



Review Additive Manufacturing Methods for Thermal Energy Storage

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Abstract. The field of energy storage is undergoing significant transformation through the integration of additive manufacturing (AM). However, current challenges persist in addressing the optimization of material properties, precision, and manufacturing constraints in thermal energy storage (TES) systems. The aim of this study is to review the advancements in AM techniques as applied to TES systems, focusing on their ability to enhance thermal efficiency, reduce material wastage, and improve economic viability. The methodology employed is a systematic literature review (SLR), consolidating findings from previous studies to identify the effectiveness of AM in fabricating TES components. Key findings highlight that AM enables the creation of complex structures, such as lattices and composite phase change materials (PCMs), that improve heat transfer, thermal conductivity, and system stability. For instance, optimized fin designs produced via AM have reduced conduction resistance by up to 17 times. Additionally, integrating lattice frameworks and porous matrices has enhanced energy storage capabilities by improving temperature uniformity and reducing phase change material melting times. AM demonstrates transformative potential in TES by enabling innovative designs and efficient material usage. However, further research is required to address scalability, cost-effectiveness, and high-resolution manufacturing to fully realize its application in industrial energy storage systems.

Keywords: manufacturing innovation; additive manufacturing (AM); energy storage; thermal energy storage

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1. Introduction

Since its inception in the 1980s, additive manufacturing (AM), previously referred to as rapid prototyping, has fundamentally transformed the methodologies employed in the creation and development of goods. By utilizing computer-aided design (CAD) models, this innovative technique fabricates complex three-dimensional objects incrementally, thereby offering exceptional production versatility and operational efficiency (1). Progressions in additive manufacturing (AM), which initially focused on prototyping, have expanded its applicability and facilitated the production of finalized components and tailored solutions across various sectors, including construction, healthcare, and aerospace. Notable advantages of additive manufacturing (AM) in comparison to conventional production methods encompass enhanced design latitude and a reduction in material wastage. Nevertheless, there exist challenges that must be addressed, such as the limited availability of materials and the demand for enhanced precision, which drive research aimed at fully integrating AM into traditional manufacturing processes (2,3,4).

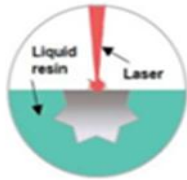
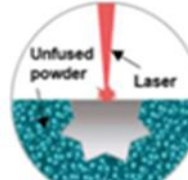
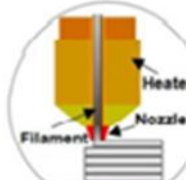
Additive manufacturing (AM), commonly known as 3D printing, exhibits significant distinctions when compared to subtractive manufacturing and traditional forming methodologies. This innovative approach facilitates the production of high-quality, customizable components from a diverse array of materials, including metals, ceramics, and polymers, without necessitating molds or machining (5). Various additive manufacturing (AM) techniques have been devised, including material jetting, extrusion, vat photopolymerization, powder bed fusion, binder jetting, sheet lamination, and direct energy deposition. These methodologies construct items incrementally by

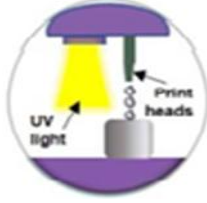
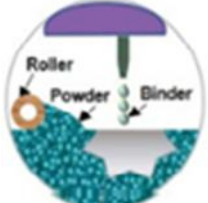
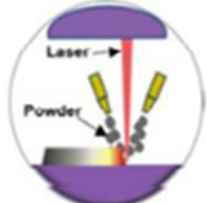
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methodically placing materials through the utilization of computer-aided design (CAD) technology (6,7). This additive approach enables the fabrication of intricate 3D structures utilizing a broad spectrum of materials and dimensions. Components produced via AM exhibit distinctive physical properties, such as enhanced stiffness, improved thermal conductivity, and superior damage resistance (8).

Beyond merely fabricating components, the engineering capabilities inherent in additive manufacturing (AM) also contribute significantly to the optimization of device architectures and material properties, thereby reducing the consumption of superfluous materials and minimizing production durations. To enhance the efficacy of thermal management systems, contemporary research endeavors have predominantly focused on the incorporation of phase change materials (PCMs) into complex structural designs (9). PCMs exhibit a remarkable ability to augment the efficiency of energy systems by alleviating peak thermal demands or by facilitating the distribution of thermal loads over extended periods. Components utilized in electric vehicles, such as batteries, laser systems, and power electronics, frequently encounter diverse operational conditions necessitating proficient thermal dissipation mechanisms. The implementation of thermal management systems, including heat sinks that integrate PCMs, is instrumental in absorbing significant heat fluxes and sustaining stable operational temperatures (10).

