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## Engineering Advance

# Present and future caloric refrigeration and heat-pump technologies<sup>☆</sup>



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## ABSTRACT

In recent years, several emerging technologies in the domain of solid-state physics have been investigated as serious alternatives for future refrigeration, heat pumping, air conditioning, or even power generation applications. These technologies relate to what is called caloric energy conversion, i.e., barocalorics, electrocalorics, magnetocalorics, and elastocalorics. Of these technologies, the greatest progress has been observed in the domain of magnetic refrigeration. However, in the recent few years, significant research efforts have also been made in the field of electrocaloric and elastocaloric refrigeration. Many of these technologies suggest the possibility for improvements in energy efficiency, compactness, noise level, as well as a reduction in environmental impacts, so it seems very probable that they will start to fill particular market niches as a replacement for vapor-compression technology in the future.

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## Actuelles et futures technologies de froid thermique et de pompe à chaleur

Mots clés : Physique du solide ; Matériau calorique ; Magnétocalorique ; Electrocalorique ; Barocalorique ; Elastocalorique ; Conversion d'énergie ; Froid ; Pompe à chaleur ; Conditionnement d'air

<sup>\*</sup> The aim of this manuscript is to review recent articles, with particular emphasis on those articles published in the past two years. In addition to describing recent trends, the authors were encouraged to give their subjective opinion of the topics discussed. The review should be approximately 2000 words (not including references or reference notes), with approximately 50 references and, as such, the review is intended to be a concise view of the field as it is at the moment, rather than a comprehensive overview. The audience of this paper range from student to professor, so the article is intended to be accessible to a wide readership.

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Nomenclature		EST	Elastocaloric
$\Delta T_{ad}$	Adiabatic temperature change, K	HHEX	Hot heat exchanger
CHEX	Cold heat exchanger	MC	Magnetocaloric
EC	Electrocaloric		

## 1. Introduction

The world's energy demands for refrigeration and air conditioning represent nearly 20% of the energy consumption. The major cooling technology, i.e., the vapor compression of a gas refrigerant, even though it is now mature, is characterized by a rather low exergy efficiency, especially for small devices. Despite the fact that other substances are being used to substitute for existing or already-abandoned harmful refrigerants, many of these are the subject of future prohibition. Moreover, several alternatives, such as the potential replacement of existing refrigerants in vapor compression, lead to lower energy efficiency or problems related to very high pressures, flammability, explosion hazards, etc.

In the past few years, many alternatives have been proposed by different technology-foresight studies. This article focuses on the latest two. First, [Brown and Domanski \(2014\)](#) compared about 20 different technologies, from which they have emphasized the importance of magnetic (i.e., magnetocaloric) refrigeration, as being the alternative with the highest level of research activity and the best experimentally achieved exergy efficiency. However, they also noted that certain technical breakthroughs are required for most of the alternatives to become successful. They continued, that one should expect these alternatives to initially enter some specific market niches, and one should not expect the widespread displacement of vapor-compression technology in the near future.

The second study, performed by [Goetzler et al. \(2014\)](#), looked at the potential for energy savings and research opportunities for non-vapor-compression HVAC technologies. The authors of this comprehensive study selected 17 out of 20 identified viable technology options. They designated the remaining three technologies, i.e., the Bernoulli heat pump, the critical-flow refrigeration cycle, and electrocalorics as the early-stage technology options with missing demonstrations and information for a critical judgment and a comparison with vapor compression. Based on their analyses, they developed estimates for unit energy savings over baseline vapor-compression systems and identified the relevant markets and calculated the technical energy-savings potential for each considered technology. The results of the study revealed that elastocaloric refrigeration represents the most promising alternative, and magnetocaloric refrigeration is a very promising alternative for future applications.

The following text briefly describes some recent developments and research activities (with the focus being on the period of the past 2 years) on the new, alternative, caloric energy-conversion technologies that relate to the group of materials, that exhibit i.e., magnetocaloric, electrocaloric, elastocaloric and barocaloric effect. Most of these technologies,

compared to vapor compression, represent a potential for improvements in energy efficiency, compactness, noise level, as well as a reduction in environmental impacts.

## 2. Caloric refrigeration or heat pumping

The principles of operation for a thermodynamic refrigeration cycle in all the caloric technologies are similar ([Fig. 1](#)). By magnetization (magnetic refrigeration), polarization (electrocaloric refrigeration), stretching (elastocaloric refrigeration), and (com) pressing (barocaloric refrigeration), the working material will heat up. This process is analogous to the compression phase in vapor-compression refrigeration. The generated heat due to the caloric effects needs to be rejected by the system (analogous to condensation).

