Emerging HVAC Technologies

A deep dive into magnetocaloric heat pumps and interoperable demand side response

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Nomenclature

The list below defines abbreviations and symbols used throughout this document.

Magnetocaloric Heat Pumps	**Interoperable Demand side response**
VC : vapour compression FOM : figures of merit VCHP : vapour compression heat pump MCE : magnetocaloric effect MCM : magnetocaloric material MCHP : magnetocaloric heat pump AMR : active magnetocaloric regenerator IHX : internal heat exchanger COP : coefficient of performance **Characters & Symbols** T : Tessla K : kelvin T_{hot} : Temperature of the T_{cold} : Temperature of the kW : kilowatt kWh : kilowatt-hour	IDSR : Interoperable Demand Side Response DSR : demand side response UK : United Kingdom HVAC : heating ventilation and air conditioning EV : electric vehicle PAS : publicly available specification EN : European Standard SME : small to medium enterprise ESA : energy smart appliances CEM : customer energy manager DSRSP : demand side response service provider IoT : internet of things NIS : Network and Information Systems CAF : Cyber Assessment Framework

1 Magnetocaloric Heat Pump

1.1 Introduction

The UKs imminent future homes standard requiring new homes and non-domestic buildings to be 'zero-carbon ready' means gas or so called "hydrogen ready" boilers will no longer be an option for developers. [1] The UK is also one of the many countries under the Montreal Protocol that have taken action to phase out HFC's and other F gasses commonly used as refrigerants in VCHPs. VCHP manufacturers are proposing alternatives such as propane, R454C, and CO2, but these come with safety concerns: propane & R454C are highly flammable, and CO2 requires significantly higher operating pressures. The industry as is searching for green, safe, cost effective solutions. [2] Caloric technologies are alternative drivers of adiabatic temperature change that avoid refrigerant compression including electrocaloric (uniaxial mechanical stress), electrocaloric (electrical field), barocaloric (hydrostatic pressure), and magnetocaloric (magnetic field) which to date has received the majority of researchers attention. [3]

1.2 MCHP Theory and Implementation

The magnetocaloric effect (MCE) refers to the temperature change of a magnetic material associated with the application of a magnetic field due to the contribution of the changing arrangement of the magnetic sub-lattice to entropy. This effect can be used in place of compression in traditional vapour compression based heat pumps: In place of isothermal compression, isothermal magnetisation induces an alignment of the magnetic sub-lattice decreasing entropy which can be converted to heat; In place of adiabatic expansion, adiabatic demagnetisation where heat is converted into magnetic entropy i.e. disorder in the magnetic sub-lattice. [4]

There are various designs of magnetocaloric heat pump (MCHP) being actively developed (see ref [5] for a thorough review), but in general they consist of some arrangement of: a high surface area to volume structure of magnetocaloric material (MCM) usually referred to as an active magnetocaloric regenerator (AMR), a magnetic field source, heat transfer fluid, a pump, and a heat exchanger. [5] Typically the heat transfer fluid is a water/glycol mix that is pumped to move energy in from a cold reservoir to the AMR and out to a hot reservoir with heat exchangers at both ends. [5] Some designs use a standard pump controlling various flows with dedicated valves while others use reciprocating displacers trading some control authority for simplicity. [6] As for the magnetic field source, state of the art MCHP designs overwhelmingly opt for permanent magnets over electromagnets for simplicity as even with superconducting coils the energy required to produce the field strengths required (~1-2 T) are prohibitive along with the electromagnetic perturbations being much harder to confine. [5] There is still a great deal of variety in magnetic circuit design as researchers search for optimisations to provide the greatest field strength variation with the minimum permanent magnet material. The magnet itself tends to represent the majority of the cost of an MCHP and a major obstacle to cost effective commercialisation. [5], [7]

Materials scientists are continually refining magnetocaloric materials with the state of the art predominantly alloys based on either gadolinium or lanthanum-iron-silicon (LaFeSi). [8] Some designs vary properties over the length of a single AMR bed to have each section optimised for the specific temperature span it is likely to encounter. This can be done by varying the material composition or the micro / macro structure and often justifies increased costs as increasing AMR volumetric performance is vital to make optimal use of a limited magnet gap. [7]