Table 1. Additive manufacturing technology categories (10)

Categories	Vat Photopolymerization	Powder Bed Fusion	Material Extrusion
Schematics Brief Description	 Liquid Photopolymer in a vat selectively cured by light-activated polymerization	 Powder Bed Areas Selectively Fused By Thermal Energy	 Material Selectively Dispensed Through an Aperture Or Nozzle
Technologies	SLA, DLP, CLIP	SLS, SLM, DMLS, EBM	FDM, FFF, DIW
Feedstock	Liquid	Powder	Filament, Rod, Liquid
Materials	Photopolymers	Metal, Polymers	Thermoplastics, metal, concrete, viscoelastic, liquid
Bonding And Join	Cured With Laser, Projector, UV Light	Fused With Laser and Electron Beam	Fused With Heat, Adhesive Force
Applications	• Fine Details • Smooth Surface Finish • Jewelry • Medical Applications	• Functional Metals (Aerospace and automotive) • Energy Systems • Medical Treatment • Dental Care	• Functional Engineering Prototypes and Systems
Benefits	• Smooth Surface • Fine Details	• Strong Parts • Scalable (Fits Size) • Complicated Geometry • No Support	• Fast • Low Cost • Common Thermoplastics
Limitations	• Brittle • UV Sensitive • Usually Require Supports • Extensive Post Processing	• Longer Production Time • Higher Cost • (Machinery, Material, Operation)	• Rough Surface Finish • Anisotropic • Usually Require Supports • Not Scalable • Limited Accuracy
Categories	Material Jetting	Binder Jetting	Directed Energy Deposition

Schematics Brief Description	 Selective Deposition of Build-Material Droplets	 Selective Application of A Liquid Binder To Bond Powder Materials	 Material Fused by Melting During Deposition Using Focused Thermal Energy
Technologies	EHD, AJ, Polyjet, MJP	MJF, SPJ	LENS, EBAM, LDW
Feedstock	Liquid	Powder, Liquid	Wire, Powder
Materials	Photopolymers, metal, Wax	Metal, Polymers, (ABS, PA, PC), Ceramic	Metal, Alloys
Bonding And Join	Cured With UV Light, Heat	Joined By Adhesive Binder	Fused With Laser, Electron Beam, Plasma-arc, or Electric-arc
Applications	• Prototyping And Tooling (Full-Colour) • Medical Models • Molds and Casting Patterns Production in Small Batches • Electronic Device	• Functional Metal Parts • Full-Colour Model • Sand Casting	• Repairing and Remanufacturing Automotive and Aerospace Components
Benefits	• Excellent Details • High Accuracy • Realistic Prototypes • Smooth Surface	• Full-Colour Options • A Variety of Material • No Warping or Shrinking • No Support	• Strong Parts • Range Of Materials • Large Parts
Limitations	• High Cost • Anisotropic Mechanical Properties	• Low Part Strength • Lower Accuracy Than Material Jetting	• High Cost • Poor Surface Finish

Due to the capability of additive manufacturing (AM) to fabricate structural materials exhibiting superior physical properties, its relevance in the domains of energy conversion and storage is progressively escalating. The advantages of this technology encompass a reduction in material waste, an augmentation in manufacturing efficiency, and an improvement in economic viability. The transformative potential of AM in the realms of both electrochemical and thermal energy storage is evidenced by recent advancements in its application for energy storage devices, which have catalyzed extensive research in these respective fields (11).

The complex architectures necessitated for components such as current collectors, electrodes, separators, and electrolytes render the fabrication of electrochemical energy storage devices (EESDs) exceptionally challenging. Moreover, the approach employed by various 3D printing systems is contingent upon the specific type of material utilized. For instance, techniques such as vat photopolymerization, jetting, and direct ink writing (DIW) utilize liquid materials, in contrast to binder jetting and powder bed fusion, which operate with solid materials. Consequently, prior to the initiation of the 3D printing process, it is imperative to thoroughly comprehend the capabilities inherent to each printing technique, the characteristics of the materials, and the overarching design and chemistry associated with EESDs (12).