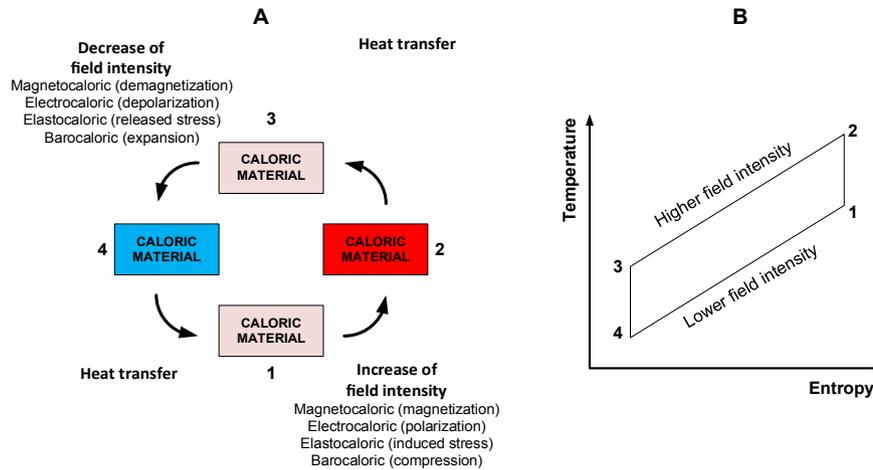
Therefore, a heat-transfer process needs to be established. In the third process, analogous to the expansion of a gas refrigerant, the demagnetization (magnetic refrigeration), depolarization (electrocaloric refrigeration), release (elastocaloric refrigeration), and expansion (barocaloric refrigeration) of the caloric material decreases its temperature. Now the caloric material is ready to accept some heat from the cooled environment. Therefore, in the last, i.e., the fourth, step, a heat-transfer process is required in order to transfer the heat from the heat source to the caloric material.

In [Fig. 1](#), the caloric Brayton thermodynamic cycle is shown. One should however note that caloric technologies enable application of several different and also more efficient thermodynamic cycles.

A recent and comprehensive general review of the technology for magnetocaloric energy conversion can be found in [Kitanovski et al. \(2015\)](#). For electrocaloric (pyroelectric) energy conversion, a recent, and the most comprehensive general review of the technology, can be found in [Correia and Zhang \(2014\)](#), and partly in [Ozbolt et al. \(2014\)](#), and [Kitanovski et al. \(2015\)](#). For the other two domains, i.e., elastocaloric and barocaloric energy conversion, except for the materials (which will be referred to later in the text), there is no comprehensive review on the engineering of these technologies. The reason for this lies in the fact that the two domains, especially elastocaloric energy conversion, are at an early stage of research, where most of the devices represent experimental set-ups with a small portion for the characterization of the material's properties.

### 2.1. Active caloric regenerative process

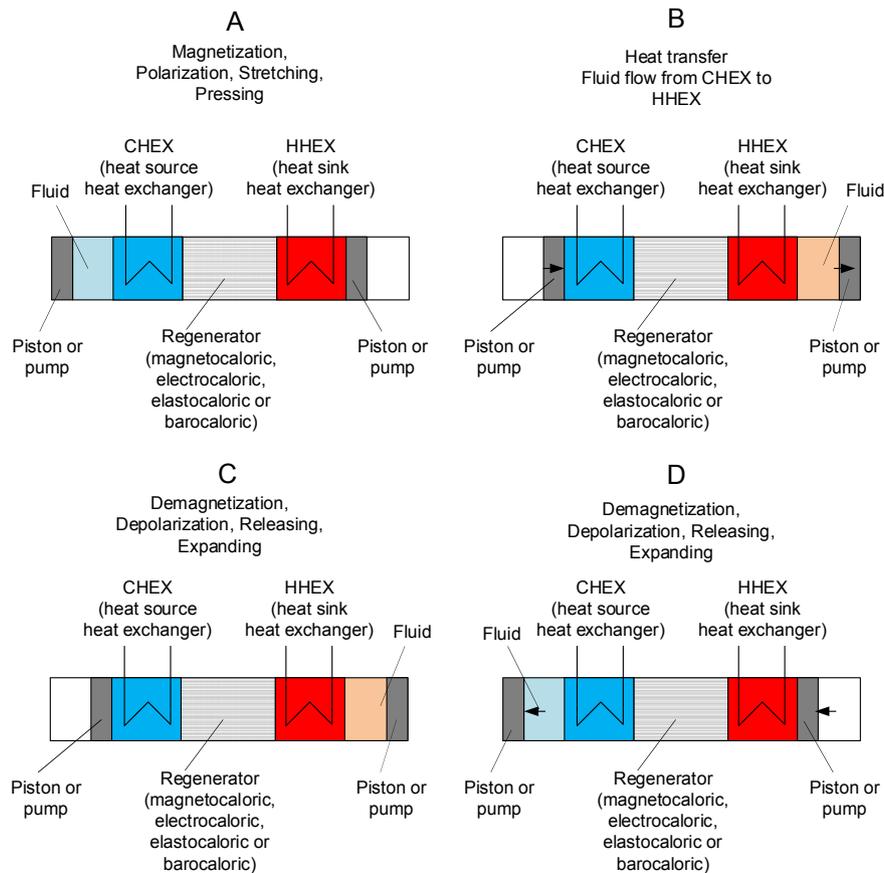
In most of caloric materials, the larger the change in the applied field, the larger will be the temperature change within the material. The exceptions are some first-order materials,



**Fig. 1 – (A) Schematic representation of an energy-conversion cycle with a caloric material. The caloric material can be considered to be magnetocaloric, electrocaloric, elastocaloric or barocaloric. Correspondingly, the material is subjected to a magnetic, electric, stress or pressure field change (B) A simple representation of the caloric Brayton thermodynamic cycle.**

where the caloric effect increases only up to a certain field. In this particular case the further increase of the applied field will not increase the caloric effect, but rather the temperature range of the caloric effect. Large changes in applied fields (magnetic, electric, stress or pressure fields) are also related to a higher energy input, weight or volume of the field source, the

breakdown of the material properties (i.e., elastocaloric and electrocaloric materials), and, finally, the costs of a potential device. Therefore, the applied fields in these technologies are mostly related to such field changes, which also lead to small temperature changes being observed in caloric materials (e.g., 0.5–4 K). The exceptions to this are elastocaloric energy



**Fig. 2 – The active caloric regeneration process and the related thermodynamic cycle in caloric refrigeration or heat-pump devices.**

conversion and, in certain materials, electrocaloric energy conversion.

