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Revolutionizing Energy Storage with 3-D Printable Batteries: A Comprehensive Review

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Abstract: This paper provides a review of different types of batteries and explores the potential of 3-D printing technology in battery fabrication. Batteries are essential for powering a wide range of devices, from small electronics to large-scale systems. With the advancement of technology, various types of batteries have been developed, each with unique properties and applications.

The emergence of 3-D printing technology has provided new opportunities for the development of batteries with custom designs and shapes. In this paper, we review the different types of batteries, including lithium-ion, nickel-cadmium, lead-acid, zinc-carbon, and alkaline batteries. We discuss their properties and applications, as well as their advantages and disadvantages. We also explore the potential of 3-D printing technology in battery fabrication, including the use of conductive polymers, graphene, and metal nanoparticles.

We examine the various design possibilities offered by 3-D printing technology, such as the ability to fabricate batteries with custom shapes and sizes, and discuss the potential applications of 3-D printable batteries, such as wearable devices and electronics. Overall, this paper provides an overview of the different types of batteries and the potential of 3-D printing technology in battery fabrication, highlighting the importance of sustainable and efficient energy storage solutions.

Index Terms - battery, 3-d printed battery, energy Density, life cycle, lithium-ion battery

I. INTRODUCTION

The demand for efficient and sustainable energy storage solutions has increased in recent years due to the rapid development of technology. Batteries play a vital role in meeting this demand, powering a wide range of devices, from small electronics to large-scale systems [1]. The development of various types of batteries has been a topic of research for decades, with the aim of improving energy density, longevity, and safety. In recent years, 3-D printing technology has emerged as a promising fabrication technique for batteries, offering the potential for customized designs and shapes [2].

In this paper, we provide a comprehensive review of different types of batteries and explore the potential of 3-D printing technology in battery fabrication. We discuss the properties and applications of various types of batteries, including lithium-ion, nickel-cadmium, lead-acid, zinc-carbon, and alkaline batteries [3][4][5][6][7]. We also examine the advantages and disadvantages of each type of battery and their potential impact on energy storage. Furthermore, we explore the potential of 3-D printing technology in battery fabrication, including the use of conductive polymers, graphene, and metal nanoparticles [8]. We examine the various design possibilities offered by 3-D printing technology, such as the ability to fabricate batteries with custom shapes and sizes, and discuss the potential applications of 3-D printable batteries, such as wearable devices and electronics [9][10].

Overall, this paper aims to provide an overview of different types of batteries and the potential of 3-D printing technology in battery fabrication, highlighting the importance of sustainable and efficient energy storage solutions. The rest of the paper is organized as follows: Section II discusses the different types of batteries and their properties; Section III explores the potential of 3-D printing technology in battery fabrication; Section IV discusses the challenges and future directions of 3-D printable batteries; and finally, Section V concludes the paper.

II. Overview of Different Types of Batteries

Batteries are electrochemical devices that convert chemical energy into electrical energy. There are various types of batteries available in the market that differ in their chemistries, materials, and applications. In this section, we provide a brief overview of some commonly used batteries, including lead-acid, lithium-ion, nickel-cadmium, zinc-carbon, and zinc-air batteries.

a. Lead-Acid Batteries

Lead-acid batteries are the most commonly used batteries in automotive and industrial applications due to their low-cost, highpower density, and durability [4]. These batteries are composed of lead and lead oxide electrodes immersed in a sulfuric acid electrolyte. During discharge, the lead electrode reacts with sulfuric acid to form lead sulfate and releases electrons. The lead oxide electrode reacts with sulfuric acid and water to form lead sulfate and oxygen. During charging, the reverse reactions occur, and the battery is restored to its original state.

b. Lithium-Ion Batteries

Lithium-ion batteries are widely used in portable electronics and electric vehicles due to their high energy density, low selfdischarge rate, and long cycle life [1]. These batteries use a lithium-ion electrolyte to transport lithium ions between the anode and cathode during charging and discharging. The anode is typically made of graphite, and the cathode is made of a lithiummetal oxide or phosphate compound.

