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by

Hicham Johra

January 2022

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1. Foreword

The aim of this technical report is to give an overview of the performance of different heating and cooling caloric systems: magnetocaloric, elastocaloric, electrocaloric and barocaloric heat pumps. The performance of these innovative caloric heat pump systems is compared with that of conventional vapour-compression heat pumps. This overview is built upon experimental and numerical data collected from 140 scientific publications. This technical report serves as supplementary materials for the article “Innovative heating and cooling systems based on caloric effects: A review” presented at the CLIMA 2022 conference (REHVA 14th HVAC World Congress. 22-25 May 2022, Rotterdam, The Netherlands) [1].

2. Abstract

Heat pumps are an excellent solution to supply heating and cooling for indoor space conditioning and domestic hot water production. Conventional heat pumps 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 heat pump 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 heat pumps can have a 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 heat pump 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 large attention. These caloric effects are characterized by a phase transition varying entropy in the material, resulting in a large adiabatic temperature change. This phase transition is induced by a variation of a specific external field applied to the solid refrigerant. Therefore, the magnetocaloric, elastocaloric, electrocaloric and barocaloric effects are adiabatic temperature changes in specific materials when varying the magnetic field, uniaxial mechanical stress, electrical field or hydrostatic pressure, respectively. Heat pump cycle can be built from these caloric effects and several heating/cooling prototypes were developed and tested over the last few decades. Although not a mature technology yet, some of these caloric systems are well suited to become new efficient and sustainable solutions for indoor space conditioning and domestic hot water production. This technical report (and the paper to which this report is supplementary materials) 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 heat pumps for building applications.

3. Scientific publications on caloric effects and caloric systems over time

One can see in *Figure 1* the evolution of the number of new scientific publications (scientific papers in peer-reviewed journals, conference proceedings, books and theses: search in titles, abstract and keywords with "Magnetocaloric", "Elastocaloric", "Electrocaloric" and "Barocaloric" as search keywords) as a function of time. One can observe that the topic of magnetocaloric systems and materials took off after the years 2000s while the topics on elastocaloric, electocaloric and barocaloric systems and materials is only slowly gaining popularity since the years 2010s. However, the magnetocaloric topic seems to plateau since 2015.

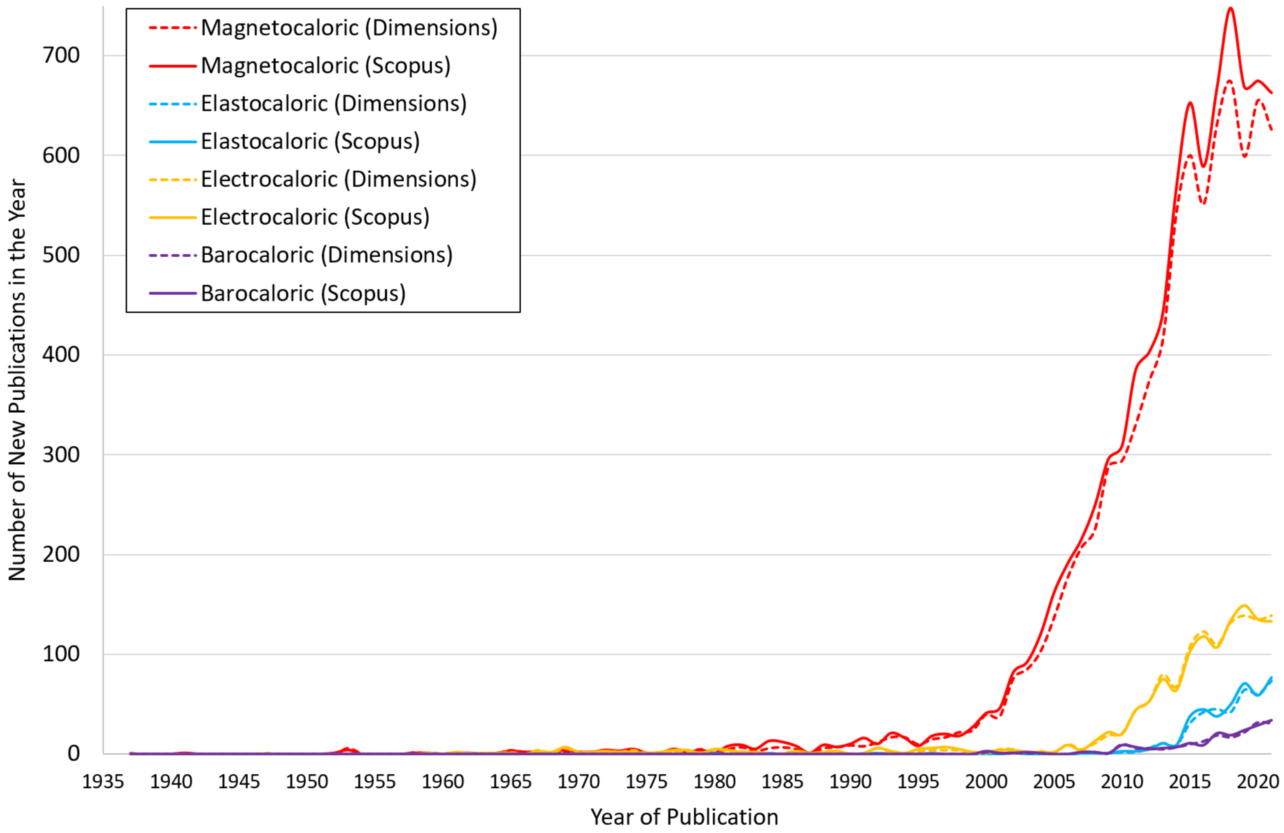


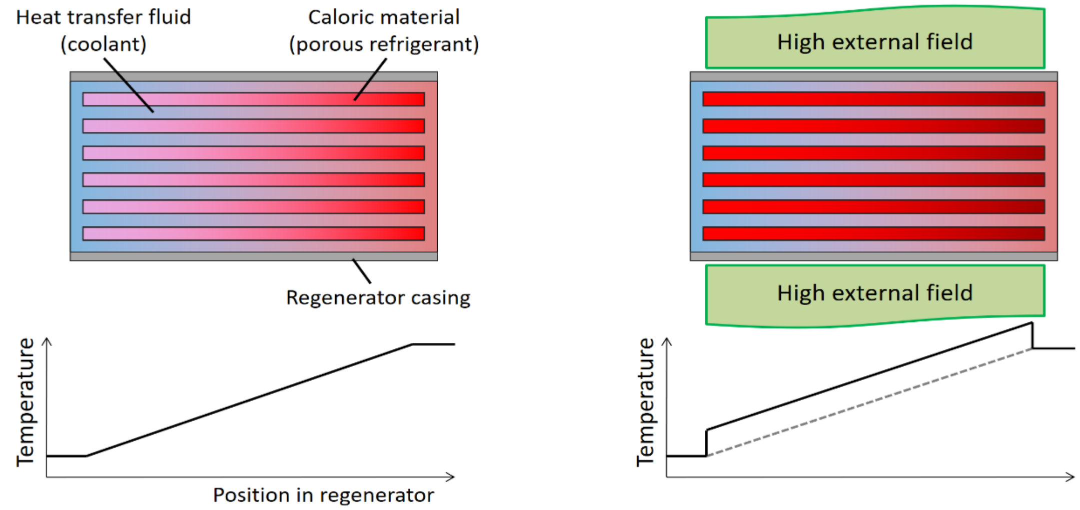
Figure 1: *Number of new scientific publications per year as a function of the year of publication for the keywords "Magnetocaloric", "Elastocaloric", "Electrocaloric" and "Barocaloric" in the Scopus and Dimensions databases.*

