Innovative heating and cooling systems based on caloric effects: A review

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Abstract. Heat pumps (HPs) are an excellent solution to supply heating and cooling for indoor space conditioning and domestic hot water (DHW) production. Conventional HPs are typically electrically driven and operate with a vapour-compression thermodynamic cycle of refrigerant fluid to transfer heat from a cold source to a warmer sink. This mature technology is cost-effective and achieves appreciable coefficients of performance (COP). The HP market demand is driven up by the urge to improve the energy efficiency of building heating systems coupled with the increase of global cooling needs for air-conditioning. Unfortunately, the refrigerants used in current conventional HPs can have large greenhouse or ozone-depletion effect. Alternative gaseous refrigerants have been identified but they present some issues regarding toxicity, flammability, explosivity, low energy efficiency or high cost. However, several non-vapour-compression HP technologies have been invented and could be promising alternatives to conventional systems, with potential for higher COP and without the aforementioned refrigerant drawbacks. Among those, the systems based on the so-called "caloric effects" of solid-state refrigerants are gaining a lot of attention. The caloric effects are large entropy and adiabatic temperature changes caused by the application or removal of an external field in certain specific solid materials. There are 4 main caloric effects: magnetocaloric, elastocaloric, electrocaloric and barocaloric. Each of them is characterized by the nature of the field and the response that induces the entropy and adiabatic temperature change: variation of the magnetic field, uniaxial mechanical stress, electrical field or hydrostatic pressure, respectively. A HP cycle can be based on these caloric effects and several heating/cooling prototypes were developed and tested over the last few decades. Although not mature technologies yet, some of these caloric systems are well suited to become new efficient and sustainable solutions for indoor space conditioning and DHW production. This paper aims to raise awareness in the building community about these innovative caloric systems. It sheds some light on the recent progress in that field and compares the performance of caloric systems with that of conventional vapour-compression HPs for building applications.

Keywords. Innovative heat pump, caloric effects, magnetocaloric, elastocaloric, barocaloric, electrocaloric, non-vapour-compression heat pump alternatives.
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1. Introduction

Current and future social, environmental and economic challenges call for the different energy sectors to take a sharp turn and accelerate their decarbonization and sustainability optimization. In that context, the building sector is a key target as it accounts for most of the energy end-use in industrialized countries. Moreover, most of the energy used in buildings is dedicated to indoor space conditioning (space heating and space cooling) and the production of domestic hot water (DHW) [1]. The tightening of energy regulations and renovation campaigns tend to decrease the space heating needs of buildings and allow for low-temperature heat emitters. However, the energy share for DHW production, which requires higher temperatures (50-65°C) to avoid legionella problems, is increasing. In addition, because of global warming, higher thermal comfort standards, purchasing power increase and population growth, especially in warm countries, cooling air conditioners (ACs) are more and more common. It is estimated that 2/3 of the world's households may end up being equipped with ACs (half of them being in China, India and Indonesia). Cooling demand is also increasing significantly in temperate and cold climates during summer, especially for office buildings. Indoor space cooling is thus the largest contributor to the growth of global building electricity demand [2].

In that context, heat pumps (HPs) have been proven to be a very efficient and flexible solution for space heating/cooling and DHW production. They are the most cost-efficient supply of heat for individual buildings outside of urban areas. In cities, large industrial HPs can be used for heat generation at district heating network plants or can be installed in buildings as decentralized booster HPs for low-temperature district heating networks. Consequently, the market demand for HPs has sustained significant growth over the last years. Vapour-compression systems are dominating the HP industry for building applications. Unfortunately, the refrigerants used in these conventional systems have a large greenhouse effect when released into the atmosphere. Several gaseous refrigerant alternatives have been identified, but they present other disadvantages such as toxicity, flammability, explosivity, low energy efficiency or high cost [3].

Non-vapour-compression alternative systems are also possible. Several of these non-conventional and innovative HP technologies have been identified as particularly promising, without the aforementioned drawbacks and with the potential for a larger coefficient of performance (COP) than that of conventional vapour-compression heat pumps (VCHPs). Among these alternatives, a particular interest has developed over the last few years for systems based on the so-called caloric effects of solid-state refrigerants to create a thermodynamic HP cycle. Although not mature technologies yet, some of these caloric systems are well suited to become new efficient and sustainable solutions for indoor space conditioning and DHW production [3].

This paper aims to raise awareness in the building community about these innovative caloric systems. Firstly, the different caloric effects are presented together with a brief history and the recent developments of these non-conventional heat pump technologies. The performances of the different caloric systems are then reviewed and compared with that of VCHPs for building applications. Finally, the article closes with some outlook on the future of caloric systems and conclusions.

