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PREFACE

We take great pride in presenting this special edition of BHOUTIKI Pradnya, devoted to the fascinating and rapidly evolving field of Energy Storage Materials. As the world moves toward a more electrified and sustainable future, the ability to store, manage, and efficiently utilize energy has become one of the defining scientific and technological challenges of our time. From portable electronics and electric vehicles to renewable-energy integration and advanced power systems, efficient energy technologies are increasingly shaping modern life.

This edition brings together a diverse collection of articles exploring the materials, mechanisms, and innovations driving progress in this field. The issue covers topics such as next-generation battery materials, solid-state electrolytes, advanced electrode architectures, nanostructured materials, ion transport, electrochemical systems, and emerging approaches for sustainable energy technologies. At the heart of these developments lies the quest for better materials and a deeper understanding of their properties—from atomic-scale interfaces and ion migration to the design of novel structures and architectures. The field therefore offers a compelling example of how physics, chemistry, materials science, and engineering converge to address challenges in performance, safety, durability, and sustainability.

The BHOUTIKI Physics Club is proud to present this edition as an exploration of this dynamic scientific landscape. Alongside the technical articles, the issue features creative and engaging content that brings these concepts closer to our readers while celebrating the curiosity, creativity, and scientific spirit of our students.

Through this special issue, we hope to spark curiosity about the science behind the technologies that power our everyday lives and encourage readers to look beyond familiar devices to appreciate the complex interplay of materials, physics, chemistry, and engineering. May this edition of BHOUTIKI Pradnya serve not only as a repository of knowledge, but also as an inspiration to explore, question, and imagine the technologies of tomorrow.

ABOUT COLLEGE



Welcome to Nowrosjee Wadia College – A Beacon of Excellence Since 1932

Established on July 21, 1932, just months after the founding of the Modern Education Society, Nowrosjee Wadia College has stood as a pillar of academic brilliance and cultural vibrancy in Pune. Guided by its inspiring motto “For the Spread of Light,” the college has been instrumental in opening doors to higher education for generations of students, especially in the eastern region of the city.

Affiliated with Savitribai Phule Pune University and proudly holding autonomous status, Nowrosjee Wadia College has earned numerous accolades, including the prestigious First Best College Award from SPPU and an A+ grade from NAAC in 2017. The college continues to shine as a consecutive Divisional Winner of JALLOSH, the university’s celebrated cultural fest.

Offering a rich blend of undergraduate and postgraduate (NEP 2.0) programs in both Science and Arts disciplines, the college attracts bright minds from across India and abroad. With world-class infrastructure, vibrant student life, and a legacy of excellence, Nowrosjee Wadia College remains the first choice for holistic education and personal growth.

ABOUT DEPARTMENT

Department of Physics – Advancing Research and Innovation

The Department of Physics at Nowrosjee Wadia College, Pune, is a recognized postgraduate teaching and research center under Savitribai Phule Pune University (SPPU). It currently offers comprehensive academic programs leading to B.Sc., M.Sc., and Ph.D. degrees, fostering a strong foundation in both theoretical and applied physics.

A hallmark of the department is the Electro-Acoustics Research Laboratory (EARL), an SPPU-recognized center for doctoral research. Building on its legacy of excellence, the department has expanded into Materials Science, with the Advanced Functional Materials Laboratory (AFML) offering cutting-edge research opportunities in nanomaterials and functional thin films. These studies focus on conductive and transient properties crucial to thin-film device technologies.

The department has successfully guided numerous Ph.D. and M.Phil. scholars and continues to mentor several active research candidates. Its commitment to innovation is supported by grants from prestigious bodies including the American Physical Society (APS), University Grants Commission (UGC), Indian Space Research Organization (ISRO), Department of Science and Technology (DST) and Board of College and University Development (BCUD-UoP).

ABOUT BHOUTIKI



The term 'BHOUTIKI' in the Physics Club logo likely signifies 'Physics' in Sanskrit, encapsulating the foundational principles of the natural sciences. It beautifully reflects the essence of exploring the physical universe, spanning phenomena from the microscopic to the cosmic scale.

Through 'BHOUTIKI,' we aim to honour the legacy of scientific excellence and inspire a new generation of physicists to delve into the mysteries of the universe.

Throughout the year, the club will host a wide variety of activities, each thoughtfully designed to spark curiosity and deepen participants' understanding of the intricate beauty of physics. These activities include: Guest Lectures and Seminars, Workshops and Skill Sessions, Experimental Demonstrations, Science Outreach Programs, Debates and Panel Discussions, Physics Quiz Competitions, Project Showcases, Movie Screenings and Discussions, Publication of Quarterly Digest, Experiment Design Competitions, Peer Teaching and Learning, Problem-Solving Sessions, Celebration of Physics Days, Collaborations and Competitions, Educational Visits, PHYSIQUEST: The department's flagship annual event.

With this diverse range of initiatives, the Physics Students Club aims to foster a vibrant community that celebrates the pursuit of knowledge and the joy of discovery in the realm of physics.

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Beyond Batteries: Supercapacitors and the Physics of Ultrafast Energy Storage

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Ask an energy-storage device two simple questions: How much energy can you hold? And how quickly can you accept or return it? They are not the same question. A battery stores substantial energy through electrochemical reactions occurring throughout active materials, whereas a supercapacitor stores much of its charge at, or very near, an enormous electrode-electrolyte interface. That difference in where charge lives explain why supercapacitors can deliver very high power, recharge rapidly and sustain long cycle lives - and also why their energy density is usually lower than that of batteries. The story of the supercapacitor therefore begins not with a device, but with an interface only nanometres across.

1. Energy Storage Is Not One Problem

Renewable electricity, electric transportation, mobile electronics and modern power systems all require storage, but on very different timescales. A grid may need energy for hours, an electric vehicle needs sustained energy for a journey, while regenerative braking asks a storage device to absorb a sharp pulse of power in only a few seconds. The central design question is therefore not simply how much energy a device can store, but how quickly that energy must move in and out.

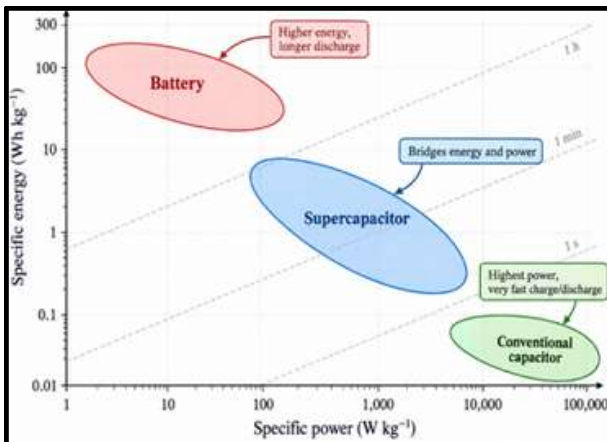


Figure 1: Energy versus power: different storage technologies, different jobs

Batteries and supercapacitors consequently occupy different regions of the Ragone plot, which compares specific energy with specific power. Batteries generally dominate when high energy is required over longer durations; electrochemical capacitors excel where rapid power delivery or absorption is critical [1,2]. A supercapacitor is therefore not a universally better battery. It solves a different part of the energy-storage problem.

A conventional capacitor stores charge on two conductors separated by a dielectric. Its most familiar relation is

$$Q = CV$$

Where, Q is stored charge in coulombs, C is capacitance in farads and V is potential difference in volts. A supercapacitor uses the same fundamental idea of charge separation, but replaces a simple flat plate with a porous electrochemical interface whose accessible area can be enormous.

2. Where Does the Charge Actually Live?

2.1 The electrical double layer

Place a conductive porous electrode in an electrolyte and apply a potential. Electronic charge accumulates in the electrode. Ions of opposite sign rearrange in the liquid to screen that charge. The two distributions - electronic charge in the solid and ionic charge in the electrolyte - form an electrical double layer. Because the effective separation between opposite charges is extremely small, and because a porous electrode can expose a very large internal interface, the resulting capacitance can be far greater than that of a conventional capacitor of similar external dimensions.

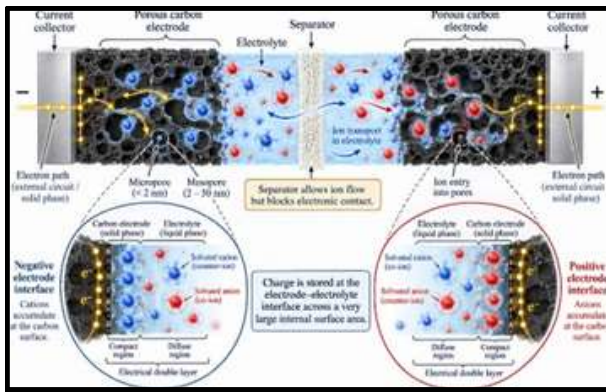


Figure 2: Inside the double layer and nanopores

This is the basis of electric double-layer capacitance (EDLC). Ideally, charge is stored mainly through reversible ionic adsorption and rearrangement rather than a permanent chemical transformation of the bulk electrode. The simple parallel-plate expression is still useful as intuition:

$$C = \epsilon A / d$$

Large interfacial area A and small effective charge-separation distance d favor large capacitance. But a real nanoporous electrochemical interface is not simply two macroscopic plates. Ion solvation, confinement, pore geometry, electrostatic screening and surface chemistry all modify the picture.

A key advance came from experiments showing that carbon pores smaller than the dimensions of fully solvated ions can still contribute strongly to charge storage [3]. Subsequent work demonstrated an important relationship between pore size and ion size, showing that confinement and partial desolvation can enhance charge storage rather than simply block it [4]. Thus, the question is not whether a material has a large measured surface area, but whether the electrolyte can access that surface on the timescale of charging.

2.2 Pseudocapacitance: when chemistry is fast enough to look capacitive

Not all supercapacitor charge storage is purely electrostatic. Some materials store charge through rapid, reversible electron-transfer reactions at the surface, near the surface or through exceptionally fast intercalation. This behavior is called pseudocapacitance. Classical examples include MnO_2

and hydrous RuO_2 . Intercalation pseudocapacitance broadened the concept further: certain structures can accept ions through Faradaic reactions without the strong diffusion limitation and major phase transformations typical of battery electrodes. Nb_2O_5 provided an influential demonstration of this behavior [5].