Table 2. Digital design and optimization strategies for energy storage systems (11)

	Design And Optimization Strategies	Descriptions
Thermal Energy Storage	Cellular Structure	Strut-based Lattice TPMS Structure
	Inverse Design	Topology Optimization Data-driven Optimization

2. Methodology

This study provides a comprehensive review of existing literature to integrate the results and methodologies from previous studies. It follows the systematic literature review (SLR) methodology, as outlined in established protocols (13). The focus of the review is on the advancements in additive manufacturing (AM) technologies and their application to thermal energy storage (TES) systems. Specifically, it examines how AM can improve thermal efficiency, reduce material waste, and make TES systems more economically viable. The literature search was conducted using academic databases such as Scopus and Web of Science, with keywords related to AM and TES. Relevant studies were analyzed to identify trends in the use of AM to create complex structures, such as lattices and composite phase change materials, which can enhance thermal conductivity and system stability. The findings suggest that AM enables the design of innovative solutions that improve the performance of energy storage systems. However, further research is needed to address challenges such as scalability, cost-effectiveness, and high-resolution manufacturing.

3. Thermal Energy Storage and Manufacturing Methods

3.1 Thermal Energy Storage

Systems for thermal energy storage (TES) are widely used because they are affordable and long-lasting. TES materials can be divided into three primary groups, as illustrated in Figure 1, those that use sensible heat for heat storage, those that depend on latent phase shifts, and those that use thermochemical reactions. The advantages and disadvantages of sensible heat storage (14), latent heat storage (15), and thermochemical energy storage strategies (16) have been compared in a number of research.

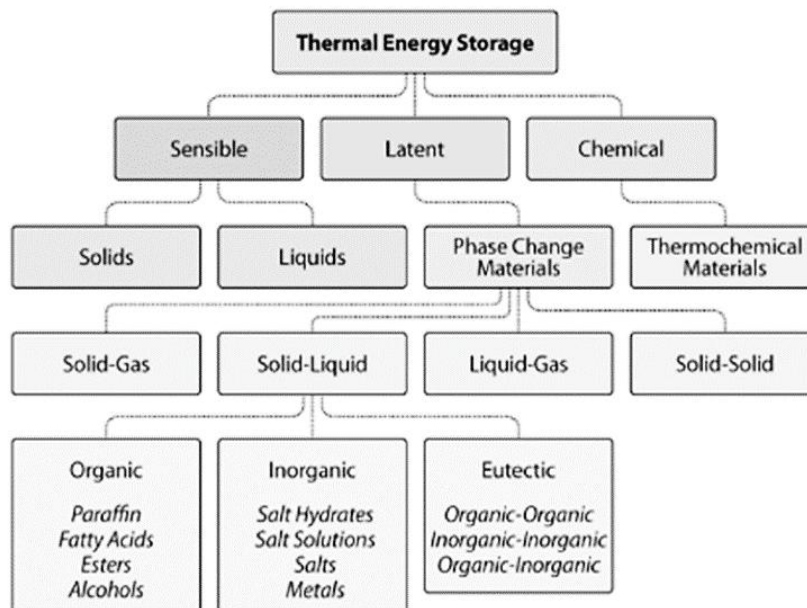


Figure 1. Characterization of thermal energy storage materials (16)

This section discusses the application of additive manufacturing (AM) in thermal energy storage (TES) systems (Table 3). The integration of additive manufacturing techniques in thermal energy conversion devices has been explored in many review articles (17). These methods provide advantages such as enhanced density, improved thermal efficiency, and greater cost efficiency. Thermal energy storage (TES) systems retain energy by either heating or cooling a medium for future utilization, as opposed to energy conversion devices. The low thermal conductivity of the molten salt medium is a major challenge in latent heat TES systems (18). One suggested solution is additive manufacturing (AM), which allows for the production of complex material structures. This approach has been utilized for various enhancement strategies, such as creating form-stable composite phase change materials (PCMs), integrating porous matrices with elevated thermal conductivity, and enhancing fin designs with larger surface areas. Given that AM techniques are often employed to

fabricate these performance-boosting structures, their relevance in diverse enhancement strategies will be assessed in the subsequent sections.