2. Caloric effects for innovative heat pump systems

Conventional HPs are typically electrically driven and operate with a vapour-compression thermodynamic cycle of refrigerant fluid to transfer heat from a cold source to a warmer sink. Although capable of a similar heat transfer with COP > 1, the caloric HPs operate with a different thermodynamic cycle based on the so-called “caloric effects”.

The caloric effect is large entropy and adiabatic temperature changes caused by the application or removal of an external field in certain specific solid materials: the caloric materials. When the external field is increased in the material, its entropy decreases and its temperature increases. Reciprocally, the external field in the material is reduced the entropy increases and its temperature decreases. This phenomenon can be employed to create a HP cooling/heating thermodynamic cycle. Because of the in-principle reversible nature of this caloric effect, it opens up the possibility for heat pump systems with COPs higher than that of conventional VCHPs [4].

There are 4 main caloric effects. Each of them is characterized by the nature of the field and the response that induces the entropy and adiabatic temperature change:

- Magnetocaloric effect: Adiabatic temperature change induced by a variation of the magnetic field (magnetization/demagnetization).
- Elastocaloric effect (a.k.a. thermoelastic): Adiabatic temperature change induced by a variation of the uniaxial mechanical stress (stretching/squeezing).
- Electrocaloric effect: Adiabatic temperature change induced by a variation of the electrical field (polarization/depolarization).
- Barocaloric effect: Adiabatic temperature change induced by a variation of the hydrostatic pressure (compression/decompression).

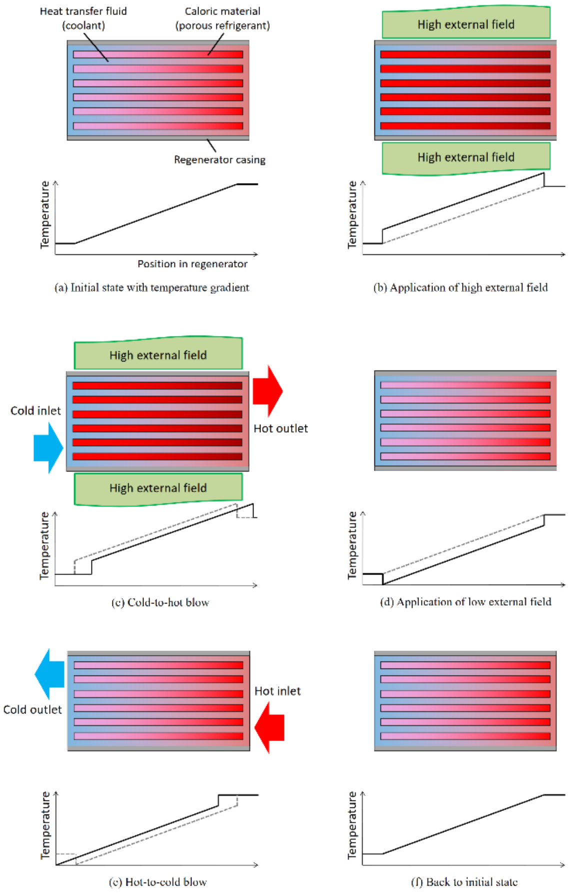
A detailed description of the different caloric effects and their heating/cooling applications can be found in Kitanovski et al., 2015a [4] (caloric effects), Kitanovski et al., 2015b [5] and Smith et al., 2012 [6] (magnetocaloric effect), Tušek et al., 2015 [7] and Kabirifar et al., 2019 [8] (elastocaloric effect), Torelló & Defay, 2022 [9] (electrocaloric effect), Aprea et al., 2020 [10] (barocaloric effect).

The basic operation principle of most caloric HP systems is similar for all 4 caloric effects. The caloric material is used as a solid refrigerant. It is contained as a porous media inside a regenerator casing that allows bi-directional circulation of the coolant fluid through the porous caloric material to transfer (by convection) the thermal energy from the cold side (heat source) to the warm side (heat sink) of the device [11].

The porous caloric material can be arranged in different configurations: irregular crushed particles, parallel plate matrices, packed sphere beds, circular or rectangular micro-channel matrices, packed screen beds or other mesh geometries [12]. The geometries of the porous solid refrigerant and the regenerator casing should be optimized to maximize the heat transfer (convection) between coolant fluid in the entire volume of caloric material, and minimize the pressure losses (pumping work) of the system.

