW Dresden, ESRF
- Universities Danube and Uppsala
- Max-Planck-Institut für Eisenforschung

Read more:

- **Magnetic Materials and Devices for the 21st Century: Stronger, Lighter, and More Energy Efficient**
  Review in Adv. Mat. **23** (2011) 821; Viewpoint Set in Scripta Mat. **67** (2012)
- **Towards high performance PMs w/o REs**
  J. Phys.: Condens. Matter **26** (2014) 064205; Scripta Mat View point (2018), Nature Com. 8:54 (2017)
- **Mastering hysteresis in magnetocaloric materials**
  Phil. Trans. R. Soc. A **374** (2016), Review in Energy Techn. 2018, Nature Com. (2018) 9:2680
- **Multi-stimuli calorics**
  Nature Mater. 11 (2012) 620, Nature Mater. 17 (2018) 929, Adv. Funct. Mater. 27 (2017) 1606735, Appl. Phys. Rev. 7 (2020) 041406, Acta Materialia 201 (2021) 425
- **Materials library of magnetic refrigeration**
  Adv. Energy Mat. (2019)
- **Shaping and Additive manufacturing**
  J. Appl. Phys. 114 (2013) 043907, Adv. Mat. 22 (2010) 3735, Acta Materialia 127 (2017) 389

contact

Keep cool and get in touch…

Prof. Oliver Gutfleisch
Institut für Materialwissenschaft
FG Funktionale Materialien
Technische Universität Darmstadt
L2|07, Alarich-Weiss-Str. 16
64287 Darmstadt
Germany

oliver.gutfleisch@tu-darmstadt.de
http://www.mawi.tu-darmstadt.de/fm

Telefon +49-6151-16-221 50
Sekretariat +49-6151-16-221 40

1 ☺ ☺ % magnetically cooled beer, tastes even better

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Functional Materials

TU Darmstadt

Prof. Oliver Gutfleisch

☎ 06151 16 22140

oliver.gutfleisch@tu-darmstadt.de

http://www.mawi.tu-darmstadt.de/fm

https://scholar.google.de/citations?user=IMtVJ68AAAAJ&hl=de

ResearcherID: C-7241-2011

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