4. Operation principle of the caloric heating and cooling systems

The caloric effect is large entropy and adiabatic temperature variations generated 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. Conversely, when the external field in the material is reduced, the entropy increases and its temperature decreases. There are 4 main caloric effects:

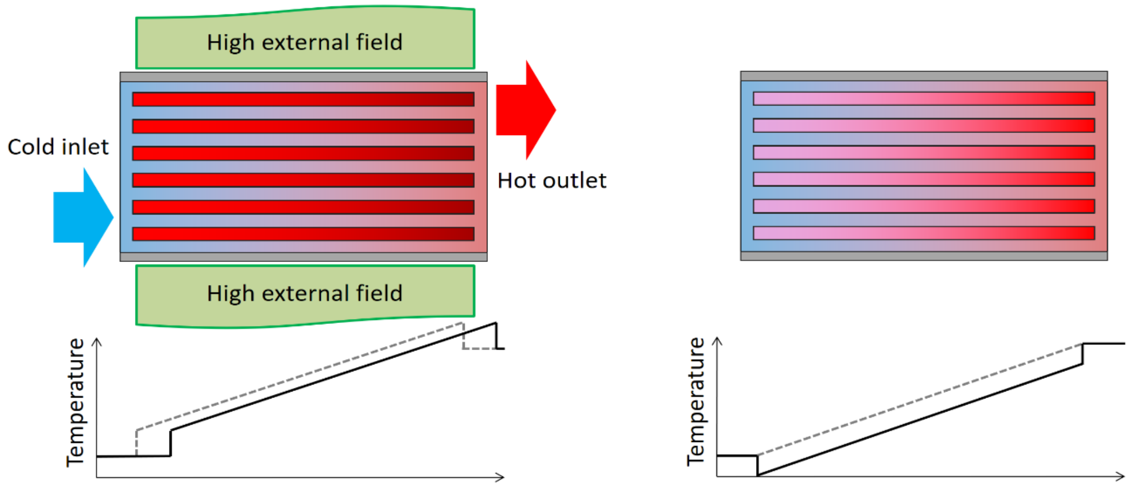
- Magnetocaloric effect: Adiabatic temperature change induced by a variation of the magnetic field (magnetization/demagnetization).
- Elastocaloric effect (a.k.a. thermoelastic): Adiabatic temperature change induced by a variation of the uniaxial mechanical stress (stretching/squeezing).
- Electrocaloric 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).

These caloric effects can be used to create a heat pump cooling/heating thermodynamic cycle. 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 heat-carrier 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 [2]. *Figure 2* details the 4processes that form the active caloric regenerative thermodynamic cycle of a caloric heat pump. *Figure 2* (a): The regenerator has an initial temperature gradient over its length and zero external field is applied to the caloric material. *Figure 2* (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. *Figure 2* (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. *Figure 2* (d): The external field is removed (e.g., demagnetization, squeezing, depolarization or decompression) leading to a temperature decrease over the length of the regenerator. *Figure 2* (e): 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). *Figure 2* (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 [2].



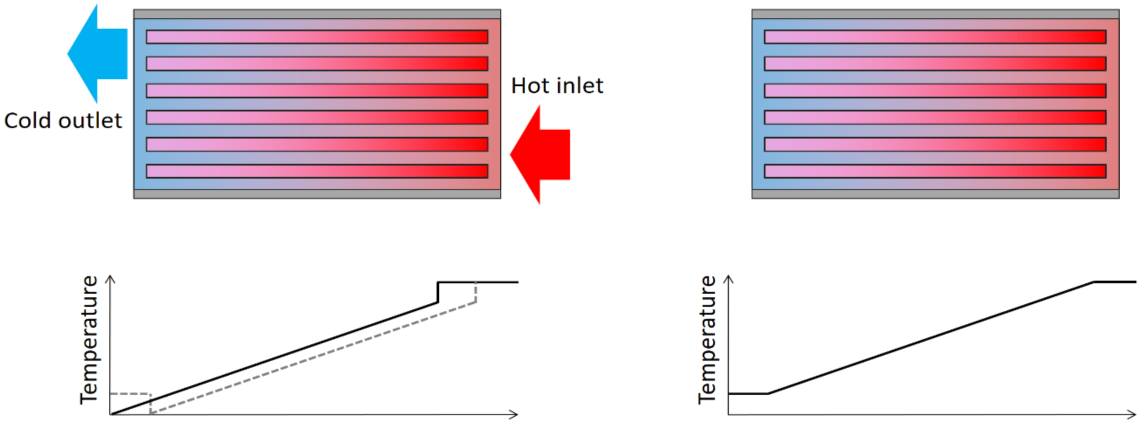
(a) Initial state with temperature gradient

(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

Figure 2: *The different phases of the active caloric regenerative cycle for the operation of a generic caloric heat pump system (adapted from [2]).*

5. Performances overview of caloric heating and cooling systems

Figure 3 and *Figure 4* give an overview of the COP of caloric heating/cooling systems as a function of their temperature span (temperature lift between the heat source and the heat sink). The performance of magnetocaloric, elastocaloric, electrocaloric and barocaloric heat pumps is put in perspectives with that of conventional vapour-compression heat pumps. One can observe that conventional vapour-compression heat pumps typically have a Carnot efficiency between 40% and 60% for temperature spans compatible with building applications. Current caloric heat pump prototypes typically have a maximum Carnot efficiency around 20%, however, some recent prototypes have much better performance with COPs comparable or higher than conventional vapour-compression heat pumps. Simulation results suggest that caloric systems could also be employed for higher temperature lift (necessary for domestic hot water production and high-temperature heating systems) with very good COPs.