c. Nickel-Cadmium Batteries

Nickel-cadmium batteries were widely used in portable electronics before the introduction of lithium-ion batteries [5]. These batteries use a nickel-hydroxide cathode and a cadmium anode, and an alkaline electrolyte containing potassium hydroxide. During discharge, the nickel-hydroxide cathode releases electrons, and cadmium anode oxidizes to form cadmium hydroxide. During charging, the reverse reactions occur, and the battery is restored to its original state.

d. Zinc-Carbon Batteries

Zinc-carbon batteries are low-cost primary batteries used in low-drain devices such as clocks and remote controls [6]. These batteries use a zinc anode, a carbon cathode, and a manganese dioxide electrolyte. During discharge, the zinc anode oxidizes to form zinc oxide, releasing electrons. The manganese dioxide cathode reduces to form manganese oxide. During charging, the battery cannot be recharged, and the reactions are irreversible.

e. Zinc-Air Batteries

Zinc-air batteries are low-cost primary batteries that are used in hearing aids and other medical devices due to their high energy density [7]. These batteries use a zinc anode and an air cathode. Oxygen from the air is used as the cathode material, and a potassium hydroxide electrolyte is used to transport ions between the anode and cathode. During discharge, the zinc anode oxidizes to form zinc oxide, releasing electrons. The oxygen from the air reacts with water to form hydroxide ions, which migrate to the anode. During charging, the reverse reactions occur, and the battery is restored to its original state.

2.1 Energy Density

Table 1: Comparison of 3D Printable Batteries with Conventional Batteries based on Energy Density.

Battery Type	Energy Density (Wh/kg)
Lead-Acid	30-40
Lithium-Ion	100-250
Nickel-Cadmium	50-60
Zinc-Carbon	50-60
Zinc-Air	120-180
3D Printable Battery	10-100

The energy density values may vary depending on the specific design and materials used for 3D printable batteries. The energy density of a battery is a measure of how much energy it can store per unit mass. It is an important factor in determining the performance and application of a battery. Table I and figure 1 compares the energy density of 3D printable batteries with conventional batteries, including lead-acid, lithium-ion, nickel-cadmium, zinc-carbon, and zinc-air batteries.

Lithium-ion batteries have the highest energy density among conventional batteries, ranging from 100 to 265 Wh/kg [1]. Zinc-air batteries also have a high energy density, ranging from 120 to 180 Wh/kg [7]. Lead-acid and nickel-cadmium batteries have relatively lower energy densities, ranging from 30 to 60 Wh/kg [4, 5]. Zinc-carbon batteries have the lowest energy density, ranging from 30 to 50 Wh/kg [6]. In comparison, 3D printable batteries have a lower energy density than conventional batteries, ranging from 10 to 100 Wh/kg [2, 3, 13, 14].

This is due to the limitations of 3D printing technology and the materials used for the batteries. However, with advancements in 3D printing technology and materials, the energy density of 3D printable batteries is expected to improve in the future.



Figure.1: Comparison of 3D Printable Batteries with Conventional Batteries based on Energy Density

2.2 Charge Time

Table 2: Comparison of 3D Printable Batteries with Conventional Batteries base	1 on Charge Time	Э
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Battery Type	Charge Time	
Lead-Acid	8-16 hrs	
Lithium-Ion	1-2 hrs	
Nickel-Cadmium	1-2 hrs	
Zinc-Carbon	Non-rechargeable	
Zinc-Air	Non-rechargeable	
3D Printable Battery	30 mins-2 hrs	

The charge time values may vary depending on the specific design and materials used for 3D printable batteries. The charge time of a battery is the time it takes to recharge the battery from an empty or partially discharged state to a fully charged state. It is an important factor in determining the usability and convenience of a battery. Table 2 compares the charge time of 3D printable batteries with conventional batteries, including lead-acid, lithium-ion, and nickel-cadmium batteries.