For a realistic refrigeration or heat-pump cycle, the temperature span obtained by the simple thermodynamic cycling of a caloric material is, of course, not sufficient. One way to increase such a temperature span is the use of cascade devices. Another, more efficient process is the active caloric regenerative process (Fig. 2), for which the most recent and comprehensive review on modeling and experiments can be found in Kitanovski et al. (2015), especially for the magnetocaloric refrigeration.

According to Fig. 2, four processes form an active regenerative thermodynamic cycle. In this particular case, the caloric materials need to be produced as a porous structure through which the working fluid (in caloric cooling, this mostly relates to liquids) flows in an oscillatory, counter flow. The following text describes the caloric Brayton-like active regenerative cycle. In the first process, denoted by A in Fig. 2, the caloric regenerator is exposed to an increase in the field, which according to the four different technologies relates to the magnetic field, electric field, stress field, and pressure field, respectively. During this process, the caloric material heats up with a certain temperature difference (e.g.,  $\Delta T_{ad}$ , which denotes the adiabatic temperature change due to the sudden change of the field, and in most of these technologies, especially magnetocaloric and electrocaloric, this process is very close to isentropic). In process B (Fig. 2), the working fluid flows from the cold heat exchanger (CHEX or heat source heat exchanger) through the porous structure of the caloric regenerator to the hot heat exchanger (HHEX or heat-sink heat exchanger), where the fluid rejects the heat to, e.g., the environment. In process C (Fig. 2), the caloric regenerator is exposed to a negative change of the field (demagnetization, depolarization, release and expansion, respectively) and as a consequence, the temperature of the caloric regenerator decreases. In the last process D, the working fluid flows from the HHEX through the caloric regenerator to the CHEX. Since the fluid cools down, it now has the capability to absorb heat in the heat-source heat exchanger (CHEX), and thus provides cooling. By repeating these processes the temperature gradient will be established along the active caloric regenerator. Despite the fact that the active caloric regenerative process is one of the best-known solutions, this approach is very much restricted by the efficiency of the convective heat transfer in the regenerator (heat-transfer surface, heat-transfer coefficient, boundary layers, viscosity, fluids and the thermal properties of the materials, etc.). Since the fluid flow through the regenerator made of caloric material is oscillatory, this somehow also restricts the efficiency of the active heat-regeneration process, especially for high power densities. The latter defines the compactness and the cost of a device.

Active caloric regeneration has been very well investigated in the domain of magnetic refrigeration. For the other domains of caloric refrigeration, these kinds of models can be applied as well, by adapting them for a particular caloric material. Therefore, engineers and scientists who are entering the domain of electrocaloric or elastocaloric refrigeration, can learn a lot about active regeneration from magnetocaloric refrigeration. Note that the first comprehensive articles on the modeling of active electrocaloric regeneration as well as active

elastocaloric regeneration will be published during the next 2 years (information based on communication with experts in the field).

The most recent and comprehensive work that deals with the review on numerical and experimental investigations of active magnetocaloric regeneration can be found in Kitanovski et al. (2015). Additional to this, one can find the following most recent publications on active magnetic regeneration: Burdyny et al. (2014a, 2014b), Barbosa et al. (2014), and Brey et al. (2014).

The only recent publications that relate to the modeling of active regeneration in an elastocaloric cooling device can be found in Qian et al. (2014, 2015).

In the domain of electrocaloric refrigeration with active regeneration, the most recent modeling and the experiments have been performed in Plaznik et al. (2015), Gu et al. (2014), Guo et al. (2014), and Suchanec and Gerlach (2015). In the domain of barocaloric refrigeration, there is no evidence of any studies.

## 2.2. Regenerative caloric process with the application of thermal diode mechanism

An alternative (excluding the less-efficient passive regeneration) to active heat regeneration is the application of a thermal-diode mechanism (Fig. 3). In this particular case, the working fluid flow is not necessarily oscillating. A thermal diode is a physical phenomenon, device or a mechanism, which, by induced change of a thermal conductivity or by an additional work input, provides the manipulation and control of the heat-flow direction and sometimes also the heat rate (lately cited in Kitanovski et al., 2015).