Table 3. Examples of thermal energy storage and manufacturing using additive manufacturing

Technology	Dimension	Design Approach	Remarks	Ref.
SLM	Length: 185 mm External Diameter: 90 mm Thickness: 6 mm	Topology optimization	The first AM multi-tube energy storage device	(19)
SLM	Length x Width x Height: 27 mm x 40 mm x 130 mm	3D-graded cellular structure	Phase-change temperature control with graded cellular design and thickness adjustment of the packaging structure	(20)
SLM	100 mm x 100 mm x 40 mm with a cell size of 10 mm	3D periodic cellular structures	Aluminum body-centred cubic cellular structures were fabricated and tested.	(21)
SLM	40 mm x 40 mm x 40 mm Porosity: 90%	Porous periodic cubic cell structure	Composite PCM embedded with a porous aluminium structure is fabricated.	(22)
SLM	Cell base: 10, 20, 40 mm Height: 40 mm Porosity: 95%	3D periodic structures	Fabrication of three different aluminum 3D periodic structures with enhanced heat transfer in the PCM heat storage.	(23)
SLM	26 mm x 26 mm x 26 mm with cell sizes of 4, 6.5, and 9 mm	Lattice structures with TPMS structures	AM lattices are inserted into PCMs for heat transfer augmentation.	(24)
DMLS	27 mm x 40 mm x 130 mm rectangular acrylic container	Lattice structures with internal and external fins	Enhanced thermal energy storage systems with AM technology	(25)
SLS	Diameter: 12.7 mm Thicknesses: 2–3 mm	Square, hollow square, and star structures	Expanded graphite/paraffin wax phase change composite is made up by SLS	(26)
SLA	-	Topology optimisation	Optimal fin configurations in multi-tube LHTES systems with different PCMs	(27)
SLA	Pore dimensions ($\varnothing$ 3.2 mm; $\varnothing$ 6.4 mm)	Reticular structure	The bio-based PCMs integrated into a metallic structure made of copper and aluminum	(28)
SLA	4.5 cm x 3.5 cm x 0.25 mm	-	3D printable phase-change polysiloxane networks were developed for human body temperature management.	(29)
FDM	1.75-mm diameter Layer height: 0.2 mm	-	3D printable TPU blends with thermal energy storage capabilities	(30)
FDM	0.8-mm diameter Layer height: 0.4 mm	Miniaturized complex geometries	Microencapsulated PCM for thermal energy storage	(31)
FDM	1.75 mm diameter filaments	-	Phase change fabrics were 3D printed for multifunctional clothing.	(32)
FFF	25 mm diameter and 4 mm thick	-	Fused filament fabrication of novel PCM functional composites	(33)
DIW	0.6 mm layer height	-	3D printed polymer-PCM phase change material composites for thermal energy regulation	(34)
DIW	80–500 μ m resolution	2D/3D complex patterns	PCMs were 3D printed as electronic packaging materials	(35)

3.2 Fins and Extended Surfaces Manufactured Using Additive Manufacturing

This section addresses the application of additive manufacturing (AM) in thermal energy storage (TES) devices (Table 3). The integration of AM techniques in thermal energy conversion systems has been extensively studied in various review articles (17). These methods provide several advantages, including greater density, enhanced thermal efficiency, and affordability. Thermal energy storage (TES) systems accumulate energy by either heating or cooling a medium for future utilization, unlike energy conversion devices. The low thermal conductivity of molten salt media presents a major challenge in latent heat TES systems (18). Additive manufacturing (AM) allows for the creation of complex material structures, making it a potentially attractive choice. Creating form-stable composite phase change materials (PCMs), incorporating porous matrices with superior thermal conductivity, and refining fin designs with enlarged surfaces are merely some of the improvement strategies that have utilized this technology. The upcoming sections will explore how these performance-boosting structures are utilized in different enhancement strategies, as they are often produced using AM techniques.