The coolant fluid is usually a harmless and environmental-friendly water-based brine. Air can also be employed for direct usage in a ventilation system with an active regenerator. Coolants made of metallic fluids or nanofluids (fluids with dispersed solid nanoparticles) have also been tested for their high thermal conductivity to enhance the heat transfer in the porous refrigerant [5].

The sole adiabatic temperature change of the caloric effects (e.g., typically 0.5-4 K for the magnetocaloric effect) is usually too small for any useful direct applications in buildings or industries. Timing the oscilating fluid flow with the changing applied field, the caloric effect is employed to create an active caloric regenerative thermodynamic cycle that can generate an adequate temperature span for HP operations (5-60 K) [4, 6].



(a) Initial state with temperature gradient
(b) Application of high external field
(c) Cold-to-hot blow
(d) Application of low external field
(e) Hot-to-cold blow
(f) Back to initial state

Fig. 1 – The different phases of the active caloric regenerative cycle for the operation of a generic caloric HP system (adapted from [11]).

One can see in **Fig. 1** the 4 processes that form the active caloric regenerative thermodynamic cycle of a generic caloric HP to transfer heat from a cold source to a warmer heat sink. **Fig. 1 (a)**: The regenerator presents an initial temperature gradient over its length and zero external field is applied to the refrigerant caloric material. **Fig. 1 (b)**: The cycle starts with the application of a large external field to the caloric material (e.g., magnetization, stretching, polarization or compression) leading to a temperature increase over the length of the regenerator (shown as uniform for simplicity). **Fig. 1 (c)**: The coolant fluid is then pushed from the cold side (heat source) to the hot side (heat sink) of the regenerator (cold-to-hot blow). The warmer fluid rejects the heat into the heat sink and the regenerator is cooled down under a constant large external field. **Fig. 1 (d)**: The external field is removed (e.g., demagnetization, squeezing, depolarization or decompression) leading to a temperature decrease over the length of the regenerator (again shown as uniform for simplicity). **Fig. 1 (e)**: To complete the cycle, the coolant fluid is pushed back from the hot side to the cold side of the regenerator (hot-to-cold blow) under a zero external field, which re-heats the bulk of the regenerator caloric material (heat regeneration process and heat extraction from the cold source). **Fig. 1 (f)**: The coolant fluid and the caloric material reach local thermal equilibrium and the temperature distribution across the regenerator length is the same as at the initial stage of the cycle.

The active regenerator cycle described above (**Fig. 1**) can also be represented in a Temperature-Entropy diagram as a (caloric) Brayton thermodynamic cycle (see **Fig. 2**). This caloric Brayton active regenerative cycle is the most commonly used one for caloric HP systems. It is very similar to the Erikson cycle. Other (sometimes, more efficient) thermodynamic cycles can also be employed for caloric systems [4].

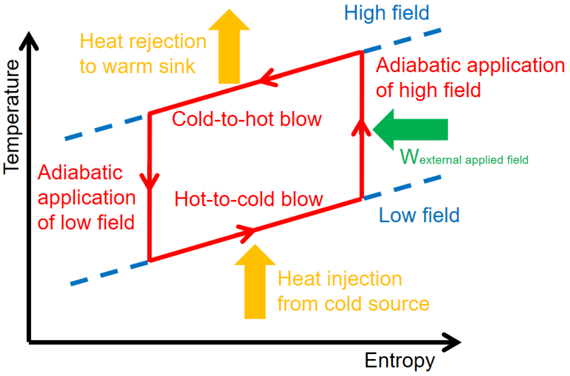


Fig. 2 - The caloric Brayton cycle: a common active caloric regenerative cycle for caloric HPs.

Certain materials can combine several types of caloric effects at the same time: multicaloric effects observed in, e.g., certain multiferroic materials. It is thus possible to conceive systems that exploit multiple-coupled caloric effects within the same refrigerant materials. This could increase the overall adiabatic temperature change and improve the system's efficiency and temperature span. Some researchers are thus developing devices combining, e.g., the magnetocaloric effect with the electrocaloric effect or the elastocaloric effect [4, 13].