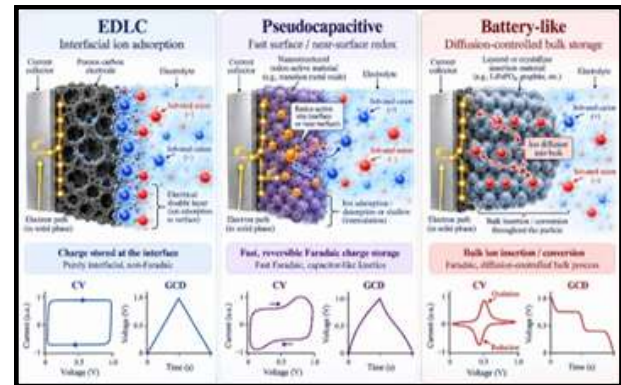


Figure 3: Three electrochemical charge-storage regimes

Terminology matters. A transition-metal material is not automatically pseudocapacitive because it displays a redox peak. Pronounced separated redox peaks, extended voltage plateaus and strongly diffusion-controlled behavior may instead indicate battery-like charge storage. The mechanism must be established from electrochemical kinetics and structural evidence, not assumed from composition alone [5].

3. From Atoms to Electrodes: Why Materials Matter

Supercapacitor performance is a structure-property problem extending across several length scales. Atomic bonding and oxidation state influence redox energetics and electronic conductivity. Defects and surface functional groups modify adsorption, wettability and active sites. Pore geometry governs ion accessibility. At the electrode scale, thickness, mass loading, binder content and conductive pathways determine whether nanoscale advantages survive in a practical device.

3.1 Carbon materials: the mature foundation

Activated carbon remains the workhorse of commercial EDLCs because it combines porosity, chemical stability, electrical conductivity, scalable processing and relatively low cost. Carbon nanotubes

can provide highly conductive networks and mechanical reinforcement. Graphene offers an atomically thin conducting platform and a high theoretical surface area, while biomass-derived carbons are increasingly explored as renewable porous precursors.

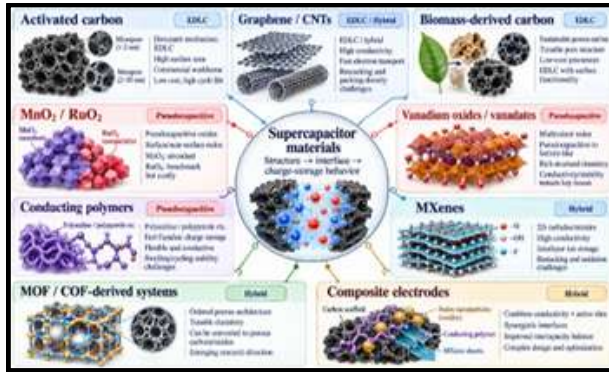


Figure 4: The supercapacitor materials landscape

3.1 Carbon materials: the mature foundation

Activated carbon remains the workhorse of commercial EDLCs because it combines porosity, chemical stability, electrical conductivity, scalable processing and relatively low cost. Carbon nanotubes can provide highly conductive networks and mechanical reinforcement. Graphene offers an atomically thin conducting platform and a high theoretical surface area, while biomass-derived carbons are increasingly explored as renewable porous precursors.

Yet nanostructuring produces trade-offs. Graphene can restack, reducing accessible surface. Extremely low-density networks may look excellent on a gravimetric basis but perform less impressively volumetrically. Highly tortuous micropores can slow ion transport. Surface functional groups may improve wettability while also increasing side reactions. Recent biomass-carbon research therefore emphasizes hierarchical porosity, heteroatom chemistry, conductivity, reproducibility and scalable processing rather than surface area alone.

3.2 Metal oxides and metal vanadates

Transition-metal oxides add redox-active sites and can store more charge per unit mass than purely electrostatic carbons. Their challenge is to combine redox activity with sufficient electronic conductivity, rapid ion transport and structural durability.

Manganese dioxide is a widely studied pseudocapacitive material because it is comparatively abundant and inexpensive, whereas RuO₂ remains a high-performance benchmark but is limited by cost and scarcity.

Vanadium-based materials are particularly interesting because vanadium supports several oxidation states and forms layered, tunnelled and open-framework compounds. Vanadium oxides and metal vanadates can therefore provide rich redox chemistry and ion-hosting pathways. Their actual electrochemical mechanism, however, must be established carefully: depending on structure and electrolyte, the response may be pseudocapacitive, mixed or distinctly battery-like.

3.3 Conducting polymers

Conducting polymers such as polyaniline and polypyrrole store charge through reversible doping and redox processes while remaining electronically conducting. Their flexibility is attractive for bendable and wearable devices, but repeated ion insertion and removal can cause swelling, contraction and mechanical fatigue. Composite designs often use carbon or other conductive scaffolds to distribute strain and maintain electron pathways.

3.4 MXenes and other emerging frameworks

MXenes – 2D transition-metal carbides and nitrides have become important research platforms because some members combine metallic conductivity, hydrophilic surfaces, tunable surface terminations and interlayer ion accessibility. Early Ti₃C₂-based work demonstrated very high volumetric capacitance and rapid cation intercalation. Current challenges include oxidation, restacking, termination control, synthesis chemistry and scalable electrode processing. Hybridizing MXenes with carbon or other phases is one active strategy to preserve ion-accessible galleries and conductive pathways.

Metal-organic frameworks (MOFs) and covalent organic frameworks (COFs) provide another route to ordered porosity and chemically tunable active sites. Their appeal is structural precision; their challenges include conductivity, packing density, long-term stability and scalable manufacturing. The broader

Feature Frame

direction of the field is increasingly hybrid: combine fast electron pathways, accessible pores, redox-active sites and mechanically stable architectures.

5. Reading a Supercapacitor: What CV, GCD and EIS Actually Tell Us

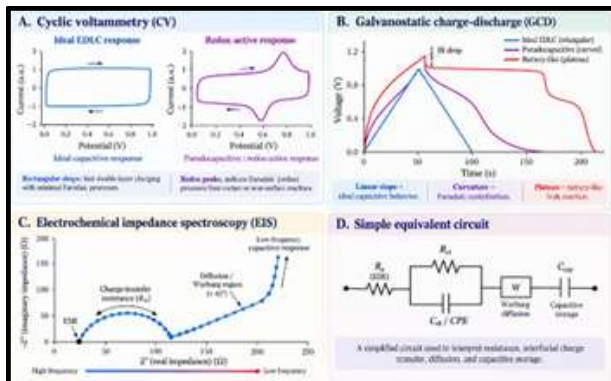


Figure 5: Reading the electrochemistry

5.1 Cyclic voltammetry (CV)

In CV, electrode potential is swept while current is measured. An ideal EDLC approaches a rectangular current-voltage response because charge adjusts rapidly as potential changes. Real porous electrodes show some distortion because finite resistance and ion transport matter. A quasi-rectangular response can still indicate strongly capacitive behavior; broad reversible redox features may indicate pseudocapacitance; sharper separated peaks may indicate stronger polarization or battery-like reactions.

Scan rate is particularly informative. At low scan rate, ions have more time to penetrate small or tortuous pores and access redox sites. At high scan rate, only fast, easily accessible regions may contribute. Strong loss of shape or normalized capacitance with increasing scan rate therefore reveals kinetic limitations.

$$C = (1 / \nu \Delta V) \int I(V) dV$$

Here ν is scan rate and ΔV is the potential window. If the absolute current is integrated over a complete forward-and-reverse cycle, the corresponding factor of two must be included.

5.2 Galvanostatic charge-discharge (GCD)

In GCD, a constant current is imposed and voltage is

recorded as a function of time. For an ideal capacitive response, $I = C(dV/dt)$, so the voltage changes almost linearly and the charge-discharge curves approach triangles. Strong curvature reflects voltage-dependent capacitance or Faradaic contributions; extended plateaus are more characteristic of battery-like reactions.

$$C = I\Delta t / \Delta V$$

$$C_{sp} = I\Delta t / (m\Delta V)$$

The sudden potential change at current reversal is usually called an IR drop and provides information about the effective series resistance. Its precise conversion to resistance depends on the current-step convention. Rate capability asks how much capacitance or capacity is retained as current density increases, while coulombic efficiency compares recovered discharge charge with supplied charge:

$$\eta Q = (Q_{\text{discharge}} / Q_{\text{charge}}) \times 100\%$$

5.3 Electrochemical impedance spectroscopy (EIS)

EIS applies a small AC perturbation across a range of frequencies. In a Nyquist plot, the high-frequency real-axis intercept is commonly associated with the device series resistance, including contributions from electrolyte, collectors, contacts and the electrode network. When physically justified, a high-to-intermediate-frequency semicircle is associated with interfacial charge-transfer processes. A roughly 45° intermediate-frequency response can reflect distributed ionic diffusion or porous-electrode transport, while a more vertical low-frequency branch indicates increasingly capacitive behavior. An equivalent circuit is a model, not a microscopic photograph of the electrode. Adding extra resistors, capacitors or constant-phase elements until a fit looks excellent does not guarantee that those elements have physical meaning. The circuit should follow a defensible mechanistic hypothesis.

5.4 Capacitance, energy, power and response time

Capacitance is an extensive electrical quantity measured in farads. Specific capacitance normalizes it by mass ($F g^{-1}$), areal capacitance by geometric area

Feature Frame

(F cm⁻²), and volumetric capacitance by electrode or device volume (F cm⁻³). These metrics answer different engineering questions and should not be compared as if they were interchangeable.

$$E = 1/2 CV^2$$
$$E \text{ (Wh kg}^{-1}\text{)} = C_{\text{sp}} V^2 / (2 \times 3.6)$$
$$P \text{ (W kg}^{-1}\text{)} = 3600 E / \Delta t$$

The commonly quoted expression $P_{\text{max}} = V^2/(4R_{\text{ESR}})$ has a specific meaning: it is an idealized maximum instantaneous power under matched-load conditions for a source represented by a voltage and a series resistance. It should not be confused with experimentally averaged discharge power in every real device.

$$\tau = RC$$

The RC time constant is the characteristic response time of a simple first-order circuit. After one τ , an ideal capacitor has moved about 63% toward its final charging voltage. A porous SC actually contains a distribution of ionic and electronic resistances and capacitances, so one RC value is a useful approximation than a complete description.