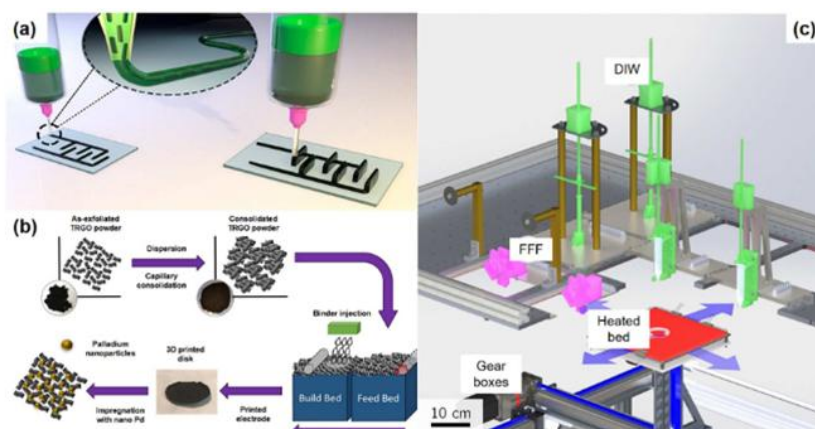


Figure 2. Additive manufacturing techniques used for supercapacitor production: (a) Direct ink writing (DIW) for micro-supercapacitors (MSCs) with an interdigital design (37), (b) Binder-jetting powder-based additive manufacturing for thick graphene-based electrodes (38), (c) Hybrid additive manufacturing (39)

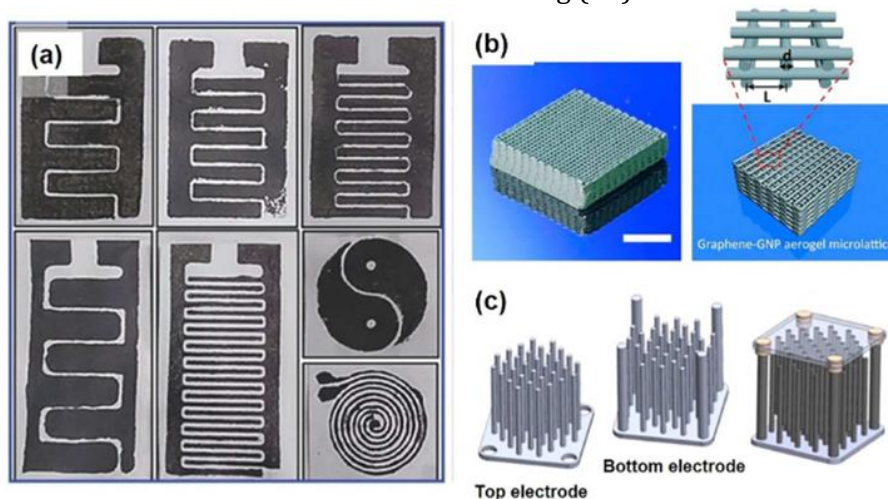


Figure 3. Supercapacitor additive manufacturing: (a) MXene-based supercapacitors with various architectural designs (40), (b) Compressible graphene aerogel micro-lattice produced using direct ink writing (41), (c) 3D interdigitated electrode structure (42)

The application of additive manufacturing (AM) techniques has significantly enhanced thermal energy storage systems by boosting the efficiency of heat transfer. For example, unlike traditional designs, a thermal energy storage system with high power density that utilizes phase change materials (PCMs) featuring internal and external fins reduced heat resistance from conduction by 17 times and by 3 times for convection, respectively (25). Optimization of fin design in multi-tube latent

heat thermal energy storage (LHTES) systems has been explored, taking into account factors like PCM type, flow configurations, and design limitations. The duration of pumping was reduced by 57.1% with fins produced through selective laser melting (SLM) and optimized using topology (43). Additionally, studies on the thermal and economic efficiency of these systems have shown that while the optimized fins offer significant thermal benefits, their cost-effectiveness is contingent upon the price ratio of the PCM to the enhancement method remaining below 6. Taking everything into account, AM methods present a practical approach to improving thermal storage systems, especially when combined with suitable design strategies and process parameters (36).

3.3 Lattice Structure Impregnation through Additive Manufacturing

A promising method to enhance the efficiency of thermal energy storage (TES) systems is to integrate lattice structures created through additive manufacturing (AM) into phase change materials (PCMs). Research indicates that AM lattices offer notable benefits compared to traditional metal foams due to their accurately controlled geometries, like those produced by selective laser melting (SLM). Enhanced heat distribution, greater thermal conductivity, and superior overall performance in TES applications are among these advantages. For example, thermal management systems can significantly improve heat transfer efficiency by integrating external packing structures and multilayer cellular materials. Key factors in this enhancement consist of the thickness of the material walls and the distribution of porosity. According to studies by Diani et al. (21) and Hu et al. (22), employing porous aluminum frameworks and slender metal structures can improve temperature uniformity throughout the system and speed up the melting of phase change materials (PCMs). Specifically, it has been shown that incorporating porous metals like copper can enhance the overall thermal efficiency and thermal conductivity of phase change materials (PCMs) by as much as 63%. Additionally, research by Zhang et al. (20) and Righetti et al. (23) found that aluminum structures with embedded PCM and 3D periodic designs can reduce charge and discharge times. It was found that reduced cell sizes (approximately 10 mm) enhanced temperature distribution and lowered junction temperatures.

