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Paving the Way for Next-Generation Solid-State Waste Heat Recovery: A Thermomagnetic Materials and Systems Roadmap

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Received: 16 July 2026 | **Revised:** 17 September 2026 | **Accepted:** 23 September 2026

Keywords: energy harvesting | low-grade waste heat | magnetocaloric material | thermomagnetic generator | thermomagnetic material

ABSTRACT

Nearly half of global primary energy is dissipated as low-grade waste heat, predominantly below 100°C. While thermoelectric technologies offer a pathway to recover such energy, their efficiency and scalability remain limited. Thermomagnetic (TM) energy conversion has recently emerged as a promising alternative, with breakthroughs in materials and system design pushing its performance toward practical viability. TM systems offer unique advantages, including scalability, high theoretical second-law efficiency, and adaptability across diverse thermal regimes. In this perspective, we examine the key challenges and emerging opportunities in thermomagnetic energy harvesting, with a focus on material selection, processing techniques, and system-level design. We propose roadmaps to guide the field's development, aiming to establish TM conversion as a versatile solution for sustainable low-grade waste heat recovery.

1 | Introduction to Thermomagnetic Energy Conversion

Waste heat represents one of the most underutilized yet abundant and growing energy resources in modern industry. With temperatures ranging from 30°C to over 120°C, low-grade thermal energy from food, wood, and paper processing, air conditioning condensers, and data center operations offers a vast reservoir—estimated at 3500 PJ annually in the EU [1]—for clean power generation and decarbonization. Harnessing this energy not only strengthens energy security through decentralized and off-grid solutions but also reduces opera-

tional costs and supports climate goals. A significant portion [1] of global waste heat—nearly 50%—is released at temperatures below 100°C, yet this low-grade thermal energy remains largely unexploited due to the lack of efficient recovery technologies [2, 3]. Thermoelectric systems are available in the range from μW [4] to above 10 kW [5]. They suffer from low efficiency and reliance on toxic or rare materials for low-temperature applications [4–6]. This technological gap has spurred interest in alternative approaches, including thermoacoustic [7, 8], thermoelastic [9], and, more recently, thermomagnetic (TM) energy conversion. Here, we highlight recent breakthroughs [10–13] in thermomagnetic systems and materials

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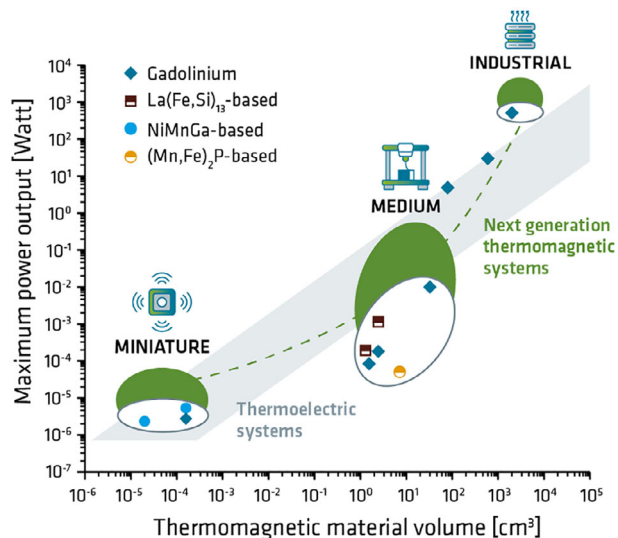


FIGURE 1 | Overview of existing TM systems by volume of TM material and power output. Note that both NiMn-based Heuslers and La(Fe,Si)₁₃-based alloys exceed the performance of Gd at small and medium system levels. Data taken from references in Table 1.

that offer a promising route for harvesting low-temperature waste heat [14].

Current research in thermomagnetic energy conversion spans a broad power output range, from microwatts [11, 12, 15] to half a kilowatt [13]; see Figure 1 and Table 1. Miniature systems make use of TM films or foils with a large surface-to-volume ratio, allowing for rapid heat transfer through solid-solid contact to the heat sink and source [11, 16–18]. Thus, compact system designs

are enabled to avoid heat transfer fluids and fluid control systems. High-performance TM generators have been developed based on the concept of resonant self-actuation [11]. This concept relies on the periodic magnetic attraction of a TM film at the front of a cantilever caused by the field gradient of a permanent magnet, which at the same time acts as the heat source; see Figure 2. Resonant oscillation of the cantilever in the order of 100 Hz is achieved when heat intake and dissipation are balanced with the mechanical cycle. In this case, thermal energy is effectively converted into kinetic energy, which in turn is converted into electricity by an integrated pick-up coil. A large power per footprint of 50 $\mu\text{W}/\text{cm}^2$ has been demonstrated [15]. Current challenges include tailoring TM films and systems integration to enable operation near room temperature [12], as well as coupling cantilever arrays to increase power. The prospects are new routes for supplying autonomous sensor systems, portable electronic devices, or electrified wearables with electricity [19–21].