Conclusion: Beyond “Battery versus Supercapacitor”

The most useful question is not whether a supercapacitor can defeat a battery. It is what timescale of energy storage the application actually requires. A battery gains its energy advantage by storing substantial charge throughout active materials

through electrochemical reactions. A supercapacitor gains its power advantage by arranging charge rapidly at enormous interfaces or through exceptionally fast Faradaic processes. Between them lies a growing family of hybrid devices. The future of energy storage will therefore probably not belong to one universal technology. It will depend on matching materials, interfaces and devices intelligently to energy, power, lifetime, safety and cost requirements. From atoms and nanopores to vehicles and power grids, the supercapacitor demonstrates a powerful lesson in applied physics: changing where charge is stored can completely change how energy can be used.

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Dr. Amol S. Vedpathak is an Assistant Professor and researcher working in Materials Science, Nanomaterials and Electrochemical Energy Storage. His research interests include supercapacitors, batteries, advanced electrode materials, metal oxides and metal vanadates, MXenes, carbon-based materials and electrochemical characterization. His work focuses on understanding how composition, structure and interfaces influence electrochemical charge storage and on connecting materials-level performance with practical energy-storage devices. His broader interests include hydrogen generation and other electrochemical energy technologies.

Powering Tomorrow: The Rise of Energy Storage and the Supercapacitor Revolution

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In the past few years, there has been a growing concern in the world regarding an impending energy crisis. This is due to the increasing demand for energy, diminishing of traditional fossil fuel resources and geopolitical tension. Clean energy sources, such as solar and wind, are unreliable and non-constant — the sun does not shine 24 hours a day, and the wind does not blow. To address this issue energy storage devices are essential which store the energy during its availability and release it when required. In today's context, energy storage technologies are becoming more and more relevant, ranging from batteries and fuel cells to advanced supercapacitors, all contributing to the development of a sustainable, energy-efficient and secure future. Rechargeable batteries hold energy in the form of reversible electrochemical reactions. The lithium-ion batteries are of particular importance due to their application in electronic devices and electric vehicles, relative high energy density and high round trip efficiency. However, the growing demand for energy storage has scientists looking for other battery technologies such as sodium-ion, potassium-ion, solid-state and other emerging systems. These technologies seek to solve issues of resource availability, safety, cost and sustainability. Meanwhile, the supercapacitors offer another way to save energy, with fast charging and discharging speeds and impressive cycle life. Batteries and supercapacitors are thus two different strategies towards satisfying the needs of energy and power, and research is now directed towards combining the benefits of both.

A supercapacitor is made up of two electrodes, an electrolyte that is in between, and a porous separator. With the application of voltage, the ions in the electrolyte move and concentrate at the surface of the electrodes creating an electric double layer. Storing energy primarily by this electrostatic double layer formation at the interface between the electrode and electrolyte is the main principle for the

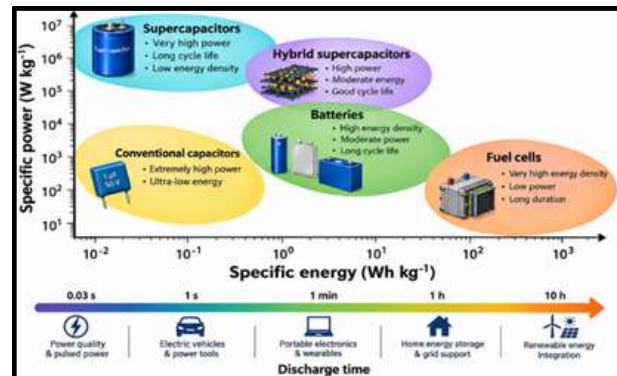


Fig.1. comparison of various energy storage technologies.

Electrochemical Double-Layer Capacitor (EDLCs). The faradaic reactions of charge transfer and, in many cases, ion insertion or conversion are used in batteries, however. Pseudo-capacitors, unlike traditional capacitors, can also store energy by fast surface redox reactions, resulting in high energy density but with the same fast response time as supercapacitors. Supercapacitors are more than just a laboratory curiosity; they are already finding application in the real world. They are used in buses and trams by regenerative braking systems to recover and quickly release braking energy, which is much quicker than regaining energy from a battery. Supercapacitors are used by cranes and forklifts for short and quick lifts, and by power grids to smooth out minute disruptions to the flow of electricity—within

milliseconds—between power generation and demand. The commonality in all these applications is that they require quick power bursts over extended periods. Graphene, carbon nanotubes and MXenes are the new classes of electrode materials that are subject of research that could provide higher energy densities without compromising power performance. Hybrid systems, which integrate supercapacitors with batteries, are becoming more popular, as they combine the energy storage properties of supercapacitors and the high-power delivery of

Feature Frame

batteries. Supercapacitors are increasingly expected to emerge in the field of electric vehicles, smart grids, and new generations of portable electronics, as industries strive to make them more efficient, improve charging speeds, and find sustainable materials. A single energy storage technology is not going to be the sole solution to the future of energy storage. Rather, batteries, supercapacitors, fuel cells and emerging hybrid systems will be used in various roles depending on the energy/power demand,

response time, lifespan, cost and sustainability. The focus is no longer just on energy storage, but on energy storage that is efficient, fast, safe, sustainable and deliverable quickly. Researchers are continuing to work on new materials and device architectures that are even smarter. Batteries will likely not be supplanted in this energy transition by supercapacitors, but they can be an important ally in the powering of the tech of the future.

India Shines at IOAA 2026



India delivered an outstanding performance at the **19th International Olympiad on Astronomy and Astrophysics (IOAA) 2026**, held in **Hanoi, Vietnam**, securing four Gold medals and one Silver medal. All five members of the Indian contingent returned with medals, marking a remarkable 100% medal haul.

Pranjal Dixit, Sumant Gupta, Akshat Srivastava, and Arnav Sehrawat won **Gold** medals, while **Harshil Amitkumar Patel** secured **Silver**. Competing against students from 64 countries, the Indian team finished joint third in the overall medal tally.

The achievement reflects the growing strength of astronomy and astrophysics education in India and the dedication of young students pursuing the sciences. With the competition testing theoretical understanding, astronomical observation, and data analysis, the success is a celebration not only of individual excellence but also of India's continuing scientific spirit.

Graphitization of Amorphous Carbon for Energy Storage

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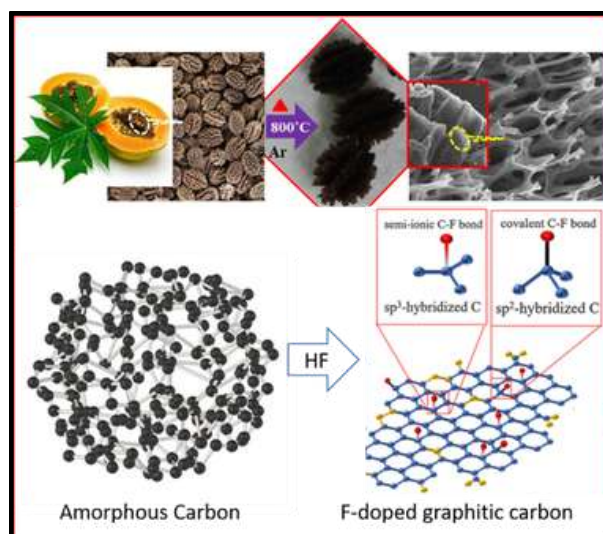
Turning disordered (amorphous) carbon into ordered, graphite-like carbon is one of the most practical levers for building better, cheaper and greener electrodes for batteries and supercapacitors. Carbon is already the workhorse of energy storage: graphite is the anode in almost every commercial lithium-ion cell, and porous carbons are the electrodes in most supercapacitors.

The problem is supply. Battery-grade graphite today comes either from mined natural graphite, which is geographically concentrated, or from synthetic graphite made by heating petroleum coke to around 3000 °C, which is energy-intensive and polluting. Biomass (wood, agricultural residues, seeds, food waste) is cheap, renewable and locally available, including in India. But when biomass is heated it gives amorphous "hard carbon", not graphite. In amorphous or "turbostratic" carbon the layers are short, curved, randomly rotated and spaced further apart. According to the Albi group, every carbon atom in cellulose starts out sp^3 -bonded, and a long chain of rearrangements must happen before flat sp^2 graphene rings can appear. Further they report, cellulose heated to 1800 °C without a catalyst gave graphene fringes only about 4 layers thick with an interlayer spacing of 0.361–0.370 nm - typical hard carbon.

Catalysts let biomass carbon become graphitic at 800 -1800 °C instead of 2500 - 3000 °C, which is the key to making it affordable. Transition metals like iron, nickel and cobalt etc. have been studied most. Cellulose has been turned into highly crystalline carbon at 800 - 900 °C with nickel, and iron has produced multilayer graphene from kraft lignin, bamboo and softwood sawdust below 1000 °C. Graphitization is the conversion of disordered carbon into stacked, flat graphene layers with the regular spacing of graphite. In graphite the layers sit 0.3354 nm apart and extend for tens to hundreds of

nanometres. So, graphitization is the bridge between the two and how catalysts such as calcium, iron and nickel make it possible at much lower temperatures, and what the resulting carbon does inside a battery or supercapacitor.

Recently, our report showed that partial graphitization with fluorine doping can lift supercapacitor performance even at 800 °C, with no activating chemicals. Dried Carica papaya seeds were pyrolysed at 800 °C under argon. Here, not only shape preservation of the seed but also forming a self-supported network of interconnected carbon rods about 2 μm across. The carbon was then washed in either hydrochloric acid or hydrofluoric acid. HF treatment removed mineral impurities (MgO , CaO , CaCO_3 , SiO_2) and converted the seeds own calcium into CaF_2 nanocrystals of about 10 nm. It doped fluorine into the carbon as semi-ionic C–F bonds, confirmed by XPS. High-resolution TEM showed new graphitic regions with a lattice spacing of about 0.34 nm, close to graphite, inside a mostly amorphous matrix. The HCl- treated carbon stayed amorphous. The work function reduced from 4.52 eV to 4.26 eV, making it easier for electrons to leave the surface.



Professor's Paradox

A symmetric HFC//HFC coin cell ran at 1.5 V, delivered up to 29 Wh/kg at 781 W/kg and up to 12,500 W/kg, and kept about 95.6% of its capacitance after 2000 cycles. Even partial graphitization at 800 °C, as in HF-treated papaya-seed carbon, nearly doubled supercapacitor capacitance despite lower surface area. The practical goal is not maximum order everywhere, but the right balance of graphitic and disordered carbon for each type of device.