Lithium-ion and nickel-cadmium batteries have relatively short charge times, ranging from 1 to 2 hours [1, 5]. Lead-acid batteries have longer charge times, ranging from 8 to 16 hours [4]. Zinc-carbon and zinc-air batteries are non-rechargeable, and therefore do not have a charge time. In comparison, 3D printable batteries have relatively short charge times, ranging from 30 minutes to 2 hours [2, 3, 13, 14]. This is due to the use of specialized 3D printing techniques and materials that enable fast and efficient charging. However, the charge time of 3D printable batteries may vary depending on the specific design and materials used.



Fig.2 Comparison of 3D Printable Batteries with Conventional Batteries based on Charge Time

2.3 Life Cycle

Table 3: Comparison of 3D Printable Batteries with Conventional Batteries based on Life Cycle

Battery Type	Life Cycle	
Lead-Acid	200-300	
Lithium-Ion	500-1000	
Nickel-Cadmium	500-1000	
Zinc-Carbon	10-25	
Zinc-Air	80-100	
3D Printable Battery	100-500	



Figure.3: Comparison of 3D Printable Batteries with Conventional Batteries based on Life Cycle

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The life cycle values may vary depending on the specific design and materials used for 3D printable batteries. The life cycle of a battery is the number of times it can be charged and discharged before its performance significantly deteriorates. It is an important factor in determining the durability and cost-effectiveness of a battery. Table 3 compares the life cycle of 3D printable batteries with conventional batteries, including lead-acid, lithium-ion, nickel-cadmium, zinc-carbon, and zinc-air batteries.

Lithium-ion and nickel-cadmium batteries have relatively high life cycles, ranging from 500 to 1000 cycles [1, 5]. Lead-acid batteries have lower life cycles, ranging from 200 to 300 cycles [4]. Zinc-carbon and zinc-air batteries have much lower life cycles, ranging from 10 to 25 cycles and 80 to 100 cycles, respectively [6, 7].

Table 4. Comparison of 3-D	printed battery with	h conventional battery
1	1 2	2

Factor	3D Printed Battery	Lead-Acid Battery	Lithium-ion Battery	Nickel-Cadmium Battery	
	A 111.1				
Manufacturing	Additive		D = 11 (11		
process	manufacturing	Casting or stamping	Roll-to-roll process	Injection moulding or welding	
		Lead dioxide			
	Zinc or magnesium	(positive), lead	Lithium cobalt oxide	Nickel hydroxide (positive),	
Electrode	alloy, silver	(negative), lead alloy	(LCO), lithium iron	cadmium hydroxide	
material	conductive ink	grid	phosphate (LFP),	(negative)	
	lla.		Also and		
Separator	D.1	Absorbent glass mat	D 1		
material	Polymer or cellulose	(AGM)	Polymer or ceramic	Nickel-plated steel of plastic	
Els stus luts	Gel polymer	Delymer Lithium salt in organic		Detective hydroxide or nickel	
Electrolyte	liquid electrolyte	Summer actu of lead	solvent of polymer	budrovide electrolute	
material	iiquid electrolyte	Oxide electrolyte	electrolyte		
Design		Service States	and the second		
flexibility	High	Low	Low	Low	
Energy density	20-70 Wh/L	30-40 Wh/L	100-265 Wh/L	40-60 Wh/L	
Dowon donaity	50 200 W/I-2	90 120 W//ra	150 250 W//ra	50 70 W//ra	
Power density	50-200 W/Kg	80-120 W/Kg	150-250 W/Kg	50-70 W/Kg	
Cycle life	100-300 cycles	200-500 cycles	500-1000 cycles	500-1000 cycles	
Self-discharge					
rate	- 1	1-3% per day	1-2% per month	20-30% per month	
				· · · · · · · · ·	
Environmental	Lower than				
impact	traditional	Higher than 3D printed	Higher than 3D printed	Moderate	
Safety	Unknown	Moderate	High	Moderate	
Safety	UIIKIIOWII	wioderate	Tigli	widdefate	
		Automotive, backup	Portable electronics,		
Application	Can be used in all	power, stationary	electric vehicles,	Portable electronics, power	
areas	types of applications	storage	aerospace	tools	

In comparison, Aa shown in the figure 4. 3-D printable batteries have a moderate to high life cycle, ranging from 100 to 500 cycles [2, 3, 13, 14]. This is due to the use of specialized 3D printing techniques and materials that enable the batteries to withstand repeated charging and discharging. However, the life cycle of 3D printable batteries may vary depending on the specific design and materials used.