For medium-sized systems, the research focuses on thermomagnetic generators, where the thermomagnetic material is used to switch the magnetic flux created by permanent magnets, cf. Figure 2. Following Faraday's law, this flux change gives an induced voltage in coils wound around soft magnetic yokes, which guide the flux. This approach has a minimum of moving parts, which promises a long lifetime with minimum maintenance. Though this principle was already patented by Tesla [28] and Edison [29] more than a century ago, it required the development of magnetocaloric materials before it was re-proposed by Srivastava [22] et al. in 2011. The next key step was the development of a magnetic circuit [23], which keeps the flux within the system, followed by a configuration that also allows for a beneficial flux reversal [10]. This work motivated several other designs for flux reversal [24], including a regenerator approach [30], a heat pipe for accelerating heat exchange [31],

TABLE 1 | Comparison of state-of-the-art TM systems at three different power output scales.

Thermomagnetic system type	Miniature	Medium	Industrial
Operating principle	Oscillating cantilever with TM material and pickup coil in a permanent magnet field	Static permanent magnet field topology (genus = 1,2,3) generator with alternating water flow	TM motor with rotor made of TM material components
Power output	$\sim \mu\text{Watt}$	$\sim \text{mWatt}$	$\sim \text{kWatt}$
TM material volume	$10^{-5} - 10^{-4} \text{ cm}^3$	$1 - 10 \text{ cm}^3$	$10^3 - 10^4 \text{ cm}^3$
Possible application fields	Internet of things and smart devices	Small off-grid appliances	Energy harvesting at residential/industrial scale
TM material: existing (future)	Gd, Heuslers (La(Fe,Si) ₁₃ , FeRh)	Gd, La(Fe,Si) ₁₃ , (Fe,Mn) ₂ (P,Si), (Heuslers)	Gd, (non-critical abundant TM materials, likely Fe-rich)
Shape of TM material: existing (future)	Thin and thick films (foils, ribbons, composites)	Plates, packed spheres (3D-printed structures)	Plates (3D-printed structures)
Biggest challenges	Microsystems integration, Reliability of TM materials	Modularity and flexibility to test new concepts and materials quickly Cost per output power	Cheap, non-critical TM materials Upscaling of materials production, Reliability of TM materials
Example references	[11, 12, 15]	[10, 22, 23, 24, 25, 26, 27]	[13]

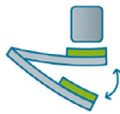
OPERATING PRINCIPLE	RECENT BREAKTHROUGHS	ENGINEERING CHALLENGES	APPLICATION FIELDS
MOTORS 	Industrial Demonstrator	Upscaling TM Materials: Abundant, non-critical Challenge: Scalability, TM materials reliability	 INDUSTRIAL > 500 W Application scenario: Industrial waste heat recovery Main benefit: Continuous off-grid electrical energy
GENERATORS 	Topology optimization Genus = 2 Genus = 3	Magnetic field topology and TM material optimization TM Materials: Abundant, 3D-printed Challenge: Return of investment	 MEDIUM > 1 – 50 W Application scenario: Powering 3D printers, medical, electronics, ... Main benefit: Powering devices independently of network infrastructure
OSCILLATORS 	TM Microsystems	Microsystems Integration TM Materials: TM films, foils, ribbons Challenge: Micro device engineering	 MINIATURE 1 – 100 μW Application scenario: Sensors, microelectronics Main benefit: Works even with body heat

FIGURE 2 | Roadmap for the development of thermomagnetic (TM) energy-conversion systems through 2035. Device engineering will require size-specific strategies because the key constraints and optimization pathways differ across miniature, intermediate, and large-scale systems.

and attempts at upscaling [10, 25]. Though most of these designs improved the performance significantly, three major challenges remain. First, the system efficiency, which is still well below 1% with respect to Carnot efficiency [10, 25], must be increased. Second, the cycle frequency, which today is around 1 Hz, must be increased. This is decisive for increasing the output power, which is the energy harvested per cycle times the frequency. Third, the scaling behavior of these devices must be understood, which is important to upscale output power. Today, these systems reach several milliwatts of output power [10, 25], and addressing these three issues should result in an output power in the watt range, which would enable first niche applications. As in most cases, low-grade waste heat is continuously available; this power range could run or charge off-grid appliances, independent of the availability of sun radiation or wind.