The direction is still promising but some advance strategies required in near future, which might be helpful reduce dependence on petroleum-derived graphite for energy storage. At present tremendous work focus toward designing an efficient

multifunctional carbon electrode like pore engineering, controlled graphitization, heteroatom doping, interlayer spacing and defect engineering, morphology and dimensional design, composites and hybrids, surface functionalization, electrode architecture, sustainable precursor selection, etc.

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Chua's Circuit: Enter the World of Chaos

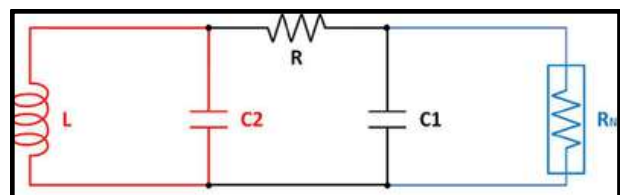
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"Chaos is a state of great disarray or, to put it simply, a type of order without periodicity." But what if a lovely and complex pattern is concealed beneath this seeming chaos?" The well-known butterfly effect illustrates that even a minor adjustment in a system can result in vastly different consequences—a butterfly flapping its wings in one part of the globe, metaphorically initiating a series of events elsewhere. This intriguing sensitivity to initial conditions is fundamental to chaos theory. But what if we could witness this seemingly erratic behaviour not in nature or the atmosphere, but within a basic electronic circuit?

Chua's Circuit is a seemingly straightforward circuit that provides a glimpse into the complex and captivating realm of chaos. It is the simplest electronic circuit which can produce continuous chaotic oscillations. The output wave pattern shifts continuously without repeating itself. Chua's circuit was proposed by Leon Chua in 1983 to demonstrate chaos in an electrical system. What makes it fascinating is that the circuit is built from ordinary components—resistors, capacitors, an inductor, and

a nonlinear element called Chua's diode—yet its output can become highly sensitive and seemingly unpredictable.



Consider the circuit as a tiny playground where energy continuously moves between different components. The capacitors store energy in electric fields, while the inductor stores energy in a magnetic field. The resistor controls the flow of energy, and Chua's diode introduces the crucial nonlinearity. This nonlinearity in the circuit can produce a waveform that never exactly repeats. If we plot the circuit's state in a phase space, something remarkable appears: the trajectory forms a structure known as the double-scroll attractor—two intertwined, butterfly-like regions that the system continually moves between.

The sensitivity to the initial conditions makes this circuit more fascinating. A tiny change in the circuit's

Professor's Paradox

starting state can eventually send its trajectory along a completely different path. This is the same fundamental idea associated with the butterfly effect in chaos theory. So, despite being made from only a handful of electronic components, Chua's circuit gives us a physical demonstration of a profound idea: A system can follow perfectly deterministic laws and still produce behaviour that is extremely difficult to predict over long periods. This is the beauty of chaos: beneath apparent randomness, there can be an intricate hidden order.

Chua's circuit may seem like nothing more than a small collection of electronic components. However its significance goes far beyond the circuit itself. It provides a simple, tangible way of understanding chaos—a phenomenon that exists all around us. The irregular beating of the heart, fluctuations in weather, turbulence in fluids, changes in financial markets, population dynamics, and even the motion of certain

mechanical systems can exhibit chaotic behaviour. These systems may follow definite physical laws, yet their long-term behaviour can be extremely difficult to predict.

Chua's circuit gives physicists a controlled environment in which such behaviour can be observed and studied. The principles explored through chaotic circuits have inspired research into areas such as secure communication, signal processing, electronic oscillators, and the analysis of complex systems. Perhaps the most important lesson Chua's circuit offers is not about electronics at all. It reminds us that complexity does not always require complexity in its ingredients. A system governed by a few simple rules can produce behaviour that appears almost impossible to predict. In that sense, Chua's circuit is more than a circuit—it is a small window into the complicated and fascinating behaviour of the world around us.

When Empty Space Strengthens Superconductivity

In a remarkable example of quantum physics defying everyday intuition, researchers have shown that **empty space itself can influence and strengthen superconductivity**. Even in a vacuum, the electromagnetic field is never completely quiet. Quantum mechanics predicts that the vacuum is filled with unavoidable fluctuations, often described as **zero-point fluctuations**.

In a 2026 study, scientists demonstrated that these quantum fluctuations can modify the interaction between electrons in an ultrathin material, enhancing its superconducting state. The effect increased the material's superconducting transition temperature by as much as **5.4%**.

Superconductors are materials that can carry electrical current with essentially zero electrical resistance below a critical temperature. Understanding how their properties can be manipulated is important for developing more efficient electronic devices, quantum technologies, and future energy systems.

The result offers a striking reminder that the quantum vacuum is not truly "empty." At microscopic scales, even apparently vacant space can interact with matter and influence its behaviour. By learning to control these subtle quantum effects, physicists are opening new possibilities for engineering materials with properties that were once thought to be fixed.

"Hop-timised": Nature's Bouncing Battery of a Different Kind

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In 1676, a scientist named Robert Hooke clocked something simple: stretch a material, and it pulls back with a force proportional to how far you've stretched it. Let go, and — if you've picked the right material — you get most of that energy back, no worries. He put it down as *ut tensio, sic vis* ("as the extension, so the force") in his published work *Lectures de Potentia Restitutiva*, back in 1678. Sounds obvious now, eh?

Hooke gave us the law. Young gave us the modulus. Centuries of physicists and engineers have chased materials that can take a load, hold it, and return it without losing much along the way — springs for mattresses, suspension for cars, rubber soles for shoes, all trying to do one simple thing well. Most of it still falls a bit short. Bounce a rubber ball a few times and watch it lose height with every bounce — that's energy leaking away, cycle after cycle.

Out on the red, sun-baked plains of central Australia, Mother Nature had already worked out how to store a bit of energy in a stretch and get it straight back on release. Sometimes the smartest storage material isn't a chemical cell at all — it's a spring. And nobody builds a better spring than the organism bouncing across the red dirt at 35 kilometres an hour, barely breaking a sweat while doing it.

Meet Skip.

The Red Kangaroo — to those who like their introductions formal — is the largest of all the roo species. He is, for sure, the undisputed heavyweight of the hopping world. (Fig. 1)



Figure 1: The Red Kangaroo (*Osphranter rufus*)

Taxonomy:
Kingdom: Animalia
Phylum: Chordata
Class: Mammalia
Order: Diprotodontia
Family: Macropodidae
Genus: <i>Osphranter</i>
Species: <i>Osphranter rufus</i> — red kangaroo

Table 1: Classification of the Red Kangaroo (*Osphranter rufus*)

A bit of Taxonomic History- Originally described as *Kangurus rufus* by Desmarest in 1822, the red kangaroo was moved to *Osphranter* by Gould in 1842, later becoming a subgenus under *Macropus*. Following taxonomic reviews in 2015 and genetic validation in 2019, *Osphranter rufus* is now the valid scientific name, leaving *Macropus rufus* as a historical synonym.

Hopping: A Different Way to Get Around

Most organisms play by a fairly strict rule of physics: go faster, pay more for it. Sprinting costs more energy than trotting, across the animal kingdom. It's about as reliable a pattern as biomechanics offers.

Watch Skip shift from a stroll to a full-tilt bound across open country, and something odd happens — his energy use barely moves. He can cover ground at speeds that would leave most mammals of his size gasping, yet his energy expenditure barely increases with speed.

Researchers first picked this up decades ago, measuring oxygen consumption in kangaroos on treadmills, and found a result that seemed to break the rules. A landmark 1998 study by Rodger Kram and Terence Dawson put this to the test directly, tracking how much oxygen red kangaroos consumed

Alumni: The Leading Wave

at hopping speeds ranging from a gentle 2 metres per second up past 6 metres per second. As red kangaroos hop faster over level ground, their rate of oxygen consumption — indicating metabolic energy consumption — remains nearly the same. [1]

Try that with a person, a dog, even a racehorse, and the cost curve rockets upward. Skip's curve just about flatlines. This trick isn't happening in his lungs or his heart — it's mechanical, and it comes down to how he moves. **Hopping**, technically known as **saltatory locomotion**, is a completely different way of using the body, one where the legs aren't just pushing the ground away each stride, but acting as springs that catch, hold, and release energy on every bound.

Skip isn't even the only one using it. A grasshopper flicking across a paddock uses the same trick — loading a spring-like leg joint and releasing that stored energy in one explosive burst to leap further than muscle power alone allows. Skip works the same basic principle, just at kangaroo scale. He isn't muscling across the outback; he's hopping. And that distinction is exactly where biophysics gets interesting.

Why Hop?

Hopping did not show up by chance. It evolved as a direct answer to one of the toughest problems an organism can face: how do you cover huge distances, in a landscape that offers next to nothing in the way of food or water, without running your own tank dry along the way?

Resources in Central Australia are thin on the ground and scattered far apart, distances between them are considerable, and droughts can drag on for years at a stretch. An animal burning energy the conventional way wouldn't last long out here. Something had to change. (Fig. 2)

Over millions of years, the ancestors of today's kangaroos underwent a shift that tackled the problem at the level of anatomy itself. Rather than relying purely on muscular contraction to generate every bit of movement, natural selection favoured animals whose legs could store and reuse mechanical energy

Wpassively, the way a spring does. Generation by generation, this produced the disproportionately long, thin, remarkably elastic Achilles tendon Skip carries today. The payoff is an animal that covers long distances, outruns predators, chases down scarce resources, and does all of it without needing to refuel like it's just run a marathon.



Figure 2: Heel-bone comparison across macropod lineages. Hoppers (macropodines) evolved a long, slender heel suited to elastic tendon storage; extinct striders (sthenurines) evolved a shorter, broader heel, poorly suited to the same mechanism. (Image

Source- agclimate.org)

Inside the Spring

Strip away the fur, the muscle, the size of the animal, and what's actually doing the clever work in Skip's leg is something almost unglamorous: a cord of collagen, no different in substance from what holds your own ankle together. The magic's in the arrangement — and in how Skip himself chooses to use it.