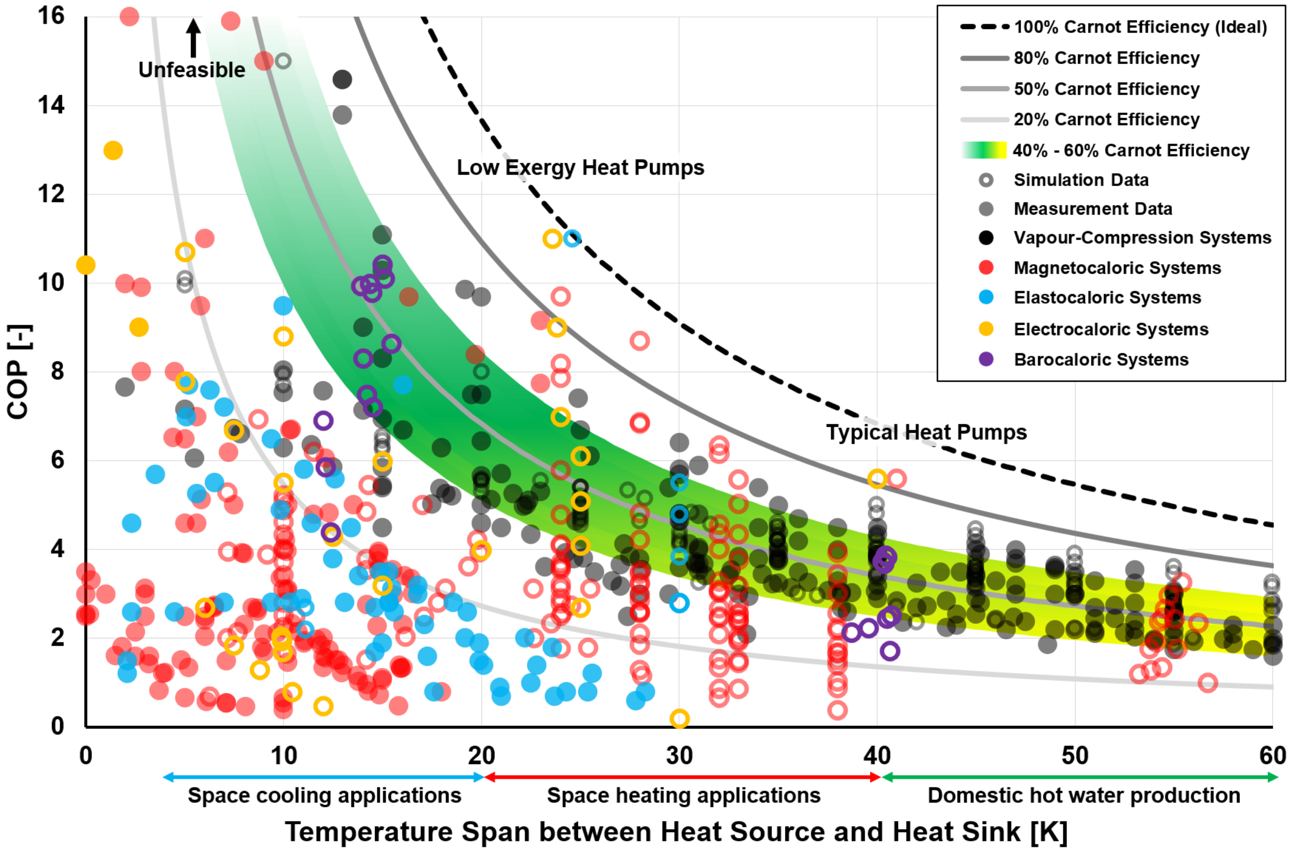


Figure 3: *Performance overview of different heat pump systems: COP as a function of temperature span for magnetocaloric, elastocaloric, electrocaloric, barocaloric and conventional vapour-compression heat pumps (simulation and measurement data).*

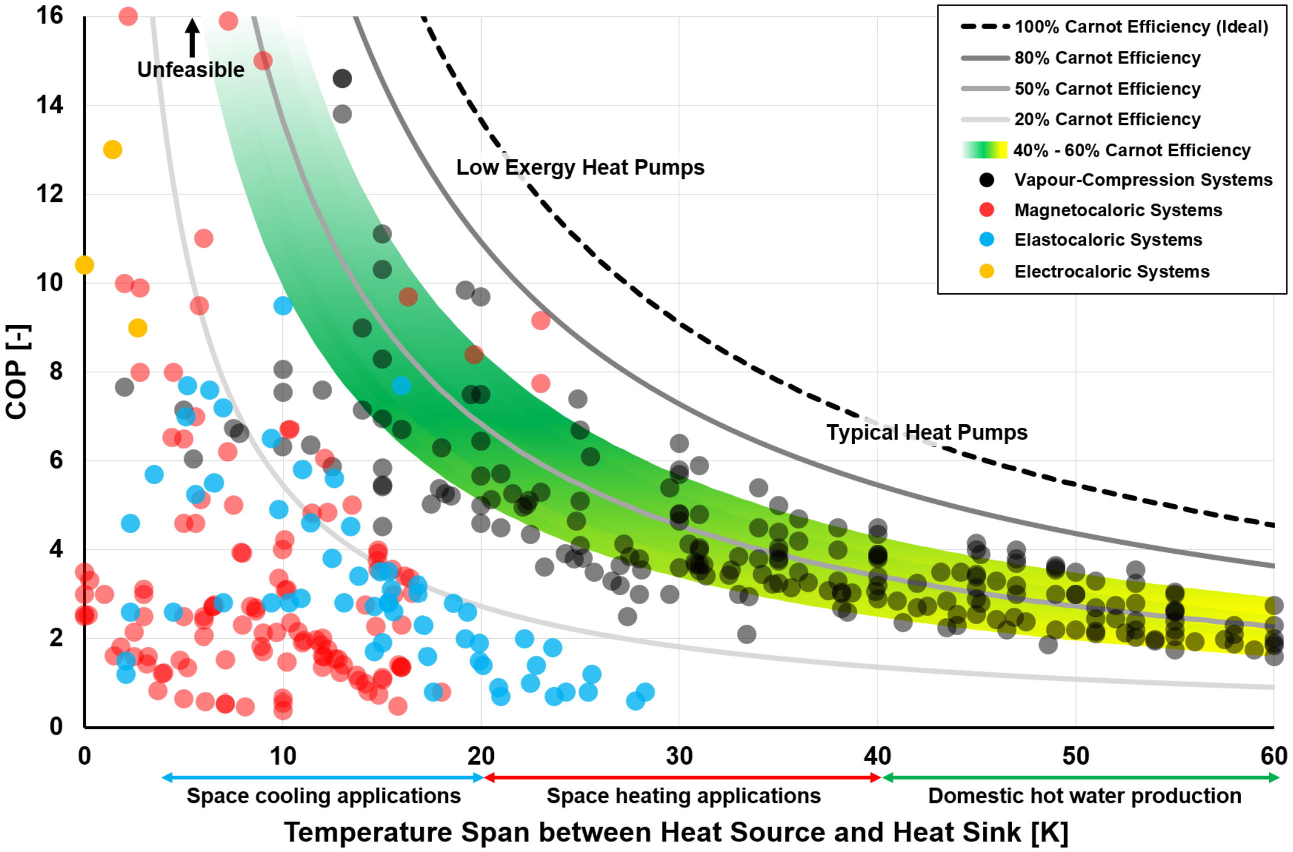


Figure 4: *Performance overview of different heat pump systems: COP as a function of temperature span for magnetocaloric, elastocaloric, electrocaloric, and conventional vapour-compression heat pumps (measurement data only).*

Figure 5 and *Figure 6* give an overview of the heating/cooling power output of caloric heat pump systems as a function of their temperature span. One can observe that, currently, apart from one elastocaloric device, only magnetocaloric prototypes can reach a heating/cooling power output coupled to a temperature span that is sufficient for building applications. Apart from one device, all existing elastocaloric and electrocaloric prototypes are limited to a power output lower than 10 W. However, simulation studies indicate a possibility for significant increase of the heating/cooling power output and temperature span of all caloric systems.