Due to recent developments in Triply Periodic Minimal Surface (TPMS) designs, thermal energy storage (TES) devices are now more efficient. According to a study by Qureshi et al. (44), TPMS-based metal foam PCMs, like Gyroid, IWP, and Primitive structures, can decrease melting time by as much as 40% compared to traditional Kelvin-based foams. Additionally, Zhang et al. (24) emphasized the importance of functional gradation and lattice porosity in improving heat storage capacity. However, at times, incorporating metallic foam may hinder the movement of molten salt, potentially reducing natural convection. To ensure optimal heat transfer efficiency, optimizing the density and distribution of metallic foams is essential. Moreover, research by Almonti et al. (28) indicated that when combined with copper reticular structures, bio-based PCMs derived from agricultural waste exhibited a 10% enhancement in heat storage and release. These experiments show the significance of optimizing material choice and lattice design to enhance TES system efficiency.

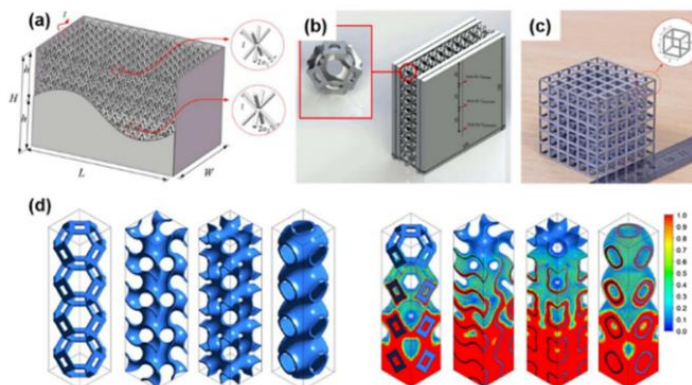


Figure 4. Integration of lattice structures created using additive manufacturing: (a) Cascading cellular design to enhance thermal conductivity (20), (b) Periodic body-centered cubic cellular structure (21), (c) Periodic simple cubic cellular structure (22), (d) TPMS-based metal foam structure (45)

3.4 Shape-Stable Composite PCMs Produced Using Additive Manufacturing

Composite phase change materials (PCMs) offer a possible solution to the issues caused by molten salts in thermal energy storage (TES) systems. Due to their enhanced properties that boost the effectiveness and stability of thermal energy storage, these materials present a vast array of potential applications, spanning from wearable devices to energy harvesting. Nofal et al. (26) created larger paraffin wax/graphite composites through selective laser sintering (SLS). These composites exhibited latent heat values ranging from 150 to 156 kJ/kg and thermal conductivity values spanning from 0.83 to 0.92 W m⁻¹ K⁻¹. These materials show potential for regulating heat in lithium-ion batteries. Thermoplastic polyurethane (TPU) and composites based on polymer filaments printed with FDM and FFF methods were examined by Rigotti et al. [30] and Freeman et al. (33), who demonstrated energy storage abilities with melting enthalpies reaching 70 J/g. Nonetheless, air gaps formed during the printing process were identified as the reason for limitations in heat conductivity. Feng et al. [35] incorporated paraffin-based PCMs into electronic packaging, achieving a latent heat of 145.6 J/g, whereas Wei et al. (34) developed the direct ink writing (DIW) method to manufacture ink-filled PCMs for energy-efficient 3D-printed designs.

The versatility of composite phase change materials produced by 3D printing is further showcased through innovative designs for wearable and electronic uses. For application in wearable fabrics, Ma et al. (29) developed phase change polysiloxane networks exhibiting latent heat values between 24.9 and 125.3 J/g. Yang et al. (32) produced flexible phase change sheets with single-wall carbon nanotubes, achieving a latent heat of 65 J/g and a thermal conductivity of 0.52 W/m·K. These advancements show how 3D printing technology can tailor PCM composites for various applications, such as efficient thermal management and the ability to create complex geometric designs. In this context, the use of composite PCMs holds significant potential for improving thermal energy storage (TES) efficiency in areas like wearable technologies, electronics, and building systems.