The field of caloric systems is relatively young. The number of international research groups working on the topic is still limited compared to other energy conversion technologies. However, significant progress has been made within the last 10-20 years: multiple theoretical, numerical and experimental studies have been conducted on the different caloric effects, new caloric materials have been discovered and manufactured, general guidelines and models have been developed for both generic caloric systems and specific ones, and a number of very peculiar engineering challenges has been addressed to improve the energy efficiency and cost affordability of the magnetocaloric [14], elastocaloric, electrocaloric and barocaloric HP prototypes. The growing enthusiasm for caloric systems is mainly driven by their theoretically high COP because of the in-principle reversible nature of the caloric effects. In addition, they have the potential for quiet and low vibration level operation, miniaturization and compactness, efficient part-load control, no use of toxic, flammable, explosive, ozone-destructive or greenhouse gases, environmental friendliness, and the possibility for recycling the caloric materials. However, the development of the different caloric technologies is very unequal. Historically, the magnetocaloric effect was the first one to be observed and studied. Consequently, the magnetocaloric technology is the most mature. In recent years, however, elastocaloric systems have seen a rapid increase in activity among the scientific community, while the electrocaloric and barocaloric technologies are still in their infancy.

2.1 Magnetocaloric heat pumps

The history of magnetocaloric technology starts in 1918 when Weiss and Piccard discovered the magnetocaloric effect. In 1976, Brown demonstrated that gadolinium (Gd) could be used for room-temperature magnetocaloric heat pumps (MCHP) and since then Gd has been the reference material for magnetocaloric applications at room temperature. A major breakthrough came in 1982 when Barclay and Steyert patented the active magnetic regenerator cycle (magnetocaloric version of the caloric Brayton active regenerative cycle presented in **Fig. 1** and **Fig. 2**). This operation design is one of the most thermodynamically efficient for MCHPs. It allowed a tremendous improvement of the energy efficiency and useful temperature of magnetocaloric systems. It has therefore been the founding principle of most following MCHPs, but also for HPs based on other caloric effects [5, 15]. From that point, magnetic heating/cooling technology gained popularity and several research groups built their prototypes. A large variety of design and engineering options have been tested to improve the overall COP, cooling/heating power and temperature span between the heat source and sink. Notable design explorations were: assembly of permanent magnets, superconducting magnets, oscillatory translating regenerator or magnet, rotating magnets or rotating regenerators, vertical or horizontal rotation. Currently, the most advanced prototypes are now rotary systems with a permanent magnet assembly rotor and a fixed regenerator (see **Fig. 3**). Static regenerators simplify the implementation and operation of the fluid distribution system (valves) [15, 16].

In the last 30 years, around 100 different prototypes have been tested and reported [16, 18]. Over the years, the performance of these MCHPs has been slowly rising with a tradeoff between COP (usually ranging from 0.1 to 4), temperature span (usually ranging from 0 to 25 K) and useful heating/cooling power (usually ranging from 10 W to 2000 W) [15, 18]. An extensive review of the different MCHP prototypes was made by Greco et al. [18].

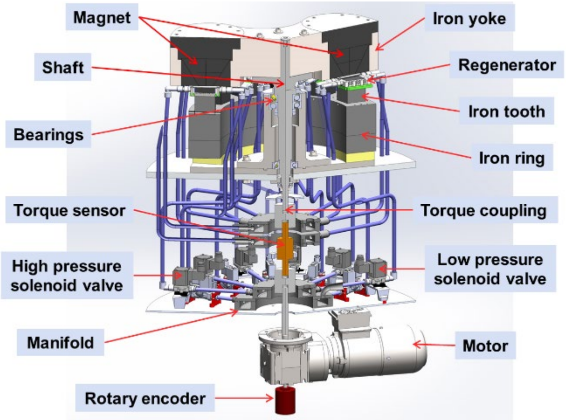


Fig. 3 – View cut of the rotary MCHP prototype “MagQueen” [15].

As aforementioned, magnetocaloric technology is the most mature of all caloric-based systems. Current MCHP prototypes can now operate near commercially relevant cooling loads and temperature spans with appreciable COPs. For instance, one of the latest MCHP studies by Dall'Olio et al. has reported impressive performances with a heating power of 340 W over a 10.3 K temperature span with a COP of 6.7, and heating power of 950 W over a 5.6 K temperature span with a COP of 7 [16]. In 2022, Masche et al. have reported heating power of 265 W over a 14.8 K temperature span with a COP of 3.97, and a heating power of 445 W over a 7.3 K temperature span with a COP of 15.9 [17]. The best MCHPs are therefore suitable for low-temperature lift cooling/heating applications in low-energy dwellings [11]. This is being explored in the H2020 project RES4BUILD [res4build.eu] Numerical studies also indicate that higher temperature lift for DHW production can be achieved by cascading magnetocaloric regenerators in series [19].