Fig. 3 presents the basic concept of the operation of the regenerative process that applies thermal diodes. On both sides of the caloric material are the layers, denoted A and B. These two layers represent the thermal diodes. When the field is induced over the caloric material, the layer A (Thermal diode A) rapidly transports heat from the caloric material to the heat-sink heat exchanger via the attached microchannel with the fluid flow. Here, the layer B (Thermal diode B) is inactive, and therefore it does not transfer heat and functions as a thermal insulator. When the field on the caloric material is removed, the layer B (Thermal diode B) rapidly transports heat from the heat-sink heat exchanger via the microchannel to the caloric material. Here, the layer A (Thermal diode A) is inactive, and therefore does not transfer heat and acts as a thermal insulator. After a certain number of thermodynamic cycles a temperature profile is also established along the caloric material embodied between the thermal diodes. The implementation of the thermal diodes substantially alters the operational characteristics of the caloric energy-conversion device. The thermal diodes can increase the power density by up to an order of magnitude compared to active caloric regeneration.

The most comprehensive and recent review on thermal-diode mechanisms for applications in magnetocaloric and also other caloric technologies is given in Kitanovski et al. (2015). Thermal diodes may be generally divided into two domains: solid-state physics and microfluidics. Sub-domain that shows a large potential for the application of solid-state thermal diodes are thin-film Peltier thermoelectric modules.

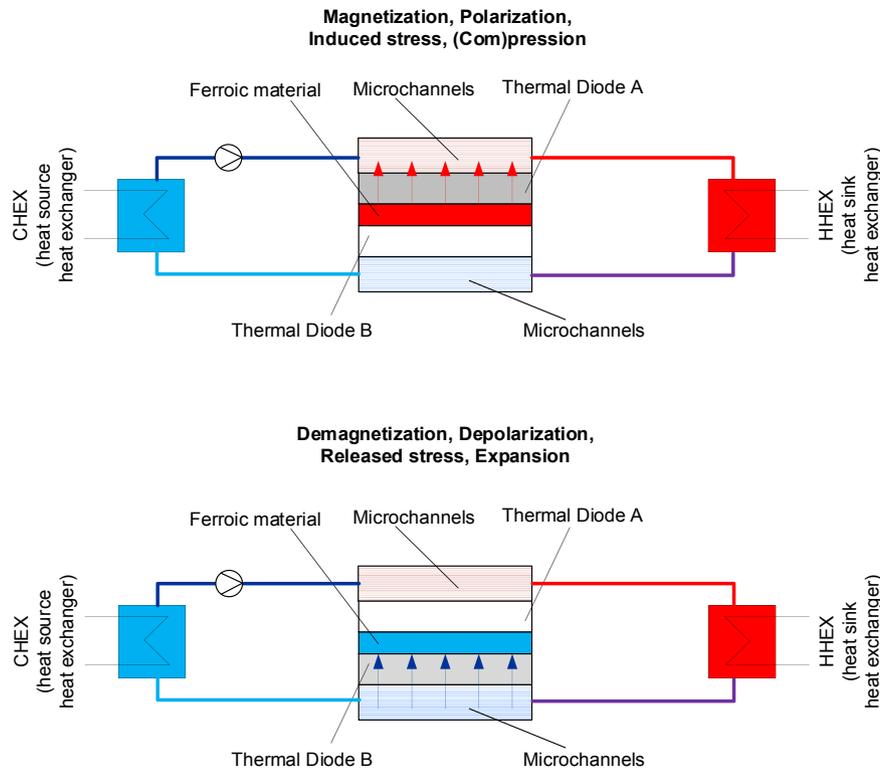


Fig. 3 – An example of the regeneration process based on thermal diodes in caloric refrigeration or heat-pump devices.

Another sub-domain relates to thermal rectifiers (i.e., by mechanical contact, the anisotropy of thermal conductivity, etc). This is a new and rather special domain of heat transfer, which arises from material science, physics, and nanoscience. For mechanical-contact-based thermal diodes, the reader is referred to the literature on polymer and metallic shape-memory materials and alloys, and this very broad domain will not be cited here. For microfluidic thermal diodes, [Kitanovski et al. \(2015\)](#) address the following domains: electrokinetics and electrohydrodynamics, magneto-hydrodynamics, ferrohydrodynamics, and electro-rheology or magneto-rheology.

In the field of magnetocaloric refrigeration, the principles of thermal diodes have been evaluated by different researchers. These regard the use of thin-film Peltier modules or contact thermal switches as the thermal-diode mechanism. The results of most of these studies (reported in [Kitanovski et al. \(2015\)](#)) reveal that such an application is feasible and it can bring a major advantage, compared to active magnetocaloric regeneration, by boosting the power density of the device, while keeping the same efficiency as in active magnetocaloric regeneration. There is no evidence for the practical realization of a magnetocaloric device based on thin-film Peltier thermal diodes.

The only publication that relates to the application of a microfluidic thermal diode mechanism in magnetocaloric refrigeration was by [Hosoi et al. \(2014\)](#). They investigated a liquid metal driven by the electro-wetting principle. A gallium-based alloy was applied as the thermal switch fluid.

A concept of an electrocaloric refrigerator employing a thermal diode based on electrohydrodynamic flows in thin

layers of dielectric fluids was recently discussed by [Hehlen et al. \(2013\)](#). The thermal diode mechanism was experimentally tested, however, an electrocaloric refrigerator was not build.