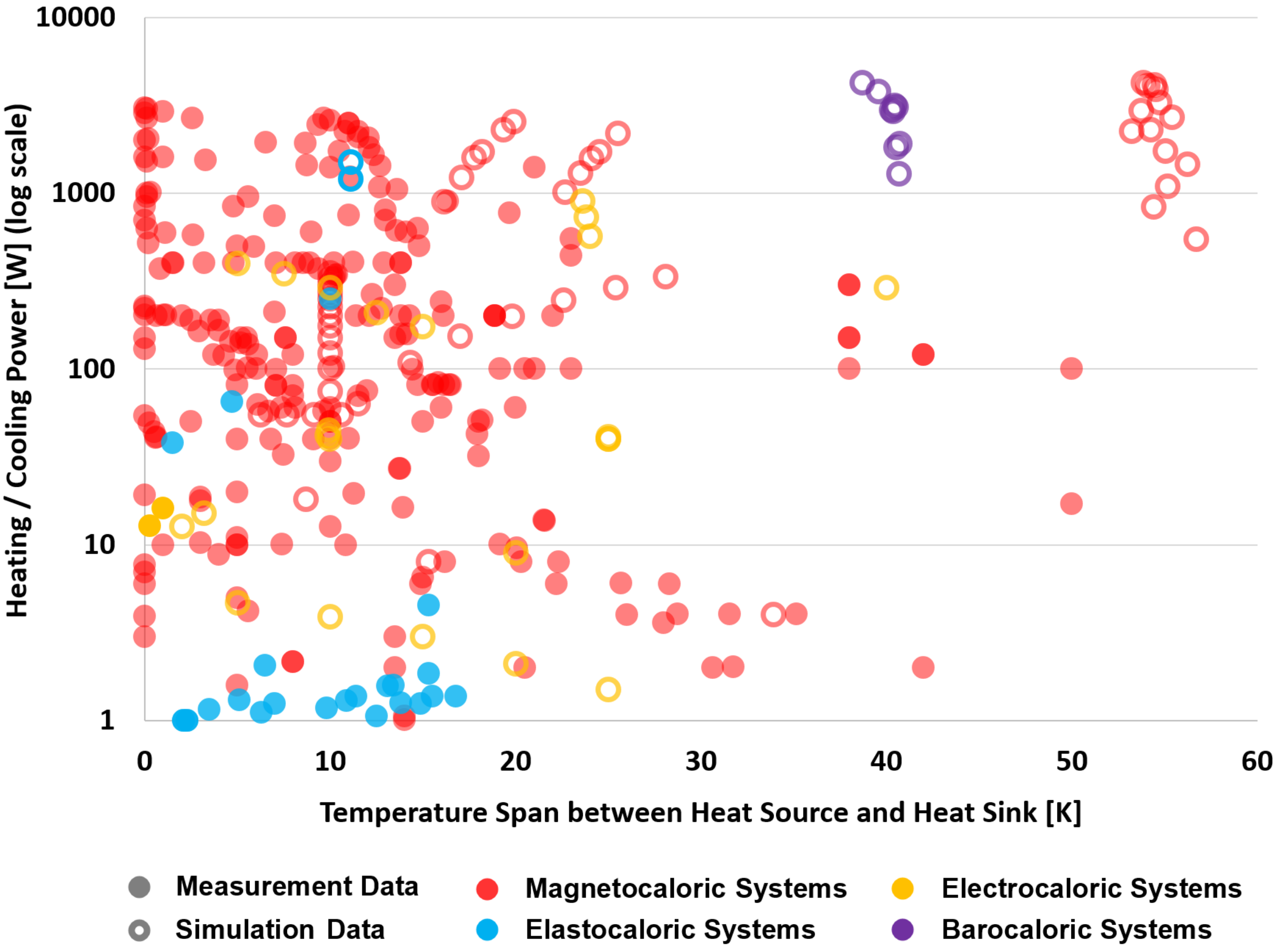


Figure 5: *Performance overview of different caloric heat pump systems: heating/cooling power output as a function of temperature span for magnetocaloric, elastocaloric, electrocaloric, and barocaloric heat pumps (simulation and measurement data).*