Under the microscope, the collagen fibres of the Achilles tendon aren't laid out straight — they're crimped, folded into a wavy, coiled pattern, stacked in layers upon layers. That structure lets the tendon stretch a long way under load and spring back to its original shape without tearing, without wearing thin, hop after hop after hop. (Fig. 3)

Here's the three-part cycle underlying it all, stride by stride:

1. **Absorption** — the impact of landing stretches the tendon, storing mechanical energy in the deformed collagen. It works the same way a spring does: the further you stretch it, the more energy it holds, following a simple relationship

physicists write as $E = \frac{1}{2}kx^2$, where x is how far the tendon stretches and k is a measure of its stiffness.

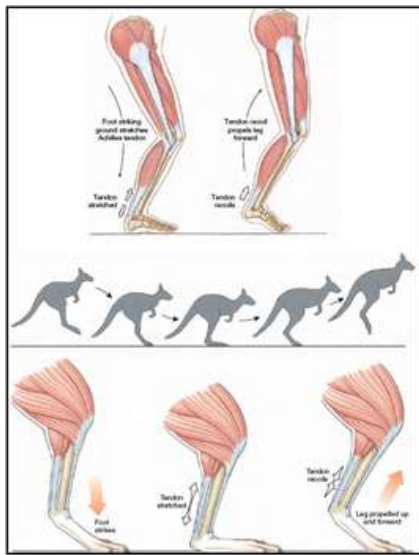


Figure 3: The stretch-recoil cycle of the kangaroo Achilles tendon during a hop, and its role in propelling successive strides. (Image Source—biocyclopedia.com)

2. **Storage** — for a split second, that energy sits held in the stretched fibres rather than dissipating.
3. **Release** — as the foot pushes off, the tendon snaps back, firing the stored energy straight into the next leap.

How efficient is the tendon's energy cycle? One way to measure this: plot the force as the tendon stretches against the force as it relaxes. A perfect spring shows the two curves overlapping. Real materials leave a small gap — that's the hysteresis loop, energy lost as heat. The tighter the loop, the more you get back. Skip's tendon runs unusually tight, storing and returning energy with barely any loss, hop after hop. [2]

For a long time, the story above was thought to be the whole picture — a spring doing a fixed job. A 2025 study found there's more to it. Tracking kangaroos hopping at different speeds using motion-capture and force plates, the researchers noticed Skip doesn't just passively rely on having a springy tendon — he actively changes how he lands as he speeds up, crouching lower through the ankle and toes. [3]

That small shift in posture loads the tendon harder,

and a harder-loaded tendon stores and returns more energy on the next push-off. Skip, in other words, isn't just built with a good spring — he knows how to lean into it. This trick has its limits, though. The same study found the tendon already runs close to its safe working limit even at ordinary hopping speeds, which likely explains why kangaroos this size, but not much bigger, can get away with hopping at all — push the tendon much harder, and the risk of it tearing starts to outweigh the benefit [3].

Chasing the Perfect Spring, Still

Back where this piece started, Hooke gave us the law, and centuries of engineers since have been chasing a single, stubborn goal: a material that can take a load, store it, and give it back without losing much along the way. Skip's tendon has been doing exactly that the whole time. The question worth asking is: how close have we actually gotten to matching it?

Not very, as it turns out — but people are still trying. A 2025 study published in *Nature Communications* engineered synthetic hydrogels mimicking resilient proteins like resilin and elastin to maximize mechanical energy recovery — proteins found in insects and connective tissue that, like collagen, are built to spring back rather than sag [4]. The team confronted a long-standing materials dilemma: synthetic elastomers are typically resilient but weak, or tough but stiff. By constructing hierarchical, layered architectures — analogous to the crimped structure of the kangaroo tendon — they achieved an unprecedented balance of toughness and elasticity.

Conclusion

So, in Skip, there's a fair case of nature beating the engineers to it — a creature that blurs the line between zoology and materials physics, between evolution and design. Strip everything else away, and the real material at the heart of this story is the collagen in his Achilles tendon — arranged in a crimped, layered structure that lets it store elastic energy on impact and hand almost all of it straight back on release. Everything else in this piece is simply the story of how Skip found that material, and how he uses it, hop after hop.

Alumni: The Leading Wave

While labs the world over are still chasing that same combination — resilient, elastic, low-loss — Skip is proof nature sorted it out a long time ago, using nothing more exotic than protein and structure. Out there on the red dirt, with every bound, something rather elegant keeps happening: energy going in, energy coming straight back out, no fuss, no waste.

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Nature's Blueprint for Better Energy Storage: The Rise of Bio-Based Energy Storage Materials

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Abstract

Can We Store Electricity in Wood? A battery is usually associated with lithium, cobalt, graphite and other industrial materials. Wood, by contrast, seems far removed from modern electronics. Yet scientists are increasingly studying plant-based substances as possible ingredients for future energy-storage devices. This does not mean that we can connect a wooden log to a charger and expect it to power a mobile phone. The real idea is more interesting: the building blocks found in wood can be redesigned into materials that help batteries and supercapacitors store and deliver electricity.

Nature's Ready-Made Design

Wood has attracted attention because it is made from natural polymers, mainly cellulose, hemicellulose and lignin. Cellulose forms the framework of plant cells and gives wood its fibrous strength. Lignin fills the spaces between these fibres and gives the material rigidity. Both substances are available in large amounts from forests, agricultural residues and industrial by-products. Instead of viewing them only as materials for paper, packaging or fuel, scientists are investigating whether they can also support the

storage of electrical energy.

The structure of wood itself provides another advantage. Trees naturally contain microscopic channels that move water and nutrients from roots to leaves. After wood is converted into carbon, some of these channels can remain as pathways for ions. Ions are charged particles that move through the device during charging and discharging. Easy ion movement can improve how quickly an electrode works. In this sense, the internal design of a tree can inspire a useful design for an energy-storage material.

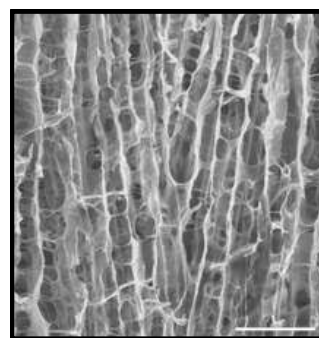


Figure: Microscopic view of wood's xylem structure, showing vessels and fibres that give wood its porous, organised architecture

Source: [U.S. National Library of Medicine Open-i](#).

Turning Lignin into Carbon

Lignin is particularly valuable because it is rich in carbon. By heating lignin under carefully controlled conditions, researchers can produce a form of carbon with a network of very small holes. Such porous carbon is useful in energy storage because it exposes a large amount of surface to the electrolyte inside a device. More available surface area means that more charged particles can gather there. This makes lignin-derived carbon a promising candidate for electrodes, which are the parts of a battery or supercapacitor where charge is stored or released.

Supercapacitors and Fast Charging

Supercapacitors are especially suitable for this type of material. Unlike a typical battery, which depends mainly on chemical reactions to store energy, a supercapacitor stores charge rapidly at the surface of its electrodes. It can therefore be charged and discharged in a very short time and can withstand many repeated cycles. Its main disadvantage is that it usually stores less energy than a battery of the same size. Scientists hope that carefully designed porous carbon from biomass may improve supercapacitor performance while also reducing its environmental footprint.

From Industrial Waste to Useful Material

The use of lignin could also reduce industrial waste. Paper-making industries separate cellulose fibres from wood, leaving large quantities of lignin behind. Often, this leftover material is burned to generate energy. While that process has a purpose, converting some lignin into higher-value battery materials could be a more advanced use. It would turn a by-product into something valuable and support the circular-economy principle.

The Role of Cellulose

Cellulose has a different but equally important role. It may be used in separators, binders and flexible membranes. In a battery, a separator prevents the two electrodes from touching, which could cause a short circuit, while still allowing ions to pass through. Cellulose fibres can form thin and strong layers for this purpose. They are also lightweight and flexible, which makes them attractive for wearable electronics and safer battery designs.

Beyond Forests: Agricultural Waste

The search for bio-based storage materials goes beyond wood. Scientists have examined rice husks, coconut shells, sugarcane waste, corn stalks, fruit peels and other plant residues. Many of these materials can be converted into useful carbon structures. This gives agricultural waste a possible second life and connects waste management with clean-energy technology.

Challenges That Remain

Bio-based energy storage is not a simple solution. Producing high-performance carbon from biomass can involve high temperatures, chemical activation and purification. These processes may require considerable energy and produce waste if they are not managed properly. Natural materials can also vary from one source to another, while battery factories need reliable and consistent materials. More research is needed before these materials can be produced on a large scale.

A Sustainable Future

For now, bio-based materials are more likely to improve existing energy-storage technologies than completely replace them. Lignin-derived carbon may become part of an electrode, while cellulose may be used as a separator or binder. Even these partial changes could reduce dependence on non-renewable materials. Researchers already use lignin, cellulose, and biomass-derived carbon in experimental batteries and supercapacitors. Wood itself does not store electricity directly, but its natural components can be processed into electrodes, separators, and binders. These materials are renewable and can be made from forestry or agricultural waste. Although they cannot fully replace lithium-ion battery materials yet, they are a promising sustainable option for future energy-storage systems.

Solid-State Batteries: Prospects and Challenges in Next-Generation Energy Storage

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Among the various technologies competing to succeed conventional lithium-ion batteries, solid-state architecture has attracted the most sustained attention from both academic researchers and industry. Major automotive manufacturers, including Toyota and several electric vehicle start-ups, have publicly committed to commercialising solid-state cells within the coming decade, while consumer electronics firms such as Samsung have pursued parallel development programmes. Despite this level of investment, the technology has repeatedly missed projected commercialisation timelines. This raises a legitimate question: what precisely accounts for the persistent gap between the conceptual simplicity of the technology and the practical difficulty of its implementation?

A conventional lithium-ion cell relies on a liquid electrolyte positioned between its two electrodes, which facilitates the transport of lithium ions during charge and discharge cycles. While functionally effective, this liquid medium introduces several well-documented risks. It is flammable, prone to leakage, and susceptible to decomposition under conditions of mechanical damage, overcharging, or elevated temperature, occasionally resulting in thermal runaway events. A solid-state battery replaces this liquid medium with a solid conductive material, typically a ceramic, glass, or polymer compound, which continues to permit ionic transport while substantially reducing the associated fire risk.