### 3. Caloric materials

This section provides brief information about the latest publications and work that relates to the developments, characterization, and processing of different caloric materials. Here the focus is not on particular materials and their properties, since many previous publications have already described them. The latest review publications on caloric materials are those of [Moya et al. \(2014, 2015\)](#), which represent a good and brief review on different materials. However the estimates on the efficiency of caloric materials in [Moya et al. \(2015\)](#) were not well defined, since they did not consider realistic conditions (i.e. temperature span) and methods for the improvement of the efficiency (i.e. regeneration of work input, regeneration of heat) for a real caloric device. Other publications refer to a specific domain of materials and are presented in the following text.

#### 3.1. Magnetocaloric materials

Within the past 2 years, further efforts have been made in material science, especially in the investigation of new magnetocaloric materials and improvements to existing ones. The most recent review on the developments in magnetocaloric materials can be found in [Jian \(2014\)](#), [Roy \(2014\)](#), and [Markovich et al. \(2014\)](#), whereas it is important to also mention

the two latest and more specific work related to particular groups of materials. For instance [Gottschall et al. \(2015\)](#) discussed the giant magnetocaloric material Ni–Mn–In–Co, and [Krautz et al. \(2014a\)](#) focused on a systematic investigation of Mn-substituted La(Fe,Si)<sub>13</sub> alloys and their hydrides.

With regard to the processing methods for magnetocaloric materials, the latest and most important contributions were published by [Kitanovski et al. \(2015\)](#), as the review on existing methods and related publications, and [Krautz et al. \(2014b\)](#).

### 3.2. Electrocaloric materials

The newest reviews on electrocaloric materials can be found in a comprehensive book on electrocalorics by [Correia and Zhang \(2014\)](#), [Alpay et al. \(2014\)](#), [Suchanec and Gerlach \(2013, 2015\)](#), and [Ozbolt et al. \(2014\)](#). In the last of these there is also a discussion about the variety of designs for electrocaloric materials with electrodes. A part of such a discussion can also be found in [Kitanovski et al. \(2015\)](#).

For particular types of materials, i.e. polymers, the most recent work has been published in [Zhang et al. \(2015\)](#), and [Kwon et al. \(2014\)](#). For ceramic electrocaloric materials, the following recent article has been published by [Zhao et al. \(2015\)](#).

### 3.3. Elastocaloric materials

For elastocaloric materials there is no particular review in this domain, except the works of [Moya et al. \(2014, 2015\)](#), [Cui \(2014\)](#), and partially also the chapter dedicated to elastocaloric refrigeration in [Kitanovski et al. \(2015\)](#), as well as in [Jani et al. \(2014\)](#). Because of the lack of review articles, below in the text are addressed some of the most important and recent articles that relate to elastocaloric refrigeration and related materials, and which were not cited in the above cited reviews.

An interesting contribution was given by [Liu et al. \(2014a\)](#), who investigated the elastocaloric effect in the electrocaloric BaTiO<sub>3</sub> material. Another group of alloys based on Ni–Mn–Co have been investigated by [Millán-Solsona et al. \(2014\)](#), [Lu et al. \(2015\)](#), and [Gueltig et al. \(2014\)](#). Most of the work related to the elastocaloric effect is still based on the Nitinol alloy (Ni–Ti). The most recent articles in this domain relate to the work of [Schmidt et al. \(2015\)](#), [Osmmer et al. \(2014\)](#), and [Tusek et al. \(2015\)](#). There is also an investigation of other types of elastocaloric materials. For instance, [Buenconsejo and Ludwig \(2015\)](#) reported on new thin-film shape-memory alloys based on Au–Cu–Al.

### 3.4. Barocaloric materials

The most recent review on barocaloric materials can be found in [Moya et al. \(2014, 2015\)](#) and [Kitanovski et al. \(2015\)](#). This area, compared to other caloric areas, is less active and there are only a small number of publications related to the barocaloric effect and the associated materials. From the latest contributions, which were not cited in above reviews, one can find the article of [Matsunami et al. \(2015\)](#), who investigated the barocaloric effect in Mn<sub>3</sub>GaN. Note that in many cases the barocaloric effect follows some other caloric materials

(multicaloric effect). Examples of this can be found in the recent studies of [Liu et al. \(2014b\)](#), [Mañosa et al. \(2014\)](#), [Czernuszewicz et al. \(2014\)](#), and [Quintero et al. \(2014\)](#).

### 3.5. Multicaloric materials

Based on novel materials research, scientists are finding a coupling between different caloric effects in the same material. This is referred to as the multicaloric effect or multicaloric materials or sometimes also multiferroic materials (see e.g., [Meng et al. \(2013\)](#), [Starkov and Starkov \(2014a\)](#), [Moya et al. \(2014\)](#), [Saxena and Planes \(2014\)](#), and [Planes et al. \(2014\)](#)). The engineering part, required to bring these materials to efficient working devices still remains to be completed. However, the first steps towards this realization have already been made ([Castan et al. \(2014\)](#), and [Starkov and Starkov \(2014b\)](#)).

## 4. Caloric prototypes and/or conceptual devices

This chapter focuses on prototype devices that have been developed for the purpose of demonstration or the conceptual operation of caloric refrigeration or heat pumping. Most of the engineering work in caloric refrigeration has been performed in magnetocaloric refrigeration and heat pumping, which led to today's 65 prototypes being produced. The most comprehensive review on all the magnetocaloric prototypes (up to the end of 2014) can be found in [Kitanovski et al. \(2015\)](#). Despite this, the emphasis is put on publications that are related to the engineering of magnetocaloric devices in the past 2 years.