For industrial systems, rotating thermomagnetic motors and static generators are the two main principles used. Large motors with rotating heavy masses suffer from increased wear and cost. Large generators, free of moving parts, need advanced fluidic and thermal designs for effective heat management. The largest prototype built by Swiss Blue Energy converted low-temperature waste heat around 60°C into mechanical energy using gadolinium regenerators and permanent magnets in a rotating thermomagnetic motor [13]. It achieved the first net electrical output (500 W). Thermomagnetic devices face low power density and efficiency resulting from irreversible heat transfer, thermal losses, and suboptimal designs. Material challenges [26] include high mass of thermomagnetic materials and magnets, limited temperature adaptability, and complex processing. Scaling from lab to functional devices adds complexity in design. Upcoming developments focus on new operating principles using additively manufactured high-frequency regenerators and thermomagnetic

materials with embedded thermal diodes. Utilizing recycled or rare-earth-free magnets and regenerators enables wider sustainable deployment. Advances in superconducting magnets may further improve scalability to high-power systems.

2 | Device Engineering of Thermomagnetic Systems

Various types of thermomagnetic systems at different power scales and employing different operating principles have been studied and developed to date [21, 32, 33]. A common challenge across all these systems is to increase the device efficiency by reducing losses and increasing power density by optimizing device engineering. For this, concurrent optimization of the thermomagnetic material geometry and the magnetic-field topology is essential. A central challenge lies in producing TM materials in shapes that support both high performance and practical device integration. For thermomagnetic generators, thin TM plates are particularly advantageous because they guide the magnetic flux between the yokes without interruption, which is required for high permeability in the ferromagnetic state. In addition, these plates must also be sufficiently thin to enable rapid heat exchange, a prerequisite for achieving high cycle frequencies and elevated power output. Heat losses in such systems can be broadly categorized into two classes. The first comprises irreversible heat transfer and the associated entropy generation occurring in the heat exchangers between the working fluid, the TM material, and the heat source and sink. The second includes parasitic losses distributed throughout the device, arising from imperfect thermal insulation and unavoidable thermal bridges between structural components. In addition, viscous losses can become significant, particularly in motors or generators that employ thermomagnetic

regenerators, and must therefore be carefully managed in high-performance designs. Achieving high power density relative to the total system mass is crucial, both for reducing overall cost and for enabling deployment in environments where weight is a limiting factor. Lower mass per unit power output also contributes to a reduced carbon footprint across the technology's life cycle. Enhancing power density therefore demands not only careful optimization of structural and assembly components, but—more critically—the development of new strategies for rapid heat transfer and the efficient execution of thermodynamic cycles.

For miniature systems, thermomagnetic films with precisely tailored dimensions, optimized thermal properties, and ferromagnetic transitions near room temperature must be developed and integrated within microsystem environments; see Figure 2. Ultimately, large arrays of oscillating cantilevers are envisioned, requiring co-integration with dedicated microelectronic circuitry for efficient power management. At larger scales, fabrication of TM films with sufficiently low brittleness will be essential for upscaling cantilever arrays. Operating several hundred cantilevers in parallel could yield power outputs on the order of 1 mW when combined with appropriate power-management electronics. Such performance would enable new applications in areas including the Internet of Things (IoT) and portable electronics. Through continuous energy harvesting and recharging, these systems could extend device lifetimes and reduce dependence on batteries, supporting maintenance-free operation in remote or inaccessible environments. On the other hand, industrial upscaling of device concepts to the kilowatt range will require fundamentally new system architectures capable of delivering high power density. In contrast to small-scale generators, these larger systems will likely rely on novel motor-type configurations that incorporate redesigned TM material topologies and simplified yet highly efficient heat-transfer pathways. In parallel, reducing reliance on critical raw materials—both in TM materials and in permanent magnets—will be essential to enable cost-effective, large-scale manufacturing; see Figure 2.