2.2 Elastocaloric heat pumps

One of the main cost limitations of MCHPs is the rare-earth-based magnet material creating the magnetic field. In recent years, some researchers working on MCHPs are thus also developing new HPs exploiting the other caloric effects. Among them, the elastocaloric effect is particularly encouraging as certain non-rare earth materials (e.g., Ni-Ti-, Cu- and Fe-based superelastic shape-memory alloys with austenitic–martensitic phase transformation; shape-memory polymers) present an elastocaloric adiabatic temperature change that is significantly larger (10-25 K) than that of the magnetocaloric effects reachable with permanent magnets (0.5-4 K). In 2014, the U.S. Dept. of Energy actually designated the elastocaloric heat pump (ElastHP) as the most promising alternative to VCHPs [3]. However, the first demonstrator of this emergent technology was only presented in 2012 [18]. The design of the first ElastHPs was largely influenced by the work on MCHPs. The refrigerant (usually in the form of thin plates, tubes or wires) is alternatively loaded (stretched) and deloaded (unstretched) inducing a large adiabatic temperature increase and decrease, respectively, to generate a regenerative elastocaloric Brayton cycle (see **Fig. 1** and **Fig. 2**).

The heat transfer from the elastocaloric refrigerant to the heat source and sink can be performed in different ways: by convection with an oscillatory by-directional flow of water-based brine (similar to MCHPs) or air, displacement of the refrigerant from a cold air stream (heat source) to a warmer air stream (heat sink), or solid-to-solid direct contact heat transfer by displacement of the refrigerant to be alternatively touching the solid heat source and heat sink. The main actuator (driver) solutions to load and deload the elastocaloric material are as follows: hydraulic, pneumatic, piezo or magnetostriction linear actuators, or rotary system with a cam track and a cam follower. One notable rotary ElastHP prototype for direct active heat recovery and extraction in a ventilation system has been developed by Kirsch et al. [20]. It shows promising simulation results with a COP of 9.5 for a 250 W thermal power over a 10 K temperature span.

The very large temperature response of elastocaloric materials allows to significantly increase the coolant mass flow rate through the regenerator without destroying the internal temperature gradient, which is not the case for MCHPs. In addition, it is possible to recover part of the loading mechanical work by coupling regenerators two by two (one is loading while the other one is unloading). A flywheel could also be a solution to retrieve, store and re-inject the kinetic energy of the unloading process. The temperature span of ElastHPs can also be improved by cascading several regenerators in series.

The first results show that ElastHP has the potential to outperform MCHPs in terms of temperature span, COP and costs. Elastocaloric devices can be much more compact than MCHPs. For the same thermal power output, it can require up to 20-times less mass than for MCHP. This opens the possibility for high-COP miniaturized cooling devices. However, this technology is at the beginning of its R&D phase and far from commercialisation. The current ElastHPs are restricted to very small-size prototypes with limited heating/cooling power below 100 W. Moreover, the ElastHP technology faces a few challenges: the durability/fatigue lifetime and functional stability/reliability of the elastocaloric materials over millions of cyclical loading, and the implementation of efficient actuators able to deliver large forces needed to induce the elastocarolic effect. A detailed review of the different ElastHP prototypes and their operation can be found in Greco et al., 2019 [18] and Kabirifar et al., 2019 [8].

2.3 Electrocaloric heat pumps

The electrocaloric technology is in its infancy and some way from any commercial applications. It is only very recently that the first few electrocaloric heat pump (ElecHP) proof of concepts were developed. The electrocaloric effect was discovered in 1930 by Kobeko & Kurtschatov. However, it was only in 1979 that the first ElecHP was developed. The electrocaloric effect is very analogous to the magnetocaloric one. The development of the latter thus largely influenced the design of ElecHPs. In 1989, Sinyavsky et al. created the first implementation of an active regenerative electrocaloric Brayton cycle (see **Fig. 1** and **Fig. 2**). The use of thermal diodes is also a possible ElecHP alternative to the active electrocaloric regenerator configuration. Until now, only about 20 small-scale ElecHP prototypes have been built and reported. They all produce very small heating/cooling power outputs with a temperature lift below 10 K.

The electrocaloric materials suitable for ElecHPs are usually dielectric Pb-based PZT or PST ceramics, or ferroelectric polymers. When implemented as thin polymer film or thin ceramic film regenerators (instead of bulk elements) it is possible to generate a high electric field with relatively low voltages and induce an appreciable electrocaloric temperature response. Compared to the magnetocaloric ones, these electrocaloric refrigerants could be cheaper and can operate over a much broader temperature range. However, the electrocaloric regenerator can be a complex assembly, which drives the manufacturing costs up.