Beyond Safety: Implications for Energy Density

Although improved safety is frequently cited as the principal motivation for solid-state development, it is not the most consequential advantage of the technology. The use of a solid electrolyte permits the replacement of the graphite anode used in conventional cells with metallic lithium. Given that lithium metal exhibits a considerably higher theoretical capacity than graphite, this substitution

offers the prospect of significantly increased energy density within an equivalent cell volume. For the electric vehicle industry, in which limited driving range remains a principal barrier to consumer adoption, this represents a potentially decisive improvement rather than an incremental one.

The persistence of technical barriers, however, explains why commercial deployment has not yet been achieved at scale. Solid materials, unlike liquids, cannot passively conform to the electrode surface as the cell undergoes expansion and contraction during normal operation. This mechanical mismatch frequently results in the formation of microscopic voids at the electrode–electrolyte interface, which impede ionic transport in a manner analogous to a physical obstruction within a conductive pathway. A further and more serious complication arises from the repeated deposition and stripping of lithium metal during cycling, which can give rise to dendritic structures capable of penetrating the solid electrolyte and inducing internal short-circuiting, precisely the failure mode that solid-state architecture was intended to eliminate.

Competing Material Approaches

Contemporary research into solid electrolytes can be broadly categorised into three material families, each presenting distinct advantages and limitations. Sulfide-based solid electrolytes exhibit ionic conductivity comparable to that of liquid electrolytes but tend to be chemically unstable and require costly, controlled manufacturing environments. Oxide-based ceramic electrolytes offer superior chemical and thermal stability but typically exhibit lower ionic conductivity, particularly at ambient temperature. Polymer-based electrolytes, meanwhile, are more readily manufactured and mechanically flexible but generally require elevated operating temperatures to achieve acceptable ionic mobility. No single material system has yet demonstrated a decisive advantage

across all relevant performance criteria, and it is plausible that the eventual commercial solution will incorporate a hybrid or composite architecture drawing on the relative strengths of multiple material classes.

It is important to note that the challenges confronting solid-state battery development are not confined to fundamental materials chemistry; they extend equally to manufacturing engineering.

A solid electrolyte formulation that performs satisfactorily within a small-scale laboratory coin cell does not necessarily retain equivalent performance when scaled to the dimensions required for automotive applications, manufactured under industrial conditions, and subjected to years of repeated cycling across a wide range of environmental temperatures. This distinction accounts for the recurring pattern in which

promising laboratory results are followed by extended delays prior to commercial deployment, as the underlying chemistry frequently precedes the engineering capability required to manufacture it reliably and at competitive cost.

In summary, solid-state battery technology should not be regarded as a speculative or overstated development. The underlying physical principles are well established, the safety rationale is scientifically sound, and the potential gains in energy density are substantial and well documented. The principal uncertainty concerns not whether the technology will ultimately reach commercial maturity, but rather the timeframe and specific material configuration in which this will occur. Given the extent to which contemporary infrastructure and mobility already depend on electrochemical energy storage, continued research into solid-state systems remains among the most consequential undertakings in current materials science.

The Power Bank in Your Wall: Understanding Energy Storage Materials

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Why We Can't Just "Use" Sunlight at Midnight

Think about the last time your phone died right when you needed Google Maps the most — maybe you were lost in an unfamiliar part of the city, phone at 1%, and the only thing standing between you and a very long walk was a tiny lithium-ion battery. That small block of chemistry is one of the most sophisticated pieces of materials science humanity has ever built, and it belongs to a much bigger family of technologies quietly deciding the future of our planet: energy storage materials. Here's the problem energy storage is trying to solve. The sun doesn't shine at night. The wind doesn't blow on command. Yet we want our lights on, our fridges cold, and our phones charged, all the time, regardless of what the weather is doing outside. Energy storage materials are the "middlemen" that catch energy when it's abundant and release it when it's needed — much like a water tank that fills up during a rainy afternoon

so you still have water to drink on a dry morning.

The Battery: A Tiny City of Moving Ions

Open up a lithium-ion battery — the kind sitting in your phone, laptop, or electric scooter — and you won't find a miniature fuel tank. Instead, you'll find two electrodes (a positive one, usually made of a lithium metal oxide, and a negative one, usually graphite) separated by a liquid electrolyte that lithium ions can swim through.

Charging your phone is essentially forcing lithium ions to swim from the positive electrode to the negative one, where they get "parked." When you use your phone, those ions swim back, and that return trip is what pushes electrons through the circuit to light up your screen. It's a bit like commuters getting off work: in the morning (charging) they travel to one side of the city (graphite), and in the evening (discharging) they travel back, and every trip they

Student Spectrum

make does some “work” along the way — in this case, powering your Instagram scroll. This is why your phone battery slowly degrades over the years. Every charge-discharge cycle is like commuters walking the same path daily — eventually, the road develops potholes. Microscopic cracks form in the electrode material, some lithium ions get “stuck” and can no longer make the return trip, and your battery that once lasted a full day now dies by lunchtime.

“Why Materials Scientists Are Obsessed with 'What's Inside'”

Here’s where the real magic — and the real research — happens. The performance of a battery isn’t decided by clever circuit design; it’s decided almost entirely by what the electrodes are made of.

Take your average petrol two-wheeler versus an electric scooter. A litre of petrol packs an enormous amount of energy into a small, light container — that’s why petrol vehicles can go far without carrying a huge tank. Batteries, in comparison, are heavy for the energy they store. This is why materials scientists are racing to find better electrode materials — ones that can hold more lithium ions per gram, so an electric scooter or car doesn’t need to lug around 300 kg of battery just to travel 250 km.

This search has led to genuinely exciting materials: silicon-based anodes that can theoretically hold ten times more lithium than graphite (imagine a parking lot that suddenly has ten times more parking spots), sulfur cathodes that are cheap and abundant, and solid electrolytes that replace the flammable liquid inside your battery with a safer, ceramic-like solid — a bit like swapping a leaky water balloon for a sturdy steel bottle.

Beyond the Phone: Storage at the Scale of Cities

Energy storage isn’t just about your gadgets. Picture a solar farm in Rajasthan generating huge amounts of electricity at noon — far more than the grid needs at

that moment — and generating almost nothing after sunset, exactly when households switch on their lights and fans. Without storage, this mismatch either wastes clean energy or forces power plants to keep burning fossil fuels after dark just to keep up.

This is where grid-scale storage steps in, often using different materials entirely. Flow batteries, for instance, store energy in liquid electrolyte tanks — think of two giant water tanks connected by a pump; the size of the tanks (energy stored) can be increased independently of the pump (power delivered), which is perfect for storing huge amounts of solar energy cheaply. Even simpler, some plants use molten salt — literally heating salt until it melts, storing the heat for hours, and using it later to boil water and spin a turbine, much like a thermos flask keeping your chai hot long after it was made.

A Materials Problem, Not Just an Engineering One

What’s beautiful about this field, and worth remembering for anyone dreaming of a research career in physics or materials science, is that the breakthroughs rarely come from a clever new gadget design. They come from someone in a lab tweaking the crystal structure of a cathode, or discovering that adding a pinch of a new element makes an electrolyte more stable — the equivalent of a chef discovering that one extra spice transforms an entire dish.

Every electric vehicle silently gliding past you, every solar-powered streetlight, and every power bank saving your evening plans is a small monument to decades of patient work on energy storage materials. The next time your phone battery outlasts your expectations — or disappoints you — you’re not just looking at a piece of engineering. You’re looking at chemistry, physics, and materials science working together, quietly, inside a box smaller than your palm.

Quantum Batteries: The Future of Energy Storage

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The evolution of quantum batteries (QBs) lies at the core of the studies connected to the high-tech energy storage technologies. The non-traditional quantum systems make use of the entanglement and the coherence alongside the out-of-equilibrium to achieve the improvements in the charging rate, scaling of the energy capacity and size. This review provides insight into how QB models have evolved since their simple theoretical frameworks such as Dicke and Tavis-Cummings models to highly sophisticated structures of spin-chain structure, open/closed quantum system and random models. It has been discussed on the specialized properties of QBs that make them capable of super extensive charging and dark state-based energy storage robustness as well as comprehensive mathematical descriptions of these theoretical models. In this research, advances in QB technology, via research of superconducting circuits coupled with NV centers and molecular photonic systems that had reached room temperature operation are covered. Individual Hamiltonians Analysis has been done to determine how extractable work and charging speed are sensitive to system size and control field parameters and the strength of the coupling. Experimental research leads to the development of QB technologies using superconducting qubits, photonic micro cavities, spin-based systems and produces recent operational success using realistic parameters beyond low temperatures up to room temperature. The importance of quantum technologies and their impact on scientific research and society are growing at an impressive pace. As the 20th century technology has been shaped by electronic and

photonic devices, whose operational principles are rooted in quantum physics (the so-called first quantum revolution), the 21st century will be characterized by a completely new class of applications based on our ability to detect and manipulate individual quantum objects (the second quantum revolution). Quantum-mechanical systems present unique characteristics, such as quantum superposition and entanglement, which, besides being conceptually fascinating, enable novel disruptive technological applications. A two-level system (referred to as qubit in the field of quantum computing) is in a quantum superposition state when it is described by the wave function $|\psi\rangle = \alpha|0\rangle + \beta|1\rangle$, with $|\alpha|^2$ and $|\beta|^2$ the probabilities of finding the system in states $|0\rangle$ and $|1\rangle$, respectively. The state of a qubit, like the state of any quantum system, can be described by a vector in a Hilbert space. Multiple quantum systems are said to be entangled when the results of measurements performed on individual systems are correlated in any measurement basis, i.e. the knowledge of the state of one qubit gives the state of the other qubit(s) with 100% certainty. Quantum technologies hold the promise of disruptive conceptual and technological advances in sensing, communications and computation, exploiting the so-called quantum advantages afforded through the science of quantum information. Now there is a deep connection between information and energy, and so one may envisage adopting these quantum advantages in an energy context to develop novel energetic systems, such as quantum batteries, which outperform classical energy storage systems.