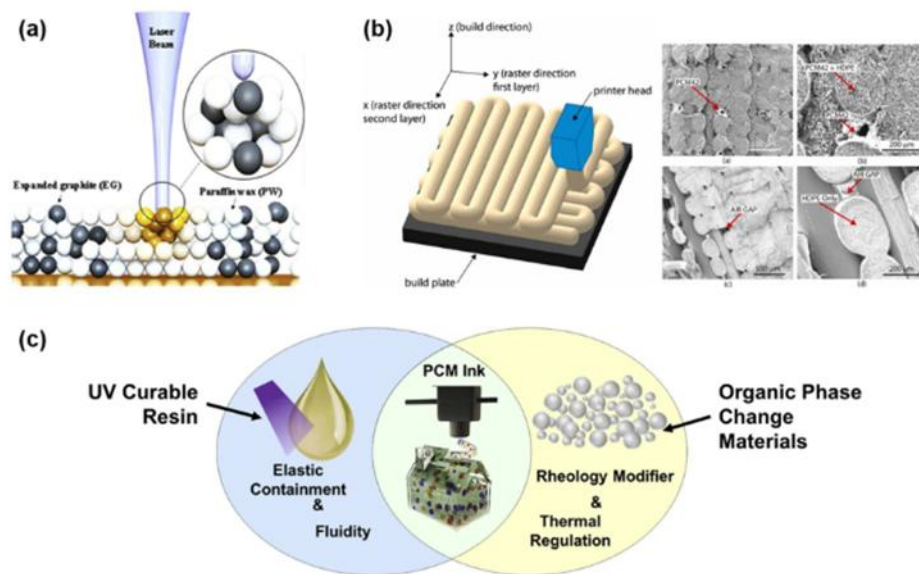


Figure 5. Illustration of additive manufacturing of composite PCMs: (a) SLS process for expanded paraffin wax/graphite composites (26), (b) FFF process for composite PCMs, showing molded samples like PCM42/HDPE and HDPE (33), (c) DIW process for polymer-PCM composites (34)

3.5 Digital Design

By adjusting parameters and settings for optimal performance, the integration of additive manufacturing (AM) and digital design methods greatly improves the efficiency of energy storage devices. More efficient design processes arise from the valuable perspectives that multiphysics numerical modeling provides on material interactions and transport methods. Powder-based additive manufacturing (AM) techniques necessitate the implementation of process modeling approaches such as finite element analysis, lattice Boltzmann (LB), and the discrete element method (DEM). These models tackle challenges such as melt pool behavior and powder distribution, which

are essential for improving the manufacturing of electrochemical energy storage devices, particularly those produced through direct ink writing (DIW). These models help enhance the overall manufacturing process by refining material application and layer bonding (Figure 6). By integrating a process-microstructure-performance framework, the design and manufacturing duration of advanced energy storage systems can be considerably reduced (46,46,47).

The application of digital design principles and optimization methods at micro and nanoscale levels can drive innovations in materials and structural design. For example, Zheng et al. demonstrated the potential of micro-lattice octets, characterized by thicknesses ranging from 40 to 210 nm, and possessing outstanding mechanical properties. The performance of the device is enhanced by topology optimization, which modifies structural elements at various scales. Design trade-offs, such as harmonizing energy density with charge/discharge rates in lithium-ion batteries, are tackled using advanced simulation methods and data-informed design approaches. Upcoming advancements are expected to create complex 3D hierarchical structures that could significantly improve energy storage capabilities, including nano-topology optimization and advanced micro-AM methods such as projection micro-stereolithography (48,49,50,51).