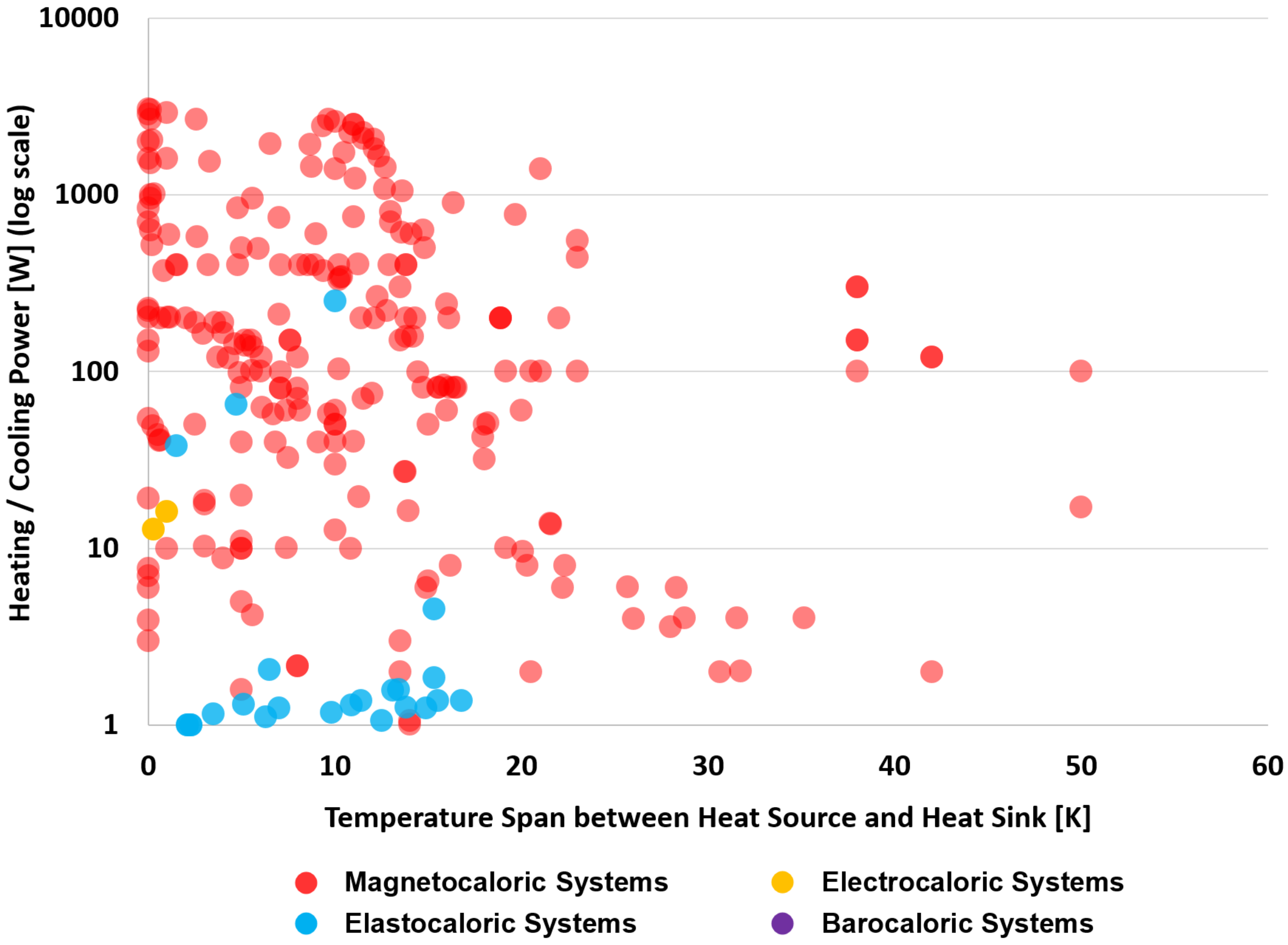


Figure 6: *Performance overview of different caloric heat pump systems: heating/cooling power output as a function of temperature span for magnetocaloric, elastocaloric and electrocaloric heat pumps (measurement data only).*

Figure 7 and *Figure 8* give an overview of COP of caloric heat pump systems as a function of their heating/cooling power output. One can observe that, currently, apart from one elastocaloric device, only magnetocaloric prototypes can reach a heating/cooling power output with an appreciable COP that is sufficient for building applications. Apart from one device, all existing elastocaloric and electrocaloric prototypes are limited to a power output lower than 10 W. However, the latter prototypes present very promising COPs. Nevertheless, simulation studies indicate a possibility for significant increase of the heating/cooling power output of all caloric systems while maintaining very high COPs.

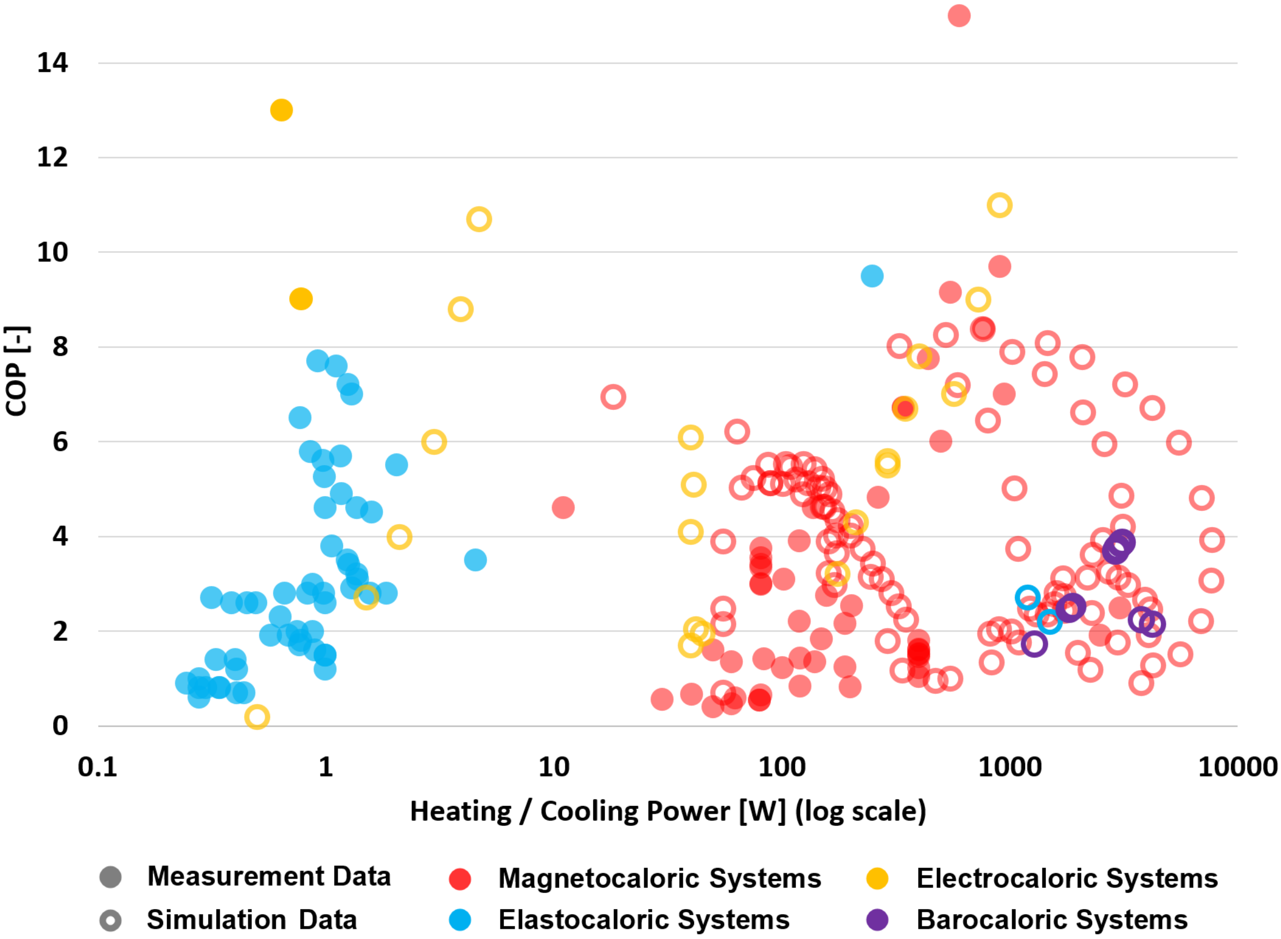


Figure 7: *Performance overview of different caloric heat pump systems: COP as a function of heating/cooling power output for magnetocaloric, elastocaloric, electrocaloric, and barocaloric heat pumps (simulation and measurement data).*