3 | A New Design Paradigm for Thermomagnetic Materials

Designing thermomagnetic materials builds on nearly three decades of magnetocaloric materials research. Good thermomagnetic [34, 35] and magnetocaloric materials [36] exhibit several Figure 3 common characteristics, including sharp first-order-like magnetostructural/magnetoelastic transitions and a corresponding steep magnetization jump, as well as low hysteresis and large thermal conductivity. Furthermore, a tunable transition temperature is essential — not only to accommodate the different operating ranges of magnetocaloric and thermomagnetic systems, but also to align the material's transition point with the available waste-heat temperature.

There are, however, important differences: For thermomagnetic materials, the adiabatic temperature change ΔT_{ad} (the temperature change of the material upon application or removal of a magnetic field under adiabatic conditions) as well as the entropy change ΔS (the magnetic-field-induced change in entropy) are of minor importance. In contrast to magnetocaloric refrigeration

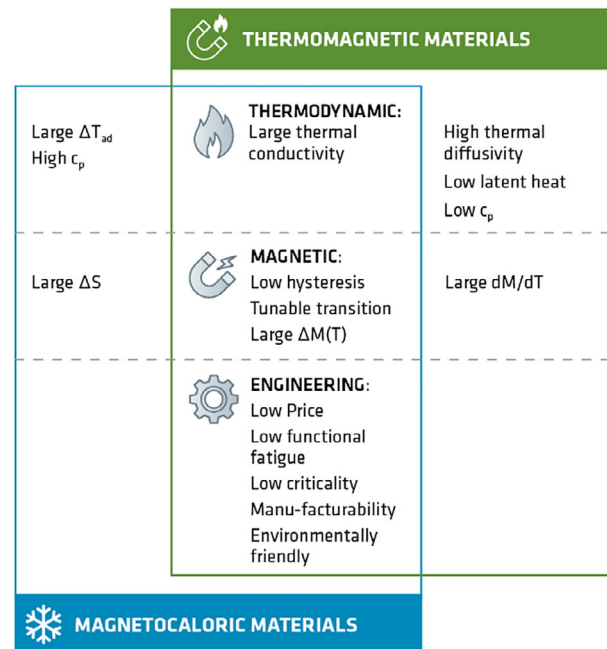


FIGURE 3 | Thermodynamic, magnetic, and engineering properties of ideal thermomagnetic materials. Overlap with magnetocaloric materials is evident, but there are specific new requirements that pose a new design paradigm for this class of magnetic materials.

materials, thermomagnetic generators require low specific heat capacity (the heat required to raise the temperature of a unit mass by one degree) and low latent heat (the heat absorbed or released during a first-order phase transition) to achieve high conversion efficiency and fast thermal cycling. Both applications, however, benefit from a large change in magnetization, ΔM , between the low- and high-temperature states, as this quantity directly determines the strength of the magnetic response to a temperature change.

Critical-point tuning can be applied to modify the nature of the magnetic phase transition at the crossover between a step-like first-order magnetic transition, which is associated with latent heat and hysteresis, and a continuous second-order magnetic transition, which exhibits neither latent heat nor hysteresis. Such tuning of composition and synthesis conditions aims to provide an optimal balance between a large temperature derivative of the magnetization, dM/dT , which characterizes how strongly the magnetization changes with temperature near the transition, and a minimal latent heat L , thereby maximizing generator performance, as demonstrated, for example, in the $(\text{Fe,Mn})_2(\text{P,Si})$ system [37].

Figure 4 assesses which well-established magnetocaloric materials can be adapted for thermomagnetic energy harvesting and which are unsuitable for this application [34]. Gadolinium will probably remain the benchmark material for testing new devices and concepts due to its good magnetic and particularly engineering properties. From the zoo of magnetocaloric materials, the $(\text{Mn,Fe})_2\text{P}$ and the $\text{La}(\text{Fe,Si})_{13}$ systems show the best thermomagnetic performance. Some Heusler alloys [38] with first- and second-order magnetic transitions (FOMT/SOMT) can compete with these values and, more importantly, due to their