The ElecHP does not require any moving elements apart from the pumping system of the coolant fluid, which is a great asset compared to other caloric systems and VCHPs. It is also possible to add an energy recovery system to lower the energy use for refrigerant polarisation. This solution can recover 65% of the work. Similarly to ElastHPs, electrocaloric technology has a great potential for miniaturized cooling solutions with minimum moving parts and no need for auxiliary coolant fluid.

Recent encouraging experimental results should be emphasized: In 2017, Ma et al. [21] made a miniature ElecHP with electrostatic actuation to rapidly oscillate a flexible electrocaloric polymer thin film that alternatively gets in direct contact with the heat source and sink. The prototype produces 0.64 W of cooling power for a 1.4 K temperature span with a COP of 13. In 2020, this prototype was cascaded in 4 layers by Meng et al. This cascade ElecHP also has a charge recovery circuit and can reach 8.7 K temperature with no load, or a 0.785 W cooling power for a 2.7 K temperature span with a COP of 9. A comprehensive review of the ElecHP technology and prototypes can be found in Torelló & Defay, 2022 [9], Greco et al., 2019 [18] and Greco & Masselli, 2020 [22].

2.4 Barocaloric heat pumps

The R&D of barocaloric technology is at an embryonic stage [18]. There is currently no reported experimental results of any functional barocaloric heat pump (BCHP) prototypes. One can only find some design ideas of BCHPs operating with an active barocaloric regenerative Brayton cycle (see **Fig. 1** and **Fig. 2**) and a handful of numerical simulation-based performance studies for BCHPs. The scientific literature mostly comprises characterizations of barocaloric effect in materials such as elastomers (e.g., natural rubber), plastic crystals (Neopentyl glycol), shape-memory alloys and other materials already presenting caloric effects (especially magnetocaloric and elastocaloric materials). Because of this last point, barocaloric technology has a good potential to be employed in multicaloric systems, e.g., barocarolic-assisted magnetocaloric heat pumps. Although the barocaloric effect can be observed in a wide range of materials, its practical applicability has yet to be proven.

3. Performances overview of caloric heat pumps

This section gives a performance overview of the different caloric heat pump systems and put them in perspective with that of conventional VCHPs for building applications. This overview is built upon experimental and numerical data collected from around 140 scientific publications. Because of space limitation in this paper, all references from which the data has been collected and additional performance overview figures can be found in a dedicated technical report (https://vbn.aau.dk/en/publications/performance-overview-of-caloric-heat-pumps-magnetocaloric-elastoc) [23]. Numerical and experimental data for MCHPs is relatively abundant. Such data also exists for ElastHPs, although much more scarce and recent (less than 10 years old). For ElecHPs, there is very little performance experimental data. The achieved temperature span is reported but the COP is rarely documented. Concerning BCHPs, only a handful of simulation-based studies could be found.

One can see in **Fig. 4** that VCHPs typically have a Carnot efficiency between 40% and 60% for temperature spans compatible with building applications. The performances of most caloric HP prototypes are modest in comparison: often below 20% Carnot efficiency and with a maximum temperature span of 30 K. However, for temperature lifts around 20-25 K (minimum limit for low-temperature space heating with high-temperature heat sources such as ground source boreholes), the best MCHP prototypes have a COP that is similar or higher than VCHPs. Simulation data suggests that MCHPs could maintain a 60% Carnot efficiency for higher temperature spans of 50-60 K. All data points for ElastHPs are below the 30 K temperature lift. The best ElastHP prototypes have a Carnot efficiency of around 20%. 2 ElastHP prototypes reach around 40% Carnot efficiency for temperature lifts of 10-16 K. The maximum temperature span that has been reported for an ElecHP prototype is 8.7 K with a very small heating/cooling power. The best ElectHP