Also in electrocaloric refrigeration, one can see important progress in engineering the first electrocaloric conceptual devices. In this case, the most comprehensive information on existing electrocaloric prototypes can be found in [Kitanovski et al. \(2015\)](#), and [Correia and Zhang \(2014\)](#). Also this case addresses those being developed in the past 2 years.

In elastocaloric refrigeration, there is no actual evidence of real prototype devices, except for the article of [Schmidt et al. \(2015\)](#). They report on an experimental elastocaloric device, which applies elastocaloric plate. Other experiments performed in elastocaloric refrigeration are mostly related to the strain manipulation of a single wire of a material, where in some cases, the heat source and the heat sink are provided. A single wire, in author's opinion, cannot represent a prototype device, but rather an investigation of the performance of the material itself. However, this certainly represents a way to do future engineering and prototyping.

In barocaloric energy conversion, the recent and, to the best of authors' knowledge, the only existing prototype device (actually the multicaloric magneto-barocaloric device) has been produced by [Czernuszewicz et al. \(2014\)](#) (see also [Kitanovski et al., 2015](#)). For this reason the following two sub-chapters relate to magnetocaloric and electrocaloric prototypes.

### 4.1. Magnetocaloric prototyping (including magnetic field sources)

The magnetic field sources that can be applied in magnetocaloric devices are: permanent magnets, superconducting

magnets, and electromagnets. All these three types of magnets have already been applied in magnetic refrigeration or heat-pump prototypes. The most recent and comprehensive review of different magnetic field sources and their design for magnetocaloric energy conversion is given in [Kitanovski et al. \(2015\)](#). Publications that relate the particular magnetic field source, are usually related to a prototype device, to which such a magnetic field source corresponds. Since the latest and most comprehensive information on the existing magnetocaloric prototypes has been published in [Kitanovski et al. \(2015\)](#), below are addressed up-to-date publications from the past 2 years, which have not been cited in the above work and that relate the design of the experimental work on magnetocaloric devices, their magnetic field sources, and modeling.

In the case of prototype devices with a linear movement of the magnetocaloric material or a linear movement of the magnetic field source (this is required in order to provide the magnetization/demagnetization), the following work has been performed within the past 2 years: [Kotani et al. \(2014\)](#), and [Chen et al. \(2014\)](#). Additional work, which relates to both the rotary and linear prototype devices, as well as hydraulic issues, has been published by [Gatti et al. \(2014\)](#) and [Barbosa et al. \(2014\)](#).

In rotary magnetic refrigeration devices, the magnetic field source rotates over the magnetocaloric material or the magnetocaloric material rotates within the magnetic field source.

With the rotation in and out of the magnetic field, the magnetization or demagnetization process is applied to the magnetocaloric material. In the past two years the only work (which was not cited in [Kitanovski et al. \(2015\)](#)), and is related to rotary magnetocaloric prototypes, can be found in [Miyazaki et al. \(2014\)](#).

The electromagnetic field source for a magnetocaloric testing device without any moving parts has been developed and reported in [Soman et al. \(2015\)](#).

Additionally, some recent numerical modeling of magnetocaloric devices can be found in [Torregrosa-Jaime et al. \(2014\)](#), [Aprea et al. \(2014\)](#), [Diguët et al. \(2014\)](#), and [Lionte et al. \(2015\)](#).

#### 4.2. Electrocaloric prototypes

The most comprehensive information on engineering electrocaloric prototypes can be found in [Kitanovski et al. \(2015\)](#) and [Correia and Zhang \(2014\)](#). Additionally, there is important information in [Özbolt et al. \(2014\)](#). In these publications all the work on existing five electrocaloric prototypes, as well as modeling, has been reported. Since then, [Plaznik et al. \(2015\)](#) gave additional information on their active electrocaloric regeneration (AER) device. This prototype device applied the AMR consisting of relaxor ceramics produced as a parallel-plate regenerator. A peristaltic pump served for the