III. 3 -D Printable Battery Technologies

3D printable batteries are a promising new technology that has the potential to revolutionize the field of energy storage. These batteries are designed using specialized 3D printing techniques and materials that allow them to be printed in complex shapes and sizes, and to be integrated directly into other 3D printed devices. In this section, we will discuss some of the key 3D printable battery technologies that are currently being developed and studied.

A. Lithium-Ion 3D Printable Batteries

Lithium-ion batteries are one of the most widely used battery technologies due to their high energy density, long cycle life, and relatively low cost [6]. Lithium-ion 3D printable batteries are being developed using a variety of printing techniques, including inkjet printing, aerosol jet printing, and direct ink writing [7]. These batteries are typically printed using lithium-ion battery ink, which contains the active materials required for energy storage, as well as conductive additives and binders that help to hold the ink together [8].

B. Zinc-Based 3D Printable Batteries

Zinc-based batteries are another promising technology for 3D printing due to their high energy density, low cost, and environmental sustainability [9]. Zinc-based 3D printable batteries are typically printed using zinc oxide ink, which contains the active materials

required for energy storage, as well as conductive additives and binders. These batteries are being developed using a variety of printing techniques, including inkjet printing, aerosol jet printing, and direct ink writing [10].

C. Solid-State 3D Printable Batteries

Solid-state batteries are a relatively new type of battery technology that use solid electrolytes instead of liquid or gel electrolytes [11]. Solid-state 3D printable batteries are being developed using a variety of printing techniques, including inkjet printing and direct ink writing [12]. These batteries are typically printed using solid-state battery ink, which contains the active materials required for energy storage, as well as solid electrolytes and conductive additives [13].

D. Graphene-Based 3D Printable Batteries

Graphene is a highly conductive and lightweight material that has unique electrical and mechanical properties [14]. Graphene-based 3D printable batteries are being developed using a variety of printing techniques, including inkjet printing and direct ink writing [15]. These batteries are typically printed using graphene ink, which contains the active materials required for energy storage, as well as conductive additives and binders [16]. Graphene-based 3D printable batteries have the potential to provide high energy density and fast charging rates.

In summary, 3D printable battery technologies are a rapidly advancing field that has the potential to revolutionize the way we store and use energy. Lithium-ion, zinc-based, solid-state, and graphene-based 3D printable batteries are just a few examples of the many different types of 3D printable batteries that are currently being developed and studied. As these technologies continue to evolve and improve, they may become an important part of our future energy infrastructure.

	Printing Technique References				
Туре	Energy Density (Wh/L)	Charge Time (hours)	Cycle Life		
Lithium- ion	800-1000	2-4	500	Inkjet printing, Aerosol jet printing, Direct ink writing	[7-8], [20-23]
Zinc- based	450	2-3	1500	Inkjet printing, Aerosol jet printing, Direct ink writing	[10], [24-28]
Solid- State	300-400	2-3	1000	Inkjet printing, Direct ink writing	[12-13], [29-32]
Graphene- based	2000	1-2	200	Inkjet printing, Direct ink writing	[15-16], [33-36]

Table 5: Comparison of 3D Printable Battery Technologies

The energy density of a battery is an important factor that determines its capacity to store energy. Lithium-ion 3D printable batteries have an energy density ranging from 800-1000 Wh/L [20], which is higher than the other 3D printable battery technologies. Zinc-based 3D printable batteries have an energy density of 450 Wh/L [24], while solid-state batteries have an energy density of 300-400 Wh/L [29]. Graphene-based 3D printable batteries have the highest energy density of 2000 Wh/L [33].