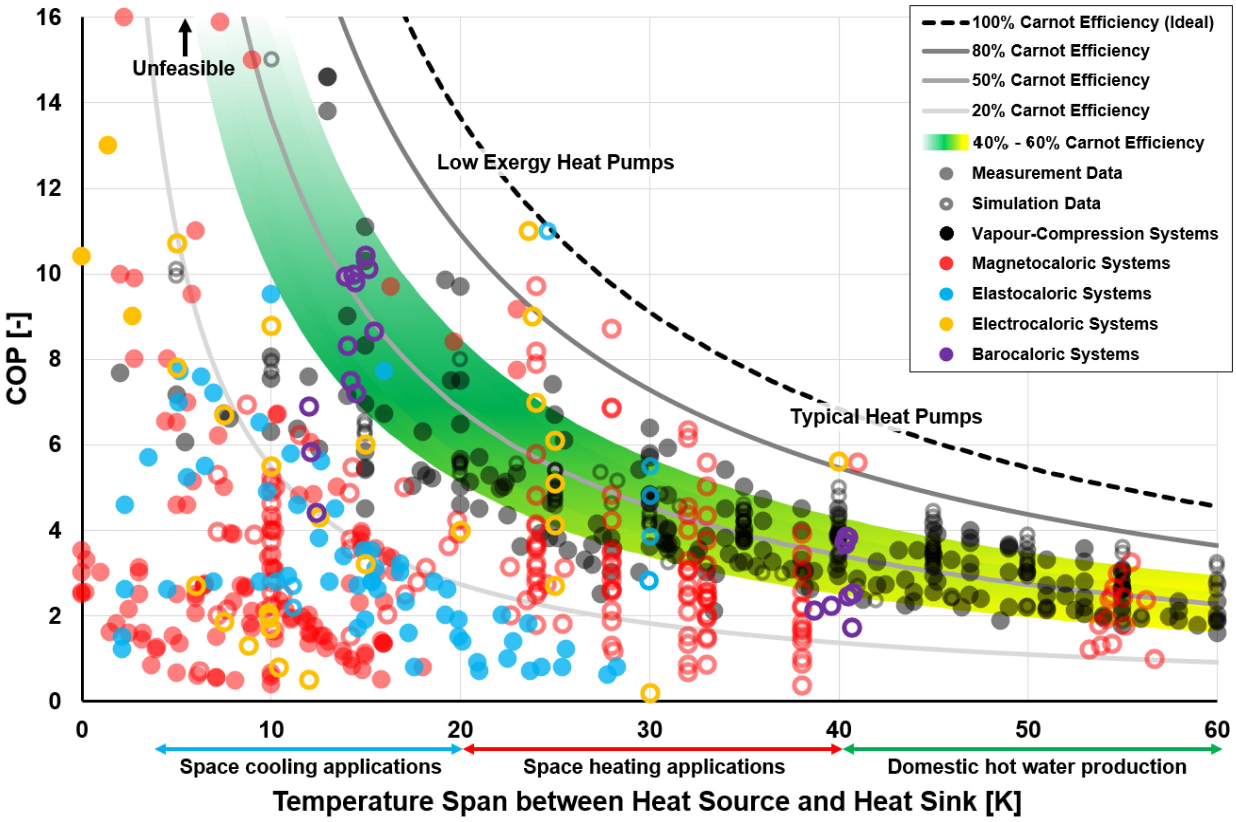


Fig. 4 – Performance overview of different heat pump systems: COP as a function of temperature span.

prototypes show promising COPs of 9-14 but for temperature lifts and effective power that insufficient for building applications. However, theoretical data suggests that an adequate temperature span for space heating and cooling can be reached with ElecHPs. Finally, there is no available experimental data for BCHPs, but simulation data suggests that such technology could sustain a 40-60% Carnot efficiency for temperature lifts up to 40 K.

One can see in **Fig. 5** and **Fig. 6** that, currently, only MCHP prototypes can reach a heating/cooling power output that is sufficient for building applications. Apart from 1 device, all existing ElastHP and ElecHP prototypes are limited to power output lower than 10 W. However, simulation studies indicate a good potential for a significant increase of the heating/cooling power output and temperature span with appreciable COP. It should, however, be noted, that modelling studies often neglect some of the system losses, leading to more optimistic performance predictions.

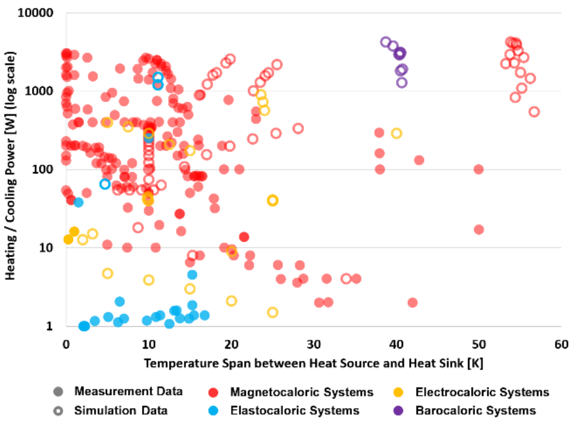


Fig. 5 – Performance of caloric HPs: heating/cooling power as a function of temperature span.