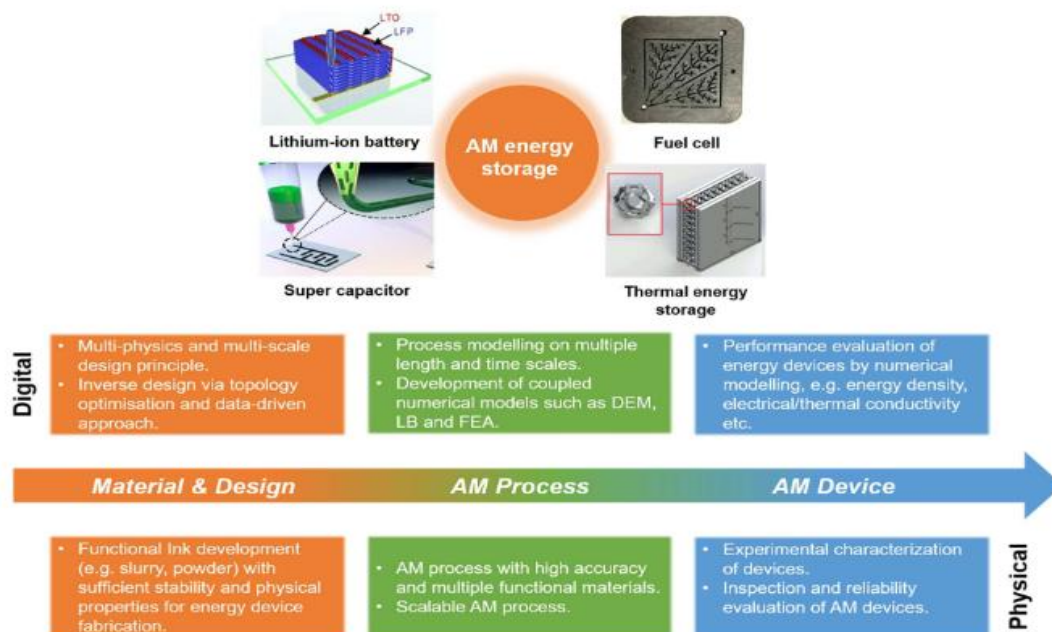


Figure 6. Multiscale digital and physical research roadmap for additive manufacturing (AM) energy storage techniques (21,37,52, 53,)

3.6 Additive Manufacturing Process

Due to its ability to precisely control material composition and eliminate the need for assembly after production, additive manufacturing (AM) has transformed the development of functional energy storage devices. This technology enables the creation of devices with enhanced charge/discharge abilities; however, further advancements in ink formulation and printing resolution are necessary. The ink should include active components such as carbon, metal oxides, and phase change materials (PCMs), and possess suitable electrical properties and viscosity. To boost the application of additive manufacturing in energy storage, a greater variety of commercially accessible options for solid materials, such as powders and filaments, needs to be created. AM systems also necessitate higher printing resolutions to create hierarchical structures at the nano and microscales, which are vital for optimizing energy storage performance. Examining anisotropic structures created through additive printing may also result in the emergence of new characteristics in energy storage and related domains (43,54,55,56,57).

The expensive nature and restricted ability for large-scale manufacturing hinder the expansion of additive production for industrial energy storage uses. Most additive manufacturing methods are presently limited to laboratory-scale prototypes. Fast and scalable additive manufacturing techniques are essential for lowering expenses and enabling mass production. Economic

assessments of thermal energy storage indicate that the cost ratio between thermal methods enhanced by additive manufacturing and phase change materials (PCMs) must be below six for these methods to be financially viable. Additional advancements in material research, improvements in resolution, and scalable manufacturing methods are necessary to address the current challenges, despite the potential of incorporating additive manufacturing into energy storage production (43, 56,57).

4. Conclusion

In this review, various additive manufacturing (AM) technologies have been evaluated for their application in thermal energy storage (TES) systems. AM, as a technology that enables the creation of complex geometric structures with high precision, has demonstrated significant potential in enhancing heat transfer efficiency and thermal energy storage capacity. Technologies such as Selective Laser Melting (SLM), Fused Deposition Modeling (FDM), and Direct Ink Writing (DIW) have been widely used to produce porous, reticular, and polymer-based structures that support the improved performance of phase change materials (PCM).

Each AM method has distinct advantages and disadvantages depending on specific conditions. For example, powder bed fusion techniques like SLM are highly suitable for creating complex metal structures with high precision but involve higher production costs. Conversely, methods such as material extrusion or FDM offer more economical solutions for prototypes with lower geometric complexity. Direct Ink Writing (DIW) enables the printing of polymer-PCM composite materials with high resolution, making it ideal for temperature regulation applications and electronic packaging. However, this study also highlights that no AM method can be universally considered superior. The choice of the best method heavily depends on specific factors such as the materials used, heat transfer requirements, thermal properties, structural durability, and production scale. Therefore, combining AM methods with optimal design approaches is crucial to meet the specific needs of TES applications.

Overall, the use of AM technology in TES presents significant opportunities for innovation in achieving more efficient and sustainable energy storage. Further studies are recommended to explore the optimization of AM methods that are more integrated with material and TES system designs to achieve higher performance.

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