Abstract

The quest for innovative materials and device architectures for energy storage is a constantly advancing scientific and technological domain that greatly influences our daily lives. The development of Li-ion batteries has contributed significantly to the portable electronics market, while the growing

number of electric vehicles and green energy production demand novel materials to enhance the energy density, lifetime, and safety of batteries. Various innovative materials and processes are being investigated to improve the properties of current batteries. Nowadays, the advancement of quantum technologies such as quantum information, computation, simulation, and sensing calls for novel and specific platforms for energy storage. Quantum devices require solutions for energy storage and energy provider components that should be highly compatible with their unique architectures, and capable of supporting the creation of a superposition of quantum states. The need for specialized energy storage units for reversible quantum operations has been recently highlighted. In this context, quantum batteries (QBs), first introduced by Alicki and Fannes in 2013, have emerged as an intriguing approach to energy storage. QBs are devices that are made of quantum systems, and they harness fundamental quantum mechanical effects to charge, store, and release energy. QBs can be charged/discharged through operations that establish coherent superposition's among various states, while the energy is stored in the excited states of the quantum systems. Entanglement effects and non-classical correlations have been shown to lead to super-extensive scaling of the charging power (that is, the ratio between the stored energy and the charging time), with a quantum advantage compared to their classical counterparts.

Introduction

The expanding world economy in the twenty-first century greatly depends on energy to power the industrial, transport, and domestic sectors, which has brought great environmental concern due to the fact that the main sources of energy are still fossil fuels. Petroleum, coal, and natural gas are sources of carbon-rich fuels, which provide nearly 36, 27, and 23.4 % of the global energy demand, respectively. The burning up of these fossil fuels emits almost 21.3 billion tons of CO₂ each year and this is a significant greenhouse gas that causes global warming and climate change. Besides the greenhouse gas emissions, mining and refining of fossil fuels lead to soil and water pollution, disturbance of the ecosystem and massive destruction of habitats.

Recently, it has been stressed that a shift to the use of energy systems that are not based on fossils is a key to reaching the net-zero emission goals and addressing the risks posed by climate change. This increasing energy needs resulted from industrial growth combined with population expansion and the shift to renewable energy systems reveal various limitations of conventional storage technologies especially Lithium-ion batteries (LIBs). LIBs fulfil their wide industrial function in portable electronics, electric vehicles and grid storage but encounter multiple serious obstacles that impede their sustainability. LIBs show high thermal sensitivity, low energy density and high diffusion barrier. The safety hazard increases in multiple applications when extreme operating conditions occur or physical damage affects the battery. The performance and functionality of LIBs decline throughout their operational period. The available research shows LIBs maintain 80 % of their original capacity throughout 500 recharge cycles although they become inadequate for applications that need extended energy efficiency. The depletion of performance in LIBs operating on the basis of from electrolyte decomposition together with electrode deterioration and lithium plating. Sustainability regarding lithium-ion battery production faces additional challenges because of environmental as well as ethical worries during their production process. The extraction process for essential materials including lithium and cobalt and nickel causes environmental destruction that results in both water contamination and unprofessional labor treatment methods. The recycling facilities for LIBs have limited development which results in substantial waste generation and diminished resources.

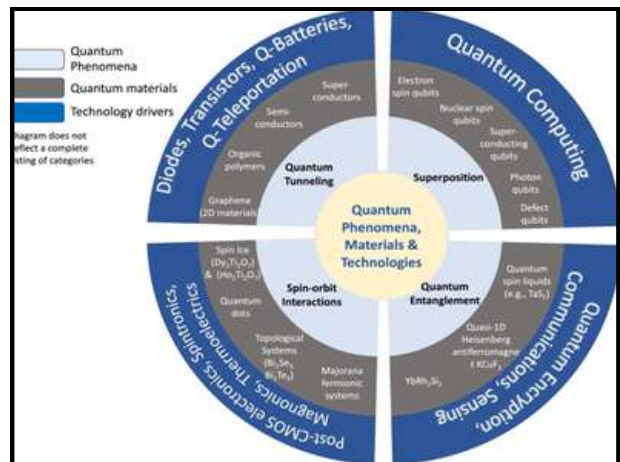
Multivalent-ion batteries as promising alternatives with four primary candidates including magnesium together with calcium, aluminum and zinc-ion batteries. The batteries incorporate multiple valence ions like Mg²⁺, Ca²⁺, Al³⁺ and Zn²⁺ as charge carriers that enable larger theoretical power storage while decreasing the need for lithium or cobalt materials. The search for stable electrolytes with high conductivity continues to be a major obstacle since traditional LIB electrolytes fail to work with multivalent cations because of their high reactivity.

and passivation problems. The research on QBs presents itself as a transformational solution because of established limitations within lithium-ion technology alongside challenges in multivalent-ion battery implementation. Application of quantum mechanics principles in the powering of energy storage is an innovative technology that could possibly revolutionize the existing power of storage. QBs are more superior to the normal electrochemical batteries as they achieve a higher level of efficiency as well as faster charge rates combined with increased storage capacity of energy through the application of quantum superposition, entanglement and coherence.

The quantum superposition capability of placing a battery in a non-monochromatic energy state allows the battery to transfer energy faster hence accelerates charging mechanisms. The quantum entanglement technology that entangles the particles and makes them interconnected provides possibilities of collective energy storage and retrieval processes that increase performance and reduce the charging times. QBs exhibit the appropriate attributes to exploit in the future as powerful devices that can find applications in the quantum computing system, portable electronics, and renewable energy storage.

The concept of First QBs proposed by Alicki and Fannes in 2013, has become an interesting way to store energy. QBs are quantum mechanical systems which are quantum systems and take advantage of the underlying quantum mechanics to charge, store and release energy. The energy storage mechanism in such QBs exists in energized quantum system states although charging or discharging requires coherent superposition establishment between various states. The charging power of various quantum devices exhibits super extensive scaling properties due to entangled effects and non-classical correlations. Ferraro et al.'s original design of a laboratory, produced QB model used N two-level systems coupled with an optical cavity to create a solid-state device. This device called "Dicke QB" demonstrated excellent super linear charging behavior because its collective cavity-mediated behavior showed an improvement scaling as $\sqrt{N}$. It works as a theoretical construction following the principles of the Dicke

model in quantum optics that shows how multiple two-level quantum systems (qubits) and a shared electromagnetic field such as cavity or photon mode interact together. Within a Dicke QB, the coupled qubits interact together as a hybrid system because they strongly connect to a single cavity mode. Super enhanced energy exchange happens in super radiance because multiple qubits interact with each other while emitting or absorbing energy at faster rates than normal. The cavity receives energy during charging and distributes it in total to all qubits by virtue of their common interactive relationship. The collective charging mechanism which is quantum coherence between qubits is based on the fact that their operation is united into one system. The energy storage mechanism generates high correlation among the components of the system that enables ease in extracting the energy during the discharge phase. The study results indicate that N -entangled quantum bits are N times more powerful to charge than the non-interacting N quantum bits. Two kinds of properties can be observed in this physical system: extensive properties are dependent on the size of the system and intensive variables are not dependent on the size of the system.



The invention of QB offers good opportunities to come up with the energy storage apparatus that charges at higher speed. Experimental implementation of Dicke QB is still in a heavy developmental stage, and so, theoretical research on QBs has so far been carried out.

The research in quantum optics and cavity quantum electrodynamics (QED) as well as materials science must be improved to address the problems with decoherence, scalability and sensitivity to temperature.

For instance, experimental results utilizing superconducting qubits along with photonic cavities show that Dicke QB implementation becomes possible because strong coupling mechanisms can be achieved in superconducting qubits. The future of energy storage is expected to change dramatically because the Dicke QB possesses the potential to use quantum mechanics for reaching revolutionary efficiency and performance capabilities. Other theoretical models beyond Dicke exist to investigate QB behavior. The Tavis-Cummings model extends the Dicke model by introducing cavity quantum electrodynamics (QED) phenomena for QBs to interact with quantitative fields inside microwave or optical cavities. Two distinct research approaches using circuit QED and trapped ion systems have been developed for examining QB implementations in laboratory. QBs produce superior capabilities than ordinary batteries by using super absorption mechanisms in quantum cells allows quantum speed up to charge devices at ultra-fast rates, as the number of quantum cells increases energy transfer efficiency. Entanglement combined with coherence enables collective energy storage to achieve better capacity than conventional energy storage devices. The attractive features of QBs make them suitable for various uses in quantum computing applications and nano-devices and energy efficient quantum networking systems. Several experimental implementation hurdles prevent the realization of QBs from their theoretical concept. The primary concerns in QB development include preserving quantum coherence properties and also obtaining adequate control of quantum interactions and developing workable realizations of solid-state systems. Recently, scientists have come up with new methods that combine light-matter interaction to superconducting qubits alongside engineered quantum reservoirs to maintain battery coherence and an increase in performance. The QB development in this context will necessitate that experimental implementations are made that will facilitate the establishment of a gap between theoretical and practical implementations. Various experimental models of QBs are available although only partial demonstrations of fully operational QBs have been verified in different research studies to date.



Fig: A quantum battery stores energy in controlled states within atoms, molecules, photons, or other small systems.

These include the ultrafast pump-probe spectroscopy demonstrating super absorption in micro cavities with organic molecules, 2 min of energy retention with single-spin QBs and charging and energy storage ability with single-qubit QBs. The explores QBs beginning with their theoretical foundations and then proceeds to experimental progression and concludes with projections. The discussion of significant system models reveals the practical use and outlines challenges that developers must overcome to use quantum advantages in storage systems. By integrating the quantum theory with experimental developments we attempt to provide a comprehensive review as to the potential and feasible nature of quantum batteries.

A quantum battery is not the same as a solid-state battery. A solid-state battery uses a solid electrolyte but still stores energy through electrochemical reactions. A quantum battery uses quantum behavior to change how energy is absorbed, stored, or released.

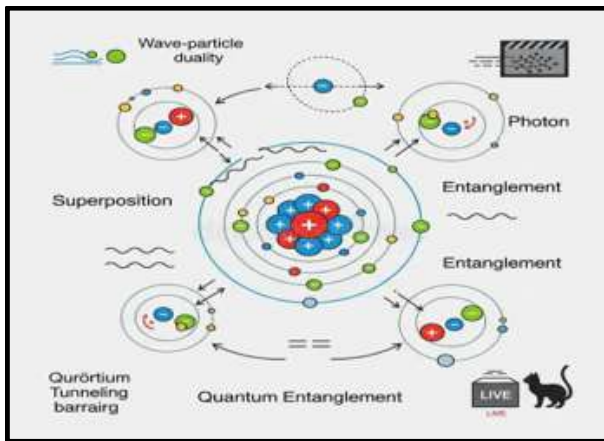
Theoretical foundations of quantum

The fundamental theory of QB's is based on the regulated storage of energy in discrete quantum states. Upon interaction between a photon of an external light source with an atom or a two-level quantum system (i.e. a quantum dot or a superconducting qubit), the system can absorb the energy of the photon and, accordingly, switch between its ground-state and excited-state. The energy that is absorbed is stored in the population of

these excited states which forms the charged state of the QB.