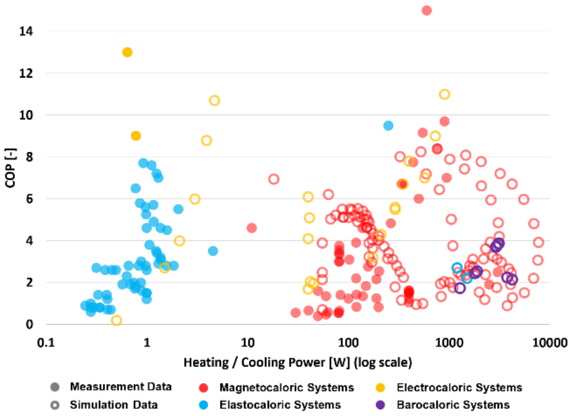


Fig. 6 – Performance of caloric HPs: COP as a function of heating/cooling power.

4. Conclusions and perspectives on the future of caloric heat pumps

Solid-state caloric refrigeration and HP technologies have made a tremendous leap forward in the last decade, and the first large-scale implementations show technical performances that are similar or superior to conventional VCHPs. The research on caloric systems has produced nice pieces of engineering with very promising capacities. However, caloric HPs have yet to prove their cost competitiveness and sustainability superiority against the mature vapour-compression systems.

At the moment, only magnetocaloric systems (the most mature caloric technology) have been experimentally proven suitable for high-COP low-temperature space heating and cooling in buildings. Elastocaloric and electrocaloric systems are still at an early R&D stage: their COPs are very promising but their power output and temperature span are rather limited for now. Since no working barocaloric HP system has been built until now, this emergent caloric technology has yet to demonstrate its feasibility and practical usefulness. However, simulation and theoretical studies tend to show that all 4 caloric effects presented in this paper could be employed for energy-efficient space heating, cooling and DHW production in buildings, and compete with conventional VCHPs because of potential lower vibration and noise level operation, compactness, efficient part-load control, no use of toxic, flammable, explosive, ozone-destructive or greenhouse gases, and better overall sustainability and environmental impact.

The expansion of caloric HPs faces a number of challenges that researchers endeavour to tackle. The main one probably resides in the development of caloric materials with larger adiabatic temperature changes and long-term durability. The creation of non-Pb electrocaloric materials (for health consideration) and non-rare-earth caloric materials (especially for magnetocaloric systems) is crucial. The durability issue is particularly problematic for elastocaloric and electrocaloric materials that are subjected to large electrical voltages and high stretching strains in HP devices. Good caloric refrigerants should keep stable caloric properties and structural integrity when exposed to coolant fluid for a long time. They should withstand the long term fatigue induced by hundreds of millions of (de)magnetization/(un)stretching/(de)polarization /(de)compression cycles. Currently, there is a lack of study on the long-term durability of caloric materials and the impact of hysteresis in caloric refrigerants. Moreover, new manufacturing processes have to be invented to inexpensively fabricate and shape these caloric materials into useable forms for regenerators (spheres, wires, foils, plates, etc) without degrading mechanical stability or weakening the strength of the external field applied to the caloric refrigerant.

The performance of active regenerators should be improved by decreasing the pumping pressure losses and enhancing heat transfer between the refrigerant and the auxiliary heat transfer fluid. Tuning the Curie temperature of caloric materials for optimum layered active regenerators can also improve performance. The use of nanofluids as a coolant in caloric regenerators should be explored further. For elastocaloric regenerators, different geometries (plates with various shapes, wires, tubes, cascaded tube bundles, foams, thin films) should be tested with different loading techniques (tension, compression, bending or twisting). For MCHPs, new and affordable permanent magnet assembly with optimum magnetic field distribution in the regenerator and minimum eddy current and counter-torque should be developed. Joule heating effect should be curtailed electrocaloric refrigerant. To increase the caloric systems' capacity, the fluid flow rate through the regenerator should be increased while maintaining a high heat transfer efficiency (NTU) and a stable temperature gradient inside the regenerator. Parasitic heat losses in regenerators and hydraulic systems should be minimized. Caloric systems are often implemented with auxiliary systems (motors, valves, pipes and pumps) that have been designed for other purposes but have not necessarily the most optimum specifications for caloric HPs. Customized hydraulic elements might be necessary to achieve accurate coolant flow control.

The synergy of coupling multiple caloric effects within the same system should be explored further and implemented in a prototype. Finally, cascading regenerators in series is probably the most promising solution to increase the temperature span of all caloric systems.

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