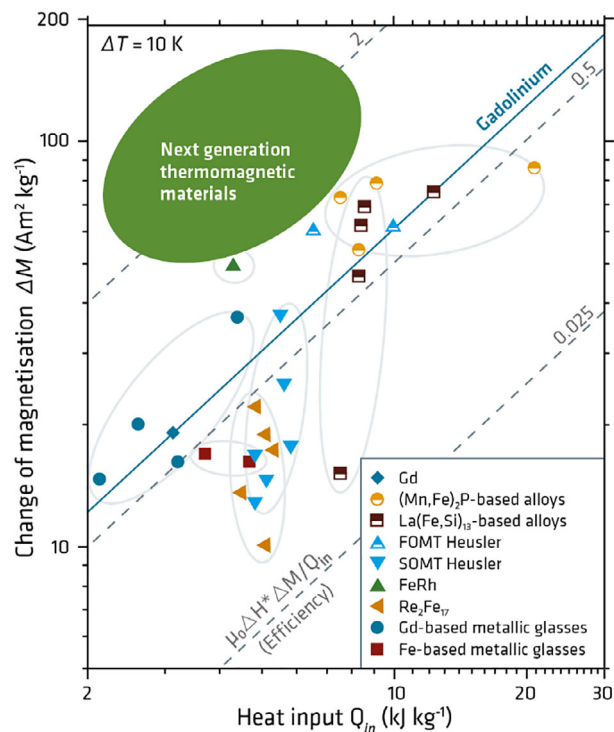


FIGURE 4 | Ashby plot summarizing key functional properties of existing thermomagnetic materials. While Gadolinium remains a benchmark material for testing new device concepts in the foreseeable future, superior efficiency and power output will likely require tailored new materials. Adapted from Dzekan et al. [34].

chemical versatility and largely unexplored composition space, new Heusler candidates are waiting to be uncovered that match the requirements listed in Figure 3. It may also be worthwhile to revisit candidate systems that were previously rejected for insufficient magnetocaloric performance (for example, due to a too low ΔT_{ad}), as they may prove promising in light of the new requirements.

4 | Search Strategies for New Thermomagnetic Materials

It is likely that new material systems unrelated to known magnetocaloric materials and with better thermomagnetic properties than those will be discovered soon. The search space for new stable materials is currently expanding fast with datasets and materials models recently published by, e.g., DeepMind [39] and Microsoft [40], so data mining and modeling will help and guide the quest for new TM materials. Experimental thin-film-based high-throughput screening combined with machine learning also holds much potential. A search strategy which is hierarchical with respect to properties is typically applied. For thermomagnetic materials, a suitable hierarchy would be to select (i) a large ΔM for maximized electrical power output, (ii) low heat capacity to reduce thermal load, (iii) high thermal conductivity for fast cycling, (iv) a steep switching for large dM/dT for higher power output, and (v) minimal hysteresis for durability and high-frequency operation. Screening these properties can be challenging, as some result from coupling

effects that are highly sensitive to, e.g., chemical composition and defects.

Once a promising material class has been identified, experimentally calibrated Ginzburg–Landau modeling [41, 42] can guide its compositional and microstructural optimization. By fitting the magnetic, elastic, and magnetoelastic energy contributions to measured temperature-dependent magnetization and lattice parameters, the model captures the coupling between magnetic ordering and structural changes near the transition. It can then be used to assess how composition, internal strain, defects, grain size, and crystallographic texture influence T_C , ΔM , dM/dT , thermal hysteresis, and mechanical stability. Such modeling can help identify composition and processing windows that maintain a sharp magnetic transition while limiting hysteresis and internal stress. An important step, particularly for upscaling toward industrial-scale energy harvesting systems, lies in excluding elements with a high supply risk [36]. This particularly concerns certain heavy rare earths such as Dy and Tb, but lately even the supply of Gd and the light rare earth La has experienced major export restrictions by China. Even though today there are some suitable thermomagnetic material classes without rare earths, research in this direction should be enhanced.

One promising approach for exploring new materials is to examine spin transitions between two different magnetically ordered states. Some systems that have magnetic order up to a relatively high temperature T_{m1} show a second magnetic transition at a lower temperature T_{m2} where the spin arrangement shows a spontaneous reconstruction (see Figure S1). An example is the antiferromagnetic (AFM) to ferromagnetic (FM) transition, where at T_{m2} a large step in magnetization ΔM is observed for a small latent heat L . Spin order-order transitions are always weakly first order as the magnetic entropy is already reduced by the magnetic order. Hence, we expect a large dM/dT . This strategy has so far only been applied to magnetocaloric materials for cooling applications and includes Mn_2Sb -based systems [43]. The main reason that it has not yet been applied to thermomagnetic materials for energy harvesting is that the spin-transition temperature T_{m2} needs to be located above room temperature. This condition requires a new search for candidates, which include Mn_2Sb -based materials [44], orthorhombic $(Mn,Co)_2P$ and $(Fe,Ni)_2P$ alloys [45], and Fe_3Ga_4 -based materials [46]. For miniature thermomagnetic systems, one may consider an exchange-biased AFM system which undergoes a spin flip in low magnetic fields [47].