**Table 1 – Comparison of different caloric technologies.**

Characteristic	MC	EC	ESC	Comment
Hysteresis	++	+	–	MC – some Mn-Based materials and Heusler alloys possess hysteresis, EC – some relaxor ferroelectric materials show almost no or only a very slim hysteresis ESC – some elastocaloric materials show no hysteresis (Fe–Pd)
Cyclic stability	++	+	–	There exists no long term stability test (i.e. 10–100 mio cycles) for most of caloric materials. Cycling is proven to be a problem for ESC, however, Ni–Ti–Cu–Co shows good stability. Long term stability problems may occur also in some sintered MC or EC materials.
Joule heating	++	++	+++	In MC it can occur due to the eddy currents or electric coils (as magnets). Joule heating can also occur in EC due to leakage current through the EC material or due to Joule heating in connecting wires.
Exergy efficiency	+++	+++	+++	In all the caloric technologies and related materials with low or no hysteresis, with heat regeneration and partly also the energy (work) regeneration, the potential efficiency is high.
Silent operation, No vibration	++	+++	+	Depends on design of a particular device.
*GWP = 0, ODP = 0	+++	+++	+++	Lack of information about environmental impact caused by manufacturing of caloric materials and devices.
Moving parts	–	+++	–	MC (not required in the case of an electric coil)
Rare earths in field source	–	+++	+++	MC (most of prototypes comprise rare earth permanent magnets)
Rare earths in caloric material	+	+++	+++	MC (some magnetocaloric materials consist of rare earths)
Manufacturability and processing of caloric material and regenerator	+	–	+	A drawback especially in sintered caloric materials. The present problem of all the caloric technologies is in providing large heat transfer surface. This strongly depends on the processing method and the manufacturability of caloric materials.
Eddy currents	–	+++	+++	MC (depends on design of a particular device)
Caloric effect at realistic field changes	+	++	+++	MC (0.8–1.5 T; higher magnetic fields require large mass of magnets), EC (limits given by a breakdown voltage, large electrocaloric effect in polymers and thin ceramic), ESC (maximum strain)
Technology readiness	–	–	–	Despite of the high potential, caloric technologies require further R&D efforts to be able to compete with the vapor compression. Additional time required for first competitive and compact devices – MC (up to 10 years), EC and ESC (up to 15 years).

\*GWP (Global Warming Potential), ODP (Ozone Depletion Potential), MC – magnetocalorics, EC – electrocalorics, ESC – elastocalorics. + (means positive or without problems); – (means negative or problematic).

**Table 2 – A list of some national or international projects in the field of magnetocaloric technologies.**

Magnetocaloric
<b>EU projects</b>
DRREAM – Drastically Reduced Use of Rare Earths in Applications of Magnetocalorics (2013–2016), <a href="http://www.drream.eu/">http://www.drream.eu/</a>
ICE – MagnetoCaloric Refrigeration for Efficient Electric Air Conditioning (2010–2014), <a href="http://www.ice-project.webs.upv.es/home">http://www.ice-project.webs.upv.es/home</a>
ELICIT “Environmentally Low Impact Cooling Technology”, (2014–2016), <a href="http://elicit-project.eu/">http://elicit-project.eu/</a>
FRISBEE, Food Refrigeration Innovations for Safety, consumers' Benefit, Environmental impact and Energy optimization along the cold chain in Europe, (2010–2014), <a href="http://www.frisbee-project.eu/">http://www.frisbee-project.eu/</a>
FRIMAG: “Demonstrator of drinks cooler running by means of magnetic refrigeration”. France & Switzerland (INTERREG IV A), <a href="http://www.frimag.net/en-gb/home/Pages/home.aspx">http://www.frimag.net/en-gb/home/Pages/home.aspx</a>
<b>US projects</b>
Air Conditioning With Magnetic Refrigeration, Program: BEETIT, ARPA-E AWARD (2010–2014), <a href="http://arpa-e.energy.gov/?q=slick-sheet-project/air-conditioning-magnetic-refrigeration">http://arpa-e.energy.gov/?q=slick-sheet-project/air-conditioning-magnetic-refrigeration</a>
Magnetocaloric Refrigeration, US DOE – CRADA PROJECT (ORNL + GE), (2013–2016), <a href="http://energy.gov/eere/buildings/downloads/magnetocaloric-refrigeration">http://energy.gov/eere/buildings/downloads/magnetocaloric-refrigeration</a>
Novel magnetocaloric air conditioner, project founded by U.S. Department of Energy, announced in 2015, <a href="http://energy.gov/eere/articles/energy-department-invests-nearly-8-million-develop-next-generation-hvac-systems">http://energy.gov/eere/articles/energy-department-invests-nearly-8-million-develop-next-generation-hvac-systems</a>
<b>Larger National projects in Europe</b>
ENOVHEAT project which is funded by the Danish Council for Strategic Research within the Programme Commission on Sustainable Energy and Environment (2013–2017), Denmark, <a href="http://www.enovheat.dk/">http://www.enovheat.dk/</a>
SPP 1599 “Ferroic Cooling”, Caloric Effects in Ferroic Materials: New Concepts for Cooling (Magnetocaloric, electrocaloric, elastocaloric), Start in 2012, Germany, <a href="http://www.ferroiccooling.de/">http://www.ferroiccooling.de/</a>
MagCool: “New giant magnetocaloric materials round room temperature and applications to magnetic refrigeration, (2011–2015), France, <a href="http://www.agence-nationale-recherche.fr/?Project=ANR-10-STKE-0008">http://www.agence-nationale-recherche.fr/?Project=ANR-10-STKE-0008</a>

oscillatory flow of silicon oil as the heat-transfer fluid. The article of Plaznik et al. (2015) also considered the numerical modeling of the active electrocaloric regenerative cooling device. Besides this publication, the newest publications related to the modeling of electrocaloric devices can be found in Gu et al. (2014), Smith et al. (2014), and Mohammadi et al. (2014).

## 5. Conclusion

As a conclusion a comparison of the different caloric technologies has been made (Table 1). Because in barocaloric refrigeration there is a significant lack of experimental as well as theoretical engineering research one cannot evaluate this technology and show its advantages or drawbacks. However,

the Table 1 shows this for magnetocaloric, electrocaloric and elastocaloric refrigeration and heat pumping.