MCHP designs tend to use several AMR beds in parallel to scale up capacity for higher output power (>1kW) however, this introduces issues with uneven flow but can be counteracted with active control. [6] Additionally as most MCMs only exhibit a small temperature change (Gadolinium exhibits $11\,K$ adiabatic temperature change at a field strength of $5\,T$ [8]) MCHPs must use several AMR stages in series to achieve a span suitable for domestic/commercial space heating (>20 K) this is referred to as cascading. [9]

Tailoring active control strategies have shown significant benefits for both capacity and efficiency but given the variety of physical designs progress in this area is scattered. [6]

1.3 Performance

MCHP domestic & commercial heating solutions are a nascent technology, but it is a promising alternative to vapour compression (VC) with several studies indicating potential for higher COP and higher temperature lift / span than existing VC based heat pump technologies. [3], [8, p. 2], [10] Figures of merit (FOM) are metrics used to compare caloric technologies, analogous to the isentropic efficiency of the compressor for a given refrigerant in traditional heat pumps or refrigerators. [8], [9] Setting aside the parasitic losses all heat pumps share i.e. motors, pumps, heat exchangers, radiative losses etc. Considering coefficient of performance COP of the ideal process: The key loss to consider in a vapour compression heat pump (VCHP) is superheating during compression due to friction in the refrigerant itself. In contrast MCHPs do work via the magnetocaloric effect (MCE) with loss due to hysteresis in the magnetocaloric material (MCM) which releases dissipative heat. [9]

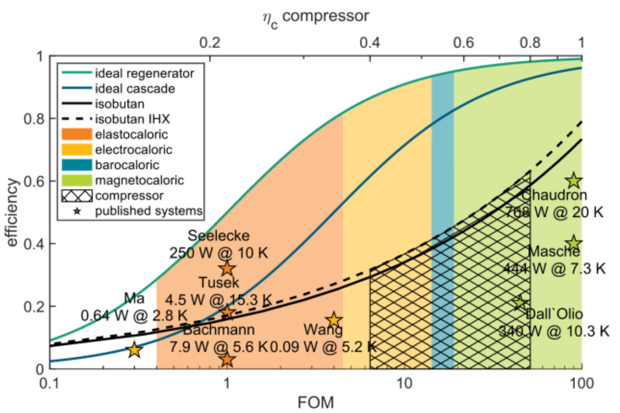

Figure 1 Comparison of achievable exergetic efficiencies of different technologies based on FOM ranges of the best-in-class materials and maximum isentropic compressor efficiency ($T_{\text{hot}} 55°C, T_{\text{cold}} 5°C$) [8]

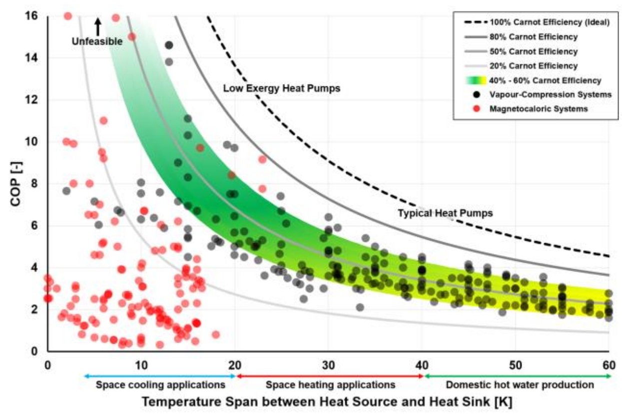

Figure 2 Measured performance of magnetocaloric heat pump prototypes against conventional vapour-compression heat pumps [3]

In both cases irreversible work is being done that reduces COP of the cycle. In a compressor some of this work can be captured by an internal heat exchanger (IHX) but even so the theoretical exergetic efficiency $\left(\frac{\text{system COP}}{\text{Carnot COP}}\right)$ limit of current VCHPs is far below that of caloric methods. [8], [10] There are already prototype MCHPs capable of 60% of the COP of Carnot [11] and studies indicating that there are still significant improvements in power and temperature span to be unlocked with optimisations in design and control. [6], [8], [12]