5 | Industrial Processing of Thermomagnetic Materials

Although new and improved materials will further advance thermomagnetic harvesting, currently available thermomagnetic materials already offer sufficiently good properties to develop and scale up devices and to test new concepts. From an engineering point of view, the material must be shaped to enable i) fast heat exchange, ii) uninterrupted magnetic flux guidance, and iii) rapid fluid flow. This typically requires complex, thin geometries that contain a high fraction of active thermomagnetic material, since any additional material in the final part, e.g., binder, reduces magnetic and thermal performance. However, the engineering

Thermomagnetic materials (TM) roadmap

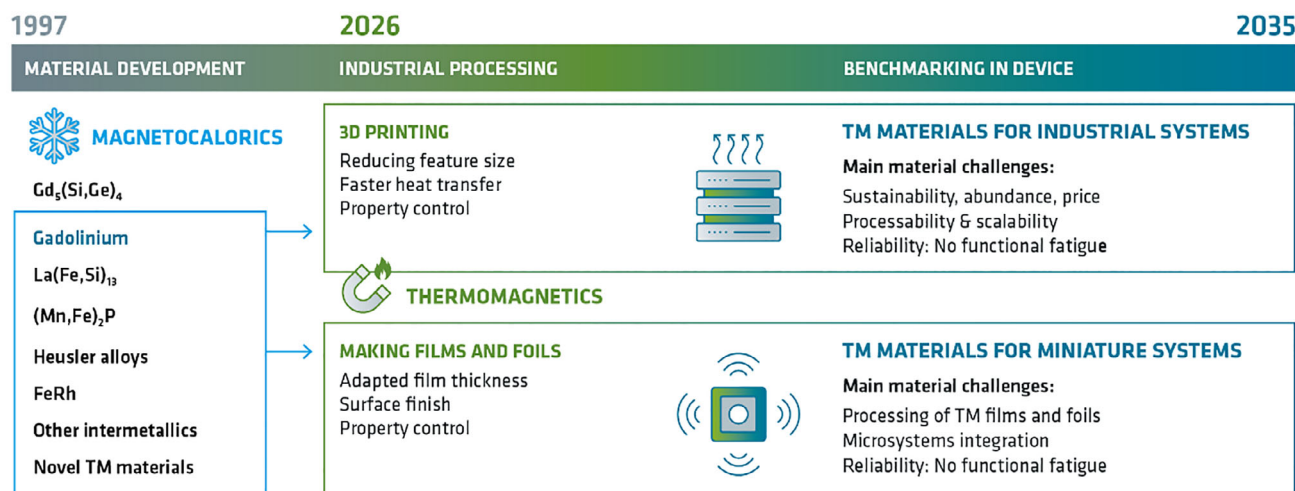


FIGURE 5 | Roadmap for the development of thermomagnetic materials up to 2035. Building on two decades of magnetocaloric material development, the targeted discovery of materials with optimized thermomagnetic properties remains a key challenge. Implementing these materials in systems across the full output-power range requires advances in their processing and in their resistance to mechanical and thermal fatigue.

requirements shown in Figure 3 present a major challenge, as manufacturability and long-term reliability are difficult to achieve for complex and/or thin shapes at all three system sizes. Furthermore, translating the functional properties achieved at laboratory scale into thin/thick films or ribbons (for miniature systems) and 3D-printed components (for industrial systems) represents a substantial challenge. The specific requirements and obstacles associated with integrating thermomagnetic materials into prototypes and industrially relevant devices again depend strongly on the system size, as illustrated in Figure 5.

For miniature systems, preserving the functional properties demands careful optimization of material preparation parameters and the application of appropriate thermal treatments to ensure phase purity. For example, in melt-spinning processes, rapid quenching can stabilize metastable phases that differ significantly from those present in the precursor material. In systems undergoing first-order transitions, internal stress and microstructural features play a decisive role. These characteristics strongly depend on synthesis methods and processing parameters and can be tailored through post-fabrication treatments such as thermal or mechanical processing. Ribbons produced under different quenching rates or films deposited at different temperatures and then subjected to various heat treatments provide an effective platform for investigating how microstructure influences transition hysteresis and width. Finally, surface roughness must be controlled to enhance thermal conductivity, and adequate mechanical integrity must be maintained. Miniature systems relying on heat transfer through solid-solid contact require TM ribbons or films with a smooth surface finish. The requirements on maximum tolerable stress and strain are low. However, brittleness should be low enough to enable system integration via transfer bonding and release technology. As the TM film is exposed to low strain at the cantilever front, a long operational lifetime is expected. This has been confirmed by running the device at ≈ 100 Hz for three days without any degradation, corresponding to more than 25 million cycles [12].