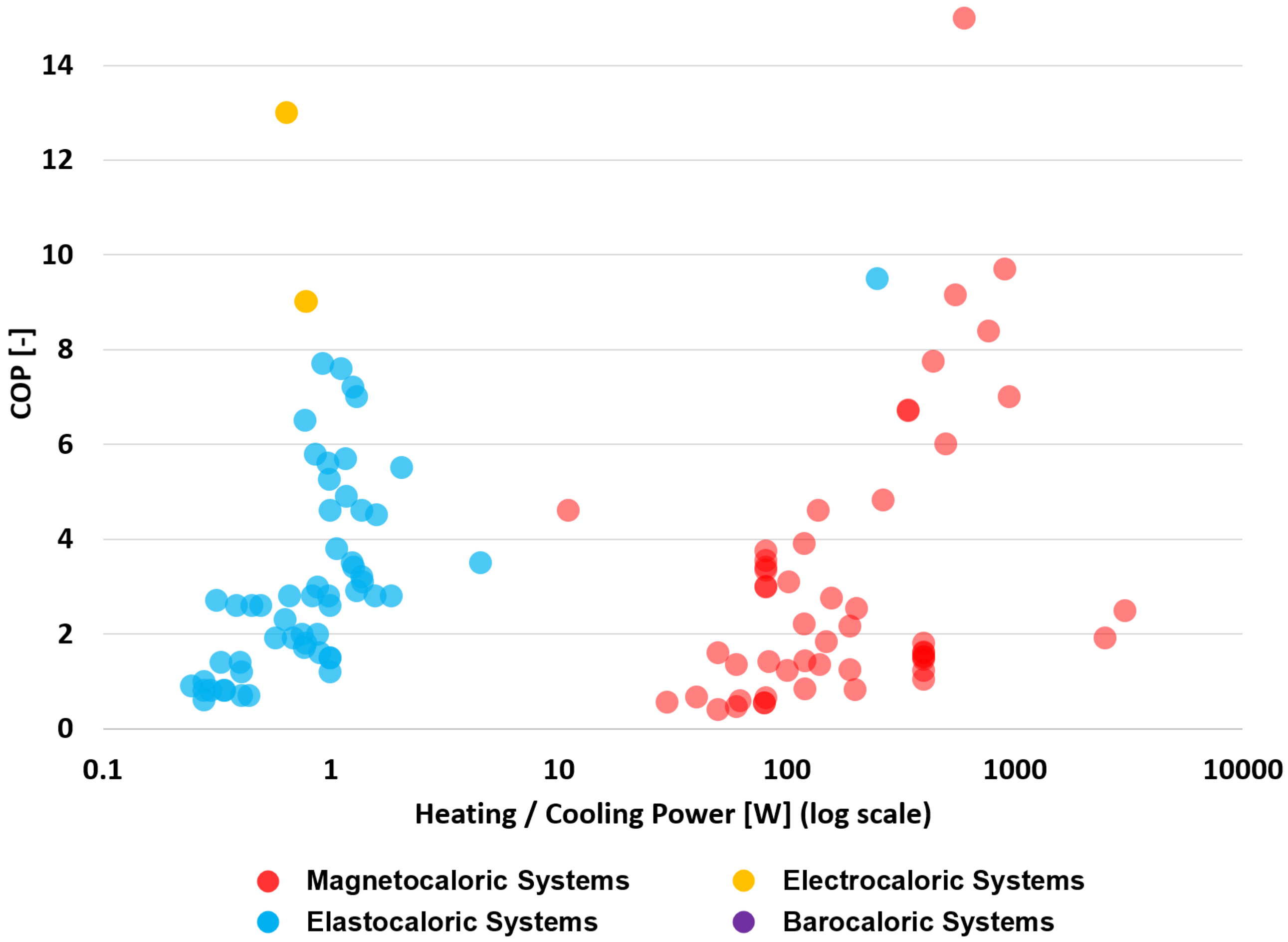


Figure 8: *Performance overview of different caloric heat pump systems: COP as a function of heating/cooling power output for magnetocaloric, elastocaloric and electrocaloric heat pumps (measurement data only).*

6. Historical evolution of the performances of caloric heating and cooling system prototypes

Figure 9, *Figure 10* and *Figure 11* give an overview of the historical evolution of the temperature span, COP and heating/cooling power output achieved by the different magnetocaloric, elastocaloric and electrocaloric heat pump prototypes over the years. It should be noted that some of the early magnetocaloric heat pump prototypes with very large COPs and temperature spans are using superconductor magnets. It is only within the last 10 years that magnetocaloric heat pump prototypes with permanent magnet assemblies have reached heating/cooling power outputs with significant temperature spans and appreciable COPs that are suitable for building applications.

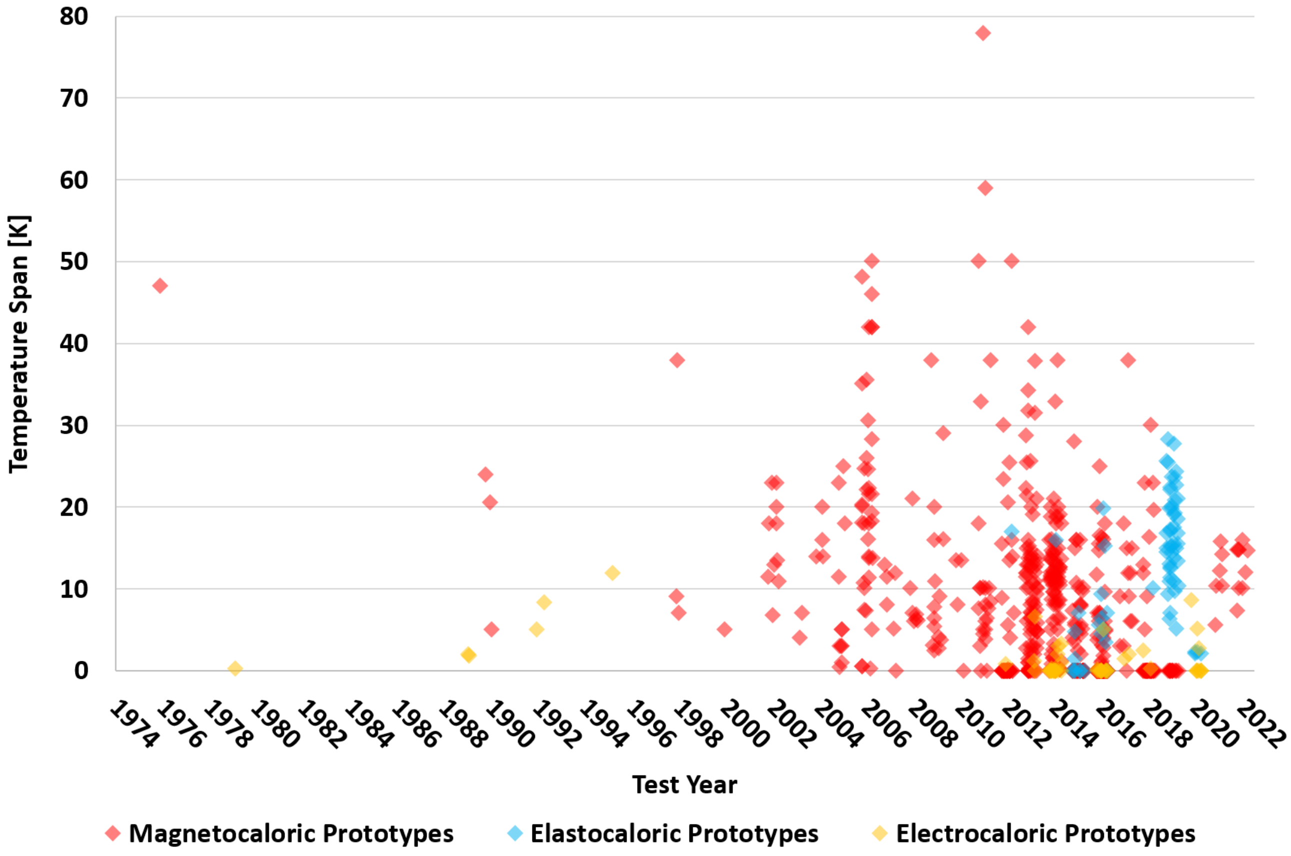


Figure 9: *Evolution of the temperature span (temperature lift between heat source and heat sink) achieved by the different magnetocaloric, elastocaloric and electrocaloric heat pump prototypes over the years.*