2 Interoperable Demand Side Response

2.1 Introduction

Electricity grids around the world are performing a perpetual balancing act to match supply and demand with little margin for error, when this can't be achieved it means power outages that can cost lives as well as capital. [13] In the UK the gird is coordinated via comprehensive market saturated with brokers that trade demands, supply, shortfalls, excesses, and a myriad of derivatives thereof based on a huge amount of data. [14] With the energy revolution taking place to meet climate goals there are significant changes in our energy supply and its usage that test the limits of the systems currently in place to maintain that balance. The "old way" was built on the assertion that most generation could be switched on and off as and when it was needed, and that storing electricity or influencing consumer demand where for the most part impractical. However, these old truths are changing, primarily because grids have to make use of intermittent renewables that generate power that is clean but difficult to predict and often not well matched with existing demand. [15]

With rapid electrification of heating, the adoption of electric vehicles, and normalisation of on premises energy storage, buildings have the potential to play a major role in providing stability though the implementation of a suitable system of communication and control to enable demand side response (DSR). [16] So called "energy smart" appliances capable of DSR especially HVAC featured heavily in the "Smart Systems and Flexibility Plan 2021" [17] with £13 million awarded to a number of public private partnerships to support development. [18] Multiple government publications indicate that demand side response functionality will be legally mandated for heat pumps and batteries by 2027 [17], [19], [20] as was done for EV chargers in 2021 [21].

2.2 IDSR Specification

The UK government has supported the development of technical standards PAS 1878 [22] and PAS 1879 [23] to enable domestic and small to medium enterprise (SME) consumers to participate in demand side response. PAS 1878 specifies energy smart appliances (ESA) themselves, the attributes and functionalities required of devices to participate in DSR. [22] PAS 1879 specifies roles and operations through thought the energy supply chain necessary to facilitate DSR in domestic or small business buildings. [23] The cyber security of energy smart appliances is also regulated by EN 303 645 [24] which is the baseline applicable to all IoT devices. Given IDSR involves remote control authority over safety critical infrastructure and by proxy the stability of the electricity grid, load controllers managing over 300 MW are subject to Network and Information Systems (NIS) regulations [25] and held to account under the Cyber Assessment Framework (CAF) [26].

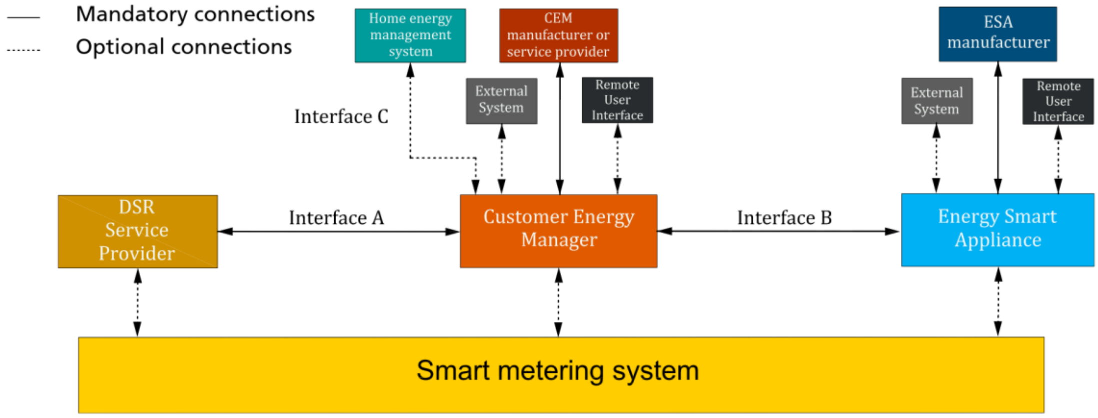

Figure 3 Logical DSR architecture as described by PAS 1878. Adapted from [22]