While the cost of critical materials will hinder their use in large-scale devices, this is not the case with microsystems. Instead, processing costs, which strongly depend on footprint, chip size, processing time, as well as degree of automatization, will be the dominant factor. A straightforward assembly and interconnection approach, featuring high quality standards and well-defined interfaces for integration with existing systems, is a key enabler for cost-efficient manufacturing.

When upscaling materials production for industrial-scale systems, besides the abundance and price of the raw materials, the ease of processing and how it scales is crucial. Most established and new materials are studied with equipment at lab scale, which means that when increasing the batch size, a change of equipment is needed to produce larger quantities by flow production. This often requires time and resources to readjust the processing parameters to achieve the desired material properties. 3D-printing like binder jetting [48] or 3D extrusion [49], offers a scalable route for processing brittle magnetic materials into heat exchanger geometries with high detail resolution up to typically 200–300 μm [48, 50]. Both currently existing commercial magnetocaloric devices [51, 52] have implemented 3D-printed magnetic heat exchangers, and the field has immensely profited from advancements in 3D printing. As with films and laboratory-scale materials, longevity of thermomagnetic heat exchangers can be challenging due to magnetostructural coupling and the strain associated with it. This issue can be relieved by tuning the transition toward a more second-order type, while a corrosion protection layer, e.g., copper [48], can protect the heat exchanger from electrochemical damage as well as microcracking by enhancing elasticity.

6 | Summary & Outlook

Low-grade waste heat released into the environment is both an unnecessary CO₂ burden and an economic opportunity, and its

volume is expected to rise sharply over the next decade due to the expansion of energy-intensive infrastructure such as air conditioning and data centers. Electrical energy consumption—and therefore waste heat—from data centers worldwide is projected to double [53] in the next five years, and the advent of quantum computing will further accelerate this trend, as cryogenic cooling systems generate additional low-temperature waste heat. Since roughly 95% of the electricity consumed by data centers ultimately becomes heat, typically at temperatures up to 40°C, even modest recovery gains could significantly improve overall energy efficiency. For data-center operators, recovering electricity from waste heat becomes economically viable at around 4% thermal efficiency [54].

Thermomagnetic conversion of waste heat below 100°C is an emerging energy-harvesting technology with strong development potential over the next decade. It offers notable strengths, including grid independence and adaptability to different temperature regimes and power scales. Recent device-engineering breakthroughs have increased efficiencies by orders of magnitude, bringing thermomagnetic systems closer to long-established thermoelectric conversion. At the same time, thermomagnetic materials research benefits from decades of magnetocaloric materials development, providing a solid foundation for further exploration through machine learning and other computational methods. Advances in 3D printing now make it possible to shape these functional materials into heat exchanger geometries with unprecedented repeatability and geometric resolution. Now is the time to bring these developments together to create new devices capable of harvesting waste heat across multiple power scales. Although thermomagnetic energy conversion is generally described as suitable for low-grade heat below 100°C, its practical performance is governed by the absolute (and usable) temperature span, the temporal profile of the heat source (continuous, intermittent, cyclic), the heat flux density, and the working medium. Table S1 gives an overview of the available heat sources and their properties, as well as recommendations for matching thermomagnetic materials and device concepts.

The largest industrial thermomagnetic system [13] demonstrated to date has achieved approximately 500 W electrical power output. Incorporating novel heat regeneration principles and thermal switch mechanisms [33], well-engineered thermodynamic cycles with high specific energy, and optimized layering of thermomagnetic materials [55] could propel the technology toward economically viable performance in the kW range. Based on material costs alone, the best thermomagnetic materials are predicted to achieve a cost per output power of approximately €0.01 W⁻¹ [34], compared with about €1 W⁻¹ for utility-scale photovoltaics, which is currently the lowest-cost electricity-generation technology [56]. This suggests that a substantial portion of the total system cost budget remains available for device integration and system-level components, although these costs cannot yet be reliably estimated at the current technology readiness level (TRL). In comparison, thermoelectric generators typically exhibit costs of approximately €11 W⁻¹ [57], highlighting the potentially superior cost-effectiveness of thermomagnetic energy conversion. Although abundant thermomagnetic materials are already available at large scale for <10 EUR/kg [49], a potential bottleneck lies in the permanent magnets required for magnetic circuits, which must be rare-earth-free or based on