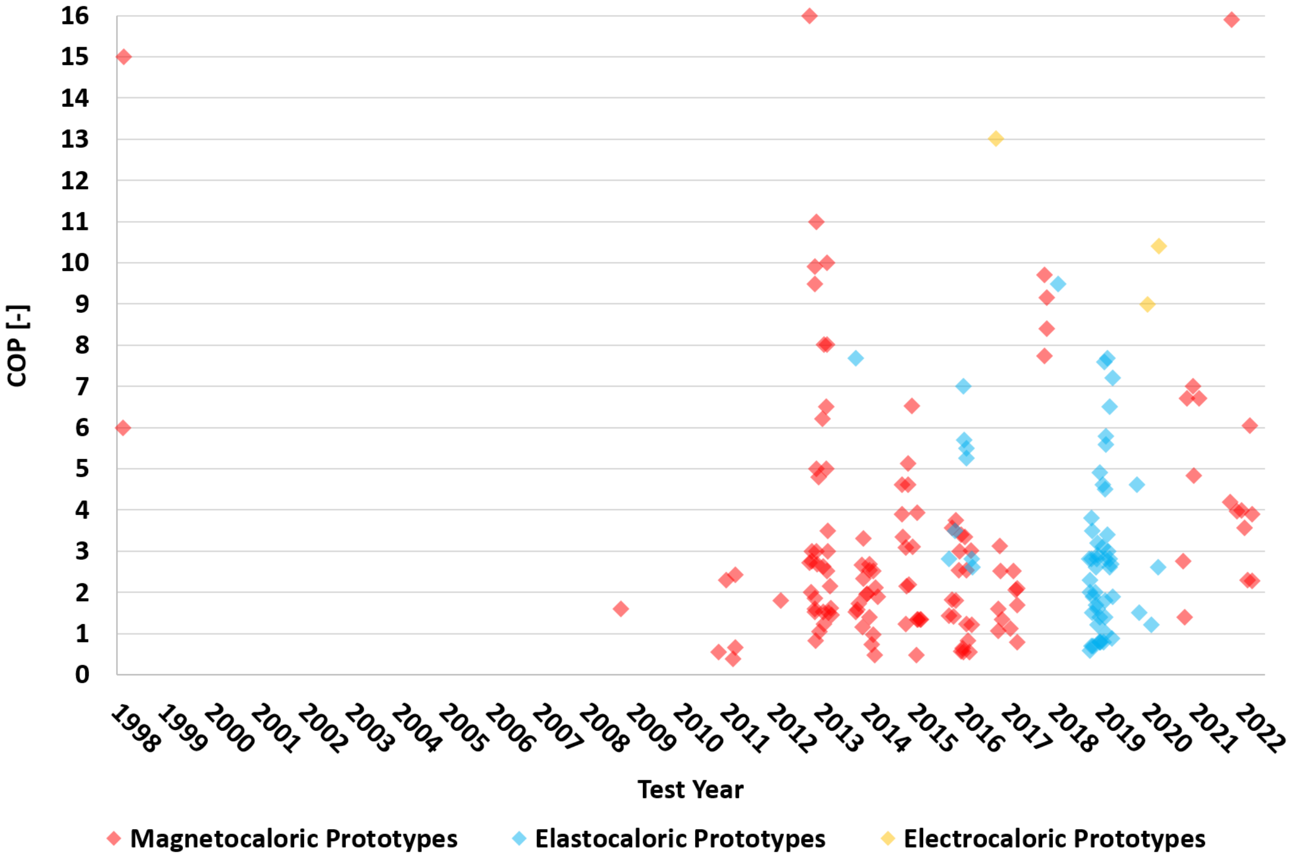


Figure 10: *Evolution of the COP achieved by the different magnetocaloric, elastocaloric and electrocaloric heat pump prototypes over the years.*

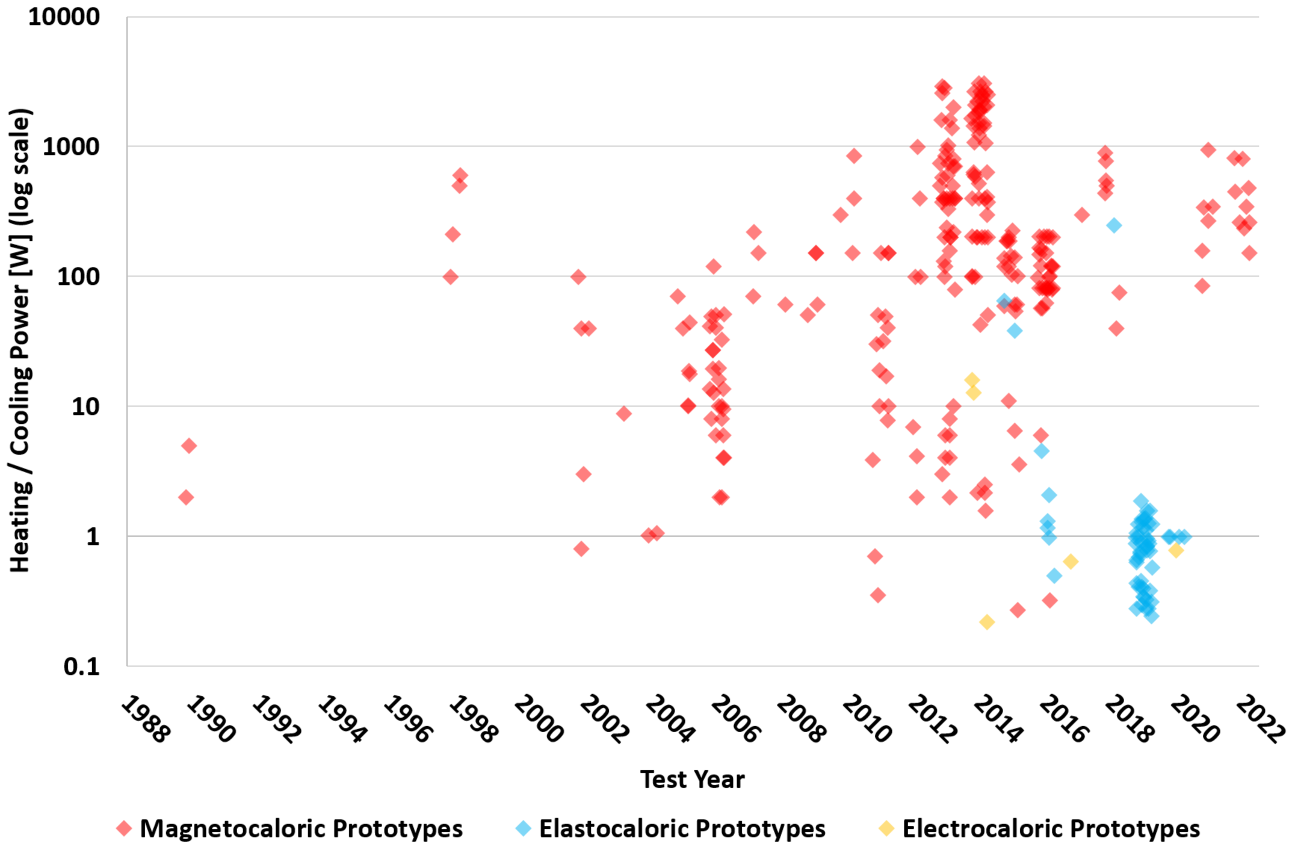


Figure 11: *Evolution of the heating/cooling power output achieved by the different magnetocaloric, elastocaloric and electrocaloric heat pump prototypes over the years.*

7. Data collection and references

All the simulation and measurement data collected for this report is originating from peer-reviewed scientific articles of international journals and conferences (except for a few exceptions in the data for conventional vapour-compression heat pumps that is originating from manufacturer's technical reports or a Master thesis). The following information was systematically researched in these publications: coefficients of performance (COP), heating/cooling power output, temperature span between the heat source and the heat sink. This information was extracted from text, tables, figures or derived from adequate auxiliary information. A distinction is always made between the data originating from experimental studies (measurements in laboratory or monitoring of existing systems in operation) and the data originating from numerical (simulation-based and theoretical) studies.