Several national or international projects are running or have been performed in the field of caloric technologies. Some of them are listed in Tables 2 and 3. Authors of this article were unfortunately not able to obtain an appropriate information for the presentation of Chinese and Japanese projects. Note also, that there exist several other projects, where the caloric materials or systems represent a work package or a minor activity.

As can be seen from the Table 4, these different caloric technologies may not be competitive with each other, but will rather penetrate different markets in the future. At the beginning of this article technology foresights being published in the past 2 years are indicated (i.e., Brown and Domanski,

**Table 3 – A list of some national or international projects in the field of electrocalorics and elastocalorics.**

<b>Electrocaloric</b>
<b>EU projects</b>
METCO – European Metrology Research Programme EURAMET - Electrocaloric cooling for clean refrigeration, <a href="http://projects.npl.co.uk/METCO/index.html">http://projects.npl.co.uk/METCO/index.html</a> (until end of 2016)
<b>US projects</b>
Solid State Cooling With Advanced Oxide Materials, AFRL-OSR-VA-TR-2014-0134, (2011–2014)
Electrocaloric heat pump, project founded by U.S. Department of Energy, announced in 2015, <a href="http://energy.gov/eere/articles/energy-department-invests-nearly-8-million-develop-next-generation-hvac-systems">http://energy.gov/eere/articles/energy-department-invests-nearly-8-million-develop-next-generation-hvac-systems</a>
<b>Larger National projects in Europe</b>
SPP 1599 “Ferroic Cooling”, Caloric Effects in Ferroic Materials: New Concepts for Cooling (Magnetocaloric, electrocaloric, elastocaloric), Start in 2012, Germany, <a href="http://www.ferroiccooling.de/">http://www.ferroiccooling.de/</a>
<b>Elastocaloric</b>
<b>US projects</b>
Thermoelastic cooling, Department of Energy (DOE) Advanced Research Projects Agency—Energy (ARPA-E), (2010–2016), <a href="http://arpa-e.energy.gov/?q=slick-sheet-project/elastic-metal-alloy-refrigerants">http://arpa-e.energy.gov/?q=slick-sheet-project/elastic-metal-alloy-refrigerants</a>
Compact thermoelastic cooling, project founded by U.S. Department of Energy, announced in 2015, <a href="http://energy.gov/eere/articles/energy-department-invests-nearly-8-million-develop-next-generation-hvac-systems">http://energy.gov/eere/articles/energy-department-invests-nearly-8-million-develop-next-generation-hvac-systems</a>
<b>Larger National Projects in Europe</b>
SPP 1599 “Ferroic Cooling”, Caloric Effects in Ferroic Materials: New Concepts for Cooling (Magnetocaloric, electrocaloric, elastocaloric), Start in 2012, Germany, <a href="http://www.ferroiccooling.de/">http://www.ferroiccooling.de/</a>

**Table 4 – Predicted first applications and proposed future R&D.**

	Predicted first applications	Future R&D
MC	Replacement of vapor compression in small refrigerators with small temperature span (i.e., wine cooler, hotel minibar refrigerator, laboratory refrigerators) + Small heat pumps	<ul style="list-style-type: none"> <li>- Improve and implement new manufacturing and processing methods for regenerators</li> <li>- Apply thermal diodes for particular solutions with high power density</li> <li>- Use solutions for higher magnetocaloric effect <math>\Delta T &gt; 4-5</math> K</li> <li>- Apply good working fluids</li> <li>- Avoid use of rare earths in MC materials and magnets</li> <li>- Search for solutions without moving parts</li> </ul>
EC	Same as in magnetocaloric + Replacement of Peltier thermoelectric refrigeration technology and its applications + Thermal management of electronic devices	<ul style="list-style-type: none"> <li>- Improve and implement new manufacturing and processing methods for materials and regenerators</li> <li>- Recover electric energy</li> <li>- Apply thermal diodes for particular solutions with high power density</li> <li>- Use solutions for higher electrocaloric effect <math>\Delta T &gt; 4-5</math> K</li> <li>- Apply good working fluids</li> </ul>
ESC	Replacement of vapor compression in small refrigerators or freezers (if noise level accepted, then applicable for household applications) + Heat pumps for automotive + Small energy harvesters	<ul style="list-style-type: none"> <li>- Remove (reduce) hysteresis</li> <li>- Increase cyclic stability</li> <li>- Design and develop appropriate regenerator's structure</li> <li>- Search for solutions without moving parts</li> <li>- Apply thermal diodes for particular solutions with high power density</li> <li>- Recover mechanical energy</li> </ul>

2014; Goetzler et al., 2014). They have correctly concluded, that caloric energy conversion technologies (i.e., refrigerators, air conditioners, freezers, heat pumps or power generators) will certainly penetrate particular market niches; however, they will not represent, in the short term, a serious alternative for the full replacement of vapor compression. However, in the medium or a long term, this may happen.

There is still a lot of very strong research effort needed, in both material science and engineering. Only strong, international and interdisciplinary collaborations between different experts can bring these technologies towards the first market applications. In order to attract strategic industrial partners, good, operating, prototype devices are needed, which do not show only the effect of a particular caloric material, but operate under conditions that fulfill the requirements of certain market applications.

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