Under this framework an ESA forecasts several (3-1000) possible power profiles to indicate its flexibility to a DSR service provider (DSRSP) through the customer energy manager (CEM), which if load shifting is required can then signal which profile to adhere to. [22]

2.3 Performance

A trial involving 17 residences in Barnsley, England tested interventions where the default behaviours of residents' heat pumps and batteries were overridden to add (turn up) and reduce (turn down) demand on the grid. The turn up interventions 1-3 p.m. when demand is typically low but local renewables are available resulted in an average increased utilisation of 2.3kWh per residence. The turn down interventions at 6-8 a.m. and 5-7 p.m. resulted in average load changes of -3.3 and -4.1 kWh per residence with most able to provide net energy exports. Further trials where appliances where set to track variable tariffs demonstrated the ability to optimise power profiles for a range of criteria as shown in Figure 4. [27]

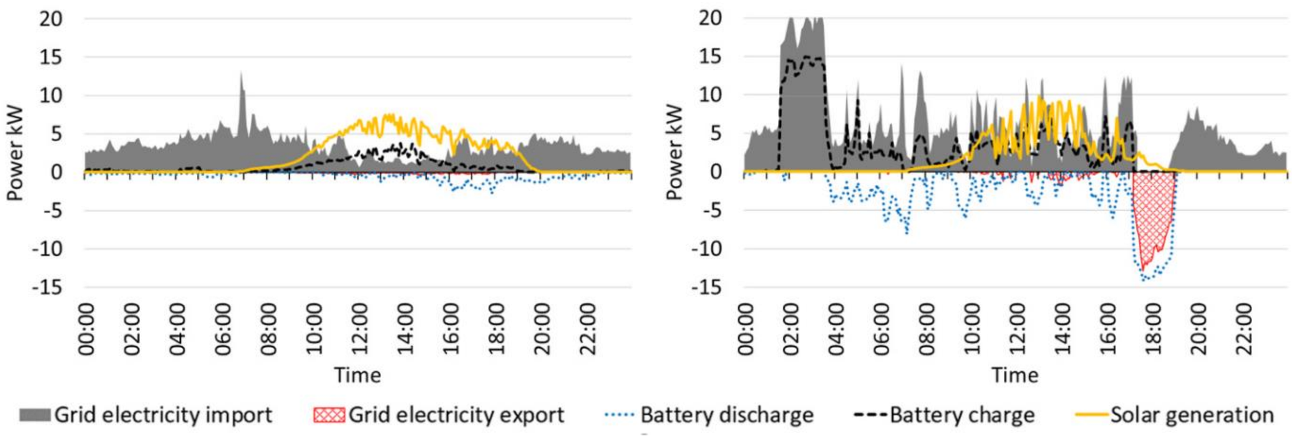

Figure 4 Aggregate daily power profiles for a 6 dwelling trial (left) baseline (right) turn down intervention (5-7 p.m.) with automated local carbon optimisation price signal response. Adapted from [27]

TraDER a trial conducted in the Orkney islands of Scotland also demonstrated the ability to reduce renewable curtailment and consumer energy prices through turn up demand side response. However, it also identified several barriers such as: The need to develop incentives to promote the sharing of data; The limited ability of existing infrastructure to collect, communicate, and act on data / signals; Conflicts of interest where distribution network operators manage both the need and the supply of system flexibility exposing the potential for profiteering. [28] Similarly as PAS 1878 [22] doesn't regulate the methodologies used by ESAs to calculate power profiles compensation schemes could potentially be exploited by exaggerated intended operation power profiles. Given household energy demand is so erratic it is generally difficult to establish counterfactuals to compare against rendered DSR services to establish their fair value. [29] However DSR schemes for larger operators have long been in operation in the UK and around the world with serviceable solutions.

Across various trials participants tend to find DSR interventions acceptable [27], [30] and public polls indicate significant interest (~30%) in domestic DSR programs and willingness to accept a degree of automation of their electricity use. [30], [31] As consumers are motivated by savings and dissuaded by the initial investment actual uptake would be highly dependent on incentive programmes. [31], [32]

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