The charge time of a battery is another important factor to consider. Lithium-ion 3D printable batteries have a charge time of 2-4 hours [21], while zinc-based batteries have a charge time of 2-3 hours [25]. Solid-state batteries have a charge time of 2-3 hours [30], while graphene-based batteries have a faster charge time of 1-2 hours [34].

Cycle life refers to the number of charge-discharge cycles a battery can undergo before it starts to degrade. Lithium-ion 3D printable batteries have a cycle life of 500 cycles [22], while zinc-based batteries have a cycle life of 1500 cycles [26]. Solid-state batteries have a cycle life of 1000 cycles [31], while graphene-based batteries have a cycle life of 200 cycles [35].

The printing technique used to fabricate a 3D printable battery also affects its performance. Lithium-ion, zinc-based, and solid-state 3D printable batteries can be fabricated using inkjet printing, aerosol jet printing, and direct ink writing [7], [10], [12]. Graphene-based 3D printable batteries can be fabricated using inkjet printing and direct ink writing [15].

Overall, each type of 3D printable battery technology has its own advantages and limitations. Lithium-ion batteries have a high energy density but a shorter cycle life, while zinc-based batteries have a lower energy density but a longer cycle life. Solid-state batteries offer a safer alternative to traditional lithium-ion batteries but have a lower energy density. Graphene-based batteries offer the highest energy density and fast charging rates, but have a shorter cycle life. The choice of 3D printable battery technology will depend on the specific application and performance requirements.

IV. Challenges and Future Directions

Despite the promising advantages of 3D printable battery technology, there are still several challenges that need to be addressed. One of the main challenges is improving the energy density of 3D printable batteries while maintaining their structural integrity. While graphene-based batteries offer the highest energy density, they still suffer from limited cycle life. Researchers are exploring various materials and designs to improve the energy density and cycle life of 3D printable batteries [37], [38].

Another challenge is improving the printing resolution and accuracy of 3D printable batteries. While inkjet printing and direct ink writing techniques have been used to fabricate 3D printable batteries, the printing resolution is still limited. Improving the printing resolution and accuracy will enable the fabrication of smaller and more complex battery designs [39].

Furthermore, the scalability of 3D printable battery production is another challenge that needs to be addressed. Current 3D printing techniques are still limited in terms of production volume and speed. Increasing the production volume and speed will make 3D printable batteries more accessible and cost-effective for commercial applications [40].

In the future, 3D printable battery technology is expected to play a significant role in the development of portable and wearable devices, as well as electric vehicles. Further research is needed to optimize the performance of 3D printable batteries and develop new materials and printing techniques. Advances in 3D printable battery technology have the potential to revolutionize the energy storage industry and address the growing demand for sustainable and efficient energy solutions.

In conclusion, 3D printable batteries have emerged as a promising technology for energy storage, with the potential to offer high energy density, fast charging rates, and customizable designs. The development of 3D printable battery technology is still in its early stages, and researchers are exploring various materials, printing techniques, and designs to optimize the performance and scalability of 3D printable batteries. The challenges and future directions discussed in this section highlight the opportunities for further research and development in this exciting field.

V. Conclusion

In this paper, we have reviewed the current state of 3D printable battery technology and compared it to conventional battery technologies. The review highlighted the advantages of 3D printable batteries, including their customizable designs, fast charging rates, and potential for high energy density. We also discussed the challenges facing 3D printable battery technology, such as improving energy density, printing resolution and accuracy, and scalability.

Despite these challenges, 3D printable battery technology has enormous potential for a wide range of applications, from portable and wearable devices to electric vehicles and grid-level energy storage. The ability to customize the shape and size of batteries using 3D printing technology opens up new possibilities for device design and energy storage optimization.

Future research in 3D printable battery technology should focus on improving the energy density, cycle life, printing resolution and accuracy, and scalability of these batteries. Advances in materials science, printing techniques, and battery management systems will be essential to realizing the full potential of 3D printable battery technology.

In conclusion, 3D printable battery technology is an exciting and rapidly evolving field with enormous potential for the development of sustainable and efficient energy solutions. With further research and development, 3D printable batteries could play a crucial role in addressing the growing demand for energy storage and powering the devices and systems of the future.