recycled magnets to enable meaningful upscaling. For upscaling of devices, all material processing steps, including powder production, 3D-printing processes, and heat treatment, must be adapted for larger throughput. 3D printing offers high flexibility for medium-sized systems, since not only the thermomagnetic heat exchanger but also the entire generator, including yoke, permanent magnets, and coils, can be printed, providing maximum freedom for novel magnetic-flux designs and thus improved efficiency. At present, miniature oscillating devices for powering sensors and small electronic appliances appear close to commercialization, with parallelly coupled devices offering a route to broaden the power range at small scales. The vision of a world that can be understood by distributed networks of various sensor devices leads to a strong demand for suitable local power sources, opening many opportunities for thermomagnetic microsystems.

Combining advances in computational screening, materials synthesis and processing, as well as device engineering will be essential to unlock the potential of thermomagnetic systems across different power scales. If these developments continue to converge, thermomagnetic generators could evolve from laboratory prototypes into widely deployed components of a more efficient, sensor-rich technological landscape. In this way, waste heat—once an unavoidable by-product—may become a valuable resource in the emerging energy ecosystem. Beyond efficiency alone, converting waste heat to electricity offers intrinsic advantages by providing grid-independent, resilient power that can be deployed across a wide range of scales. Taken together, these factors position thermomagnetic conversion as a promising contributor to future distributed energy systems.

Author Contributions

A. Waske: conceptualization, Writing – original draft, writing – review and editing. **K. Klinar:** conceptualization, writing – review and editing. **S. Fähler:** conceptualization, writing – review and editing, writing – original draft. **M. Kohl:** conceptualization, writing – review and editing. **N. M. Dempsey:** conceptualization, writing – review and editing. **F. Albertini:** conceptualization, writing – review and editing. **G. A. de Wijs:** conceptualization, writing – review and editing. **T. Schrefl:** conceptualization, writing – review and editing. **M. Maschek:** conceptualization, writing – review and editing. **S. Lionte:** conceptualization, writing – review and editing. **C. Megnin:** conceptualization, writing – review and editing. **N. van Dijk:** conceptualization, writing – review and editing. **A. Kitanovski:** conceptualization, writing – review and editing. **E. Brück:** conceptualization, writing – review and editing, project administration.

Acknowledgements

The authors gratefully acknowledge funding from the European Union under grant agreement No 101119852 (Horizon TMA MSCA Doctoral Network Heat4Energy).

Open access funding enabled and organized by Projekt DEAL.

Conflicts of Interest

Michael Maschek is co-founder of the company Magneto B.V., their main products are 3D-printed magnetocaloric/thermomagnetic heat exchangers. Sergiu Lionte is manager of the R&D department at Magnoric. Their main products are magnetocaloric cooling appliances. Christof Megnin is co-founder of memetis GmbH, their main products are in the field of ultra-compact microvalves. The authors declare the following patents/patent

families which relate to the article: A) Magnetocaloric effect of Mn-Fe-P-Si-B-V alloy and use thereof, WO 2020/080942, 23.04.2020, Inventor from group of authors: Ekkes Brück and Niels van Dijk, patent holder: Magneto B.V. (30.04.2024), B) Packed screen type magnetocaloric element, US 2023/0046873A1, 16.02.2023, Inventor from group of authors: none, patent holder: Magneto B.V. (30.04.2024), C) Machine for converting thermal energy into electrical energy or vice versa, EP 2021/4169155B1, 23.12.2021, Inventor from group of authors: none, patent holder: Magnoric (30.04.2024), D) Apparatus and method for converting thermal energy into electrical energy, US 2021/11075333B2, 27.07.2021, Inventors from group of authors: Sebastian Fähler, Anja Waske, E) Non-resonant thermo-mechanical energy converter, EP 2016/2802069 B1, 30.11.2016, Inventor from group of authors: Manfred Kohl.

Data Availability Statement

Data sharing not applicable to this article as no datasets were generated or analysed during the current study.

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Supporting Information

Additional supporting information can be found online in the Supporting Information section.

Supporting File: adfm78789-sup-0001-SuppMat.pdf.