The data for conventional vapour-compression heat pumps has been collected from 22 publications:

- Aguilar et al., 2016 [3]
- Meggers et al., 2012 [4]
- Mohanraj et al., 2018 [5]
- Kuang & Wang, 2006 [6]
- Ito et al., 1999 [7]
- Torres-Reyes & Cervantes de Gortari, 2001 [8]
- Gorozabel et al., 2005 [9]
- Izquierdo & de Agustín-Camacho, 2015 [10]
- Moreno-Rodríguez et al., 2012 [11]
- Li et al., 2007 [12]
- Gasser et al. 2017 [13]
- Zhang et al., 2007 [14]
- Trillat-Berdal et al., 2006 [15]
- Sarbu & Sebarchievici, 2014 [16]
- Sanner et al., 2003 [17]
- Sanaye & Niroomand, 2010 [18]
- sparenergi.dk, 2013 [19]
- DVI VV [20]
- Gillan, 2016 [21]
- Haller et al., 2014 [22]
- Pospisil et al., 2019 [23]
- Ruhnau et al., 2019 [24]

The data for magnetocaloric heat pumps has been collected from 80 publications:

- Aprea et al., 2014 [25]
- Aprea et al., 2015a [26]
- Aprea et al., 2015b [27]
- Aprea et al., 2016 [28]
- Aprea et al., 2018 [29]
- Arnold et al., 2011 [30]

- Arnold et al., 2014 [31]
- Bahl et al., 2008 [32]
- Bahl et al., 2014 [33]
- Balli et al., 2012 [34]
- Baser et al., 2018 [35]
- Blumenfeld et al., 2002 [36]
- Bohigas et al., 2000 [37]
- Bour et al., 2009 [38]
- Brown, 1976 [39]
- Chaudron et al., 2018 [40]
- Chen et al., 2007 [41]
- Cheng et al., 2013 [42]
- Clot et al., 2003 [43]
- Coelho et al., 2009 [44]
- Czernuszewicz et al., 2014 [45]
- Dall'Olio et al., 2021 [46]
- Dikeos & Rowe, 2013 [47]
- Dupuis et al., 2009 [48]
- Engelbrecht et al., 2009 [49]
- Engelbrecht et al., 2011 [50]
- Engelbrecht et al., 2012 [51]
- Eriksen et al., 2015 [52]
- Eriksen et al., 2016 [53]
- Gao et al., 2006 [54]
- Green & Chafe, 1990 [55]
- Gómez et al., 2013 [56]
- He et al., 2013 [57]
- Hirano et al., 2002 [58]
- Hirano et al., 2009 [59]
- Hirano et al., 2014 [60]
- Huang et al., 2006 [61]
- Huang et al., 2018 [62]
- Jacobs et al., 2013 [63]
- Jacobs et al., 2014 [64]
- Johra et al., 2018 [65]
- Johra et al., 2019 [66]
- Kawanami, 2007 [67]
- Kim & Jeong, 2009 [68]
- Kitanovski et al., 2012 [69]
- Kitanovski et al., 2015 [70]
- Legait et al., 2014 [71]
- Lozano et al., 2013 [72]

- Lozano et al., 2014 [73]
- Lozano et al., 2016 [74]
- Lu et al., 2005 [75]
- Masche et al., 2022 [76]
- Monfared & Palm, 2016 [77]
- Nakamura et al., 2008 [78]
- Okamura et al., 2005 [79]
- Okamura et al., 2007 [80]
- Okamura & Hirano, 2013 [81]
- Qian et al., 2018 [82]
- Richard et al., 2004 [83]
- Rowe & Barclay, 2002 [84]
- Rowe & Tura, 2006 [85]
- Russek et al., 2010 [86]
- Shassere et al., 2012 [87]
- Shir et al., 2005 [88]
- Tagliafico et al., 2013 [89]
- Trevizoli et al., 2011 [90]
- Trevizoli et al., 2015 [91]
- Trevizoli et al., 2017 [92]
- Tura & Rowe, 2011 [93]
- Tušek et al., 2013 [94]
- Tušek et al., 2014 [95]
- Tomc et al., 2018 [96]
- Vasile & Muller, 2006 [97]
- Velázquez et al., 2016 [98]
- Yao et al., 2006 [99]
- You et al., 2016 [100]
- Zhang et al., 2016 [101]
- Zhang et al., 2017 [102]
- Zimm et al., 1998 [103]
- Zimm et al., 2006 [104]
- Zimm et al., 2007 [105]

The data for elastocaloric heat pumps has been collected from 13 publications:

- Cui et al., 2012 [106]
- Engelbrecht et al., 2017 [107]
- Kirsch et al., 2018 [108]
- Ossmer et al., 2014 [109]
- Ossmer et al., 2016 [110]
- Qian et al., 2015a [111]
- Qian et al., 2015b [112]

- Qian et al., 2016 [113]
- Schmidt et al., 2015 [114]
- Snodgrass & Erickson, 2019 [115]
- Tušek et al., 2015 [116]
- Tušek et al., 2016 [117]
- Ulpiani et al., 2020 [118]

The data for electrocaloric heat pumps has been collected from 16 publications:

- Aprea et al., 2016 [119]
- Blumenthal et al., 2016 [120]
- Chen et al., 2013 [121]
- Defay et al., 2018 [122]
- Feng et al., 2016 [123]
- Gu et al., 2013a [124]
- Gu et al., 2013b [125]
- Guo et al., 2014 [126]
- Jia & Sungtaek Ju, 2012 [127]
- Ma et al., 2017 [128]
- Meng et al., 2020 [129]
- Plaznik et al., 2019 [130]
- Radebaugh et al., 1979 [131]
- Shi et al., 2020 [132]
- Sinyavsky et al., 1989 [133]
- Sinyavsky et al., 1992 [134]
- Sinyavsky & Brodyansky, 1992 [135]
- Sinyavsky, 1995 [136]
- Torelló et al., 2020 [137]
- Wang et al., 2018 [138]
- Wang et al., 2020 [139]
- Zhang et al., 2017 [140]

The data for barocaloric heat pumps has been collected from 2 publications:

- Aprea et al., 2018 [141]
- Aprea et al., 2020 [142]

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