Quantum coherence and entanglement

The quantum coherence allows quantum systems to be many states at the same time. The coherent behavior is essential in the development of any of the QB functionality such as storage, transfer and retrieval of energy. The interacting dynamics of charged particle transfer are synchronized in different coherent quantum systems which leads to enhanced collective charging processes. Entanglement connects multiple particles and leads to their strong correlation that allows them to be tied even.



Single qubit model

A single-qubit QB provides the basic model of quantum energy storage that stores energy within a two-level quantum system. The core elements of a quantum battery model are the battery Hamiltonian H_B , charger Hamiltonian H_C , and the interaction Hamiltonian H_{BC} , giving rise to the full Hamiltonian $H = H_B + H_C + H_{BC}$ with explicit forms tailored to the specific implementation.

$$H_B = (\hbar\omega/2)\sigma_z$$

where σ_z is Pauli matrix and ω denotes the energy spacing between $|0\rangle$ and $|1\rangle$ states. The energy storage process takes place through under a time-dependent Hamiltonian with Rabi frequency Ω (determine charging rate).

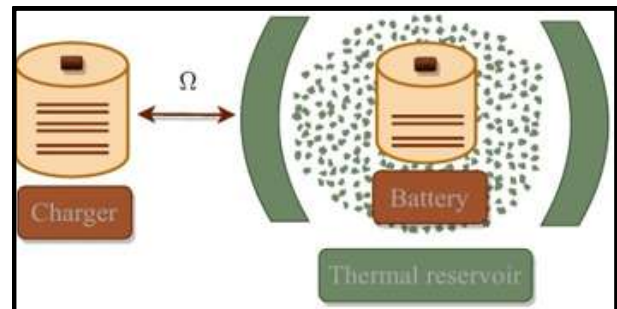
$$H_C(t) = \hbar\Omega(e^{i\omega t}\sigma_+ + e^{-i\omega t}\sigma_-)$$

Recent advances on QB

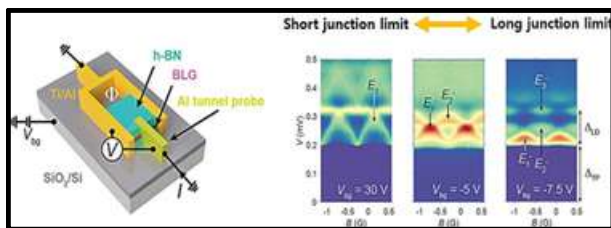
Recently QB have been realized more quickly, and ambitious theoretical models have been proposed, which are conscious of realistic dissipation, variability of fabrication and benchmarking considerations. Notably, there have been advances in charging rates in molecular microcavity systems, designed driving regimes in superconducting platforms, reservoir- and nonreciprocity-based approaches to stabilizing the dark-state, and demonstrated proof of battery performance on photonic platforms.

Superconducting quantum batteries

The Elizabeth et al. proposal demonstrates a superconducting QB (SQB) design which uses two capacitive connected superconducting charge qubits known as transmon qubits as its foundation. Superconducting circuits which contain Josephson junctions create artificial atoms with fixed energy states that represent the core element in present-day quantum computing systems because they display moderate sensitivity to charge noise.



In the sunburst quantum Ising battery, maximal ergotropy and power are achieved in the strong coupling limit and are completely independent of the initial state of the charger, simplifying experimental protocols and state preparation. In collision models, quantum coherence of the charger offers a clear performance enhancement in both charging speed and work extraction. For molecular batteries or designs with environmental baths, Markovian and non-Markovian effects alter both charging and discharging dynamics, with non-Markovian memory enabling energy backflow (recharging) and enhancing ergotropy.



Application of QBs

QBs(QBs) are conceived to be transformative across a diverse array of new quantum technologies, through the provision of controllable, fast and miniaturized energy storage. They have special promise in the powering of Quantum computers, where the high-speed delivery of energy is critical to propelling superconducting qubits as part of the computation cycles. QBs can be used as nodes of energy in photonic links in Quantum communication networks, and permit low-loss and high-speed data.



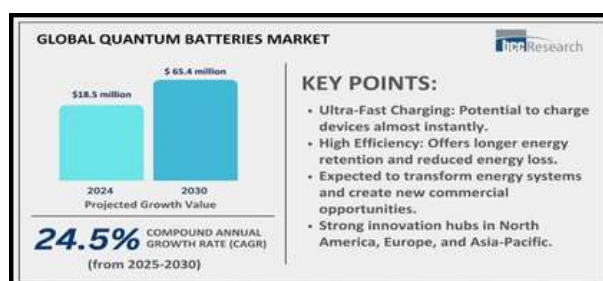
Real-World Examples: Quantum Meets Automotive & Experimental Realizations and Prospects

In 2026, several industry leaders have begun integrating quantum-inspired approaches into their battery management frameworks:

- **Volkswagen's partnership with D-Wave:** By employing quantum annealing methods, they optimize battery pack layouts and charge cycle strategies, leading to a 10-15% increase in effective range.
- **Ford's quantum research initiative:** Focused on improving thermal management through quantum simulations, reducing overheating risks and extending battery life by up to 20% in test models.
- **Tesla's experimentation with quantum-enhanced diagnostics:** Early trials show quicker detection of cell irregularities, decreasing maintenance time and costs.
- **Trapped ions, Rydberg arrays, and superconducting circuits:** Platforms for spin

chains, Dicke batteries, and the resonator–qutrit battery, enabling exploration of both collective and local charging protocols, and direct observation of quantum-advantage scaling.

- **Cavity/circuit QED and photonic systems:** Bosonic-mode implementations, parametric driving, and squeezing schemes have been proposed and are in part realized in state-of-the-art devices with tunable coupling and dissipation.
- **IBM quantum hardware:** Digital quantum simulation of kicked-Ising quantum batteries demonstrates the hardware feasibility of complex charging protocols.
- **Molecular and chemical systems:** Biomimetic molecular batteries and exciton-factory models connect quantum battery science with organic-or bio-inspired energy transduction.
- Key experimental considerations involve coherence times, tunability of couplings (e.g., strong inter-qubit or qubit–cavity couplings), robustness to disorder, and the feasibility of engineering dark or sub-radiant states for long-term storage
- Future directions and research challenges
- QBs exist as mostly theoretical concepts yet prove to be promising candidates in enhancing the storage capabilities of quantum technology. The future of QB development ought to focus heavily on the development of experimental realizations via platforms that have both superconducting circuits and trapped ions and spin systems. The application of various many-body quantum effects other than entanglement and coherence is promising to the operation speed of the charging process and energy storage



- The precise role and necessity of entanglement vs. coherence in optimal charging.
- Universality and critical phenomena in the

interplay between non-analytic energy storage and quantum phase transitions.

- Control and mitigation of environmental decoherence and noise for improved battery lifetimes and stability.
- Scalability and integrability in large-scale quantum devices, especially in the context of superconducting circuits, ion traps, and photonic networks.
- Exploiting resource-theoretic approaches—quantum non-Gaussianity, non-Markovianity, and quantum control—for optimizing all performance metrics. Cumulatively, quantum battery models have established clear theoretical protocols for achieving quantum speed-up and high extractable work, with pathways identified for experimental demonstration and future deployment in quantum energy technologies.

Conclusion and future recommendations

The QBs are a paradigm shift in energy storage where the coherence and entanglement are employed to store the energy in a way that the charging rates and energy densities are to exceed the classical limits. The concepts of quantum advantage have been demonstrated in theoretical models in the previous 10 years and experimental observations have demonstrated that quantum advantage can be utilized

in practice: with superconducting transmons, organic microcavities, and NV centers. The future of quantum batteries lies in the integration of quantum error correction (QEC) with energy storage. If we can treat energy storage as a logical operation within a QEC code, we may be able to create ‘fault-tolerant batteries’. Furthermore, the convergence of quantum thermodynamics and quantum information theory will likely lead to the discovery of new battery architectures that utilize non-equilibrium steady states to maintain energy levels. As we move toward the era of NISQ (Noisy Intermediate-Scale Quantum) devices and eventually fault-tolerant quantum computers, the quantum battery will transition from a theoretical curiosity to a critical component of the quantum technological ecosystem.

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Food waste to farads: A study on the Transformation of Biowaste into Sustainable Materials for Energy Storage

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Birth of a capacitor:

The capacitor's origins trace back to the mid-18th century with the Leyden jar, followed by Benjamin Franklin's battery and Alessandro Volta's condenser. With the advent of the 19th century came Michael Faraday's work on using dielectrics to store electrical energy, D.G. Fitzgerald's contribution to reducing capacitor size, and Karol Pollak establishing the foundation for electrolytic capacitors. The 20th century introduced mica and ceramic capacitors to support radio stations' higher frequencies and tantalum capacitors to pair with the recent invention

of transistors. Then came supercapacitors, blurring the distinction between capacitors and batteries.

Biowaste as electrode material:

To support this powerhouse of an invention, research was carried out in the early 21st century to utilize biowaste as electrode materials in supercapacitors. For electrode materials, carbon is widely used due to its higher chemical stability and large surface area. A type of carbonaceous material called activated carbon has a large surface area, and these ACs derived from biowaste are inexpensive and

eco-friendly. Hence, waste from ginger, garlic, mangosteen, coconut, soybean, etc., has been used as raw materials in the preparation of ACs. Electrical double-layer capacitors (EDLCs) are supercapacitors that store energy through an adsorption/desorption method and whose performance depends on the structure and chemical characteristics of the electrode materials. Rather than using commercially available carbon, converting biowaste into porous carbon materials is a sustainable path. Also, in an international context, urbanization and globalization have nearly exhausted the supply of fossil fuels, our main source of traditional energy, which in turn alarmingly increases greenhouse gases in the atmosphere. Given these concerns, it is necessary to take into account environmentally friendly and sustainable solutions while meeting the world's energy needs. One way to do this is by using wind and solar energy, but the solar energy obtained through the sun's heat and wind energy generated by wind turbines are quite dependent on weather conditions. They are available either when the weather is clear or when there is sufficient wind.

Due to this intermittency, we turn towards a constant supply of energy or proper energy storage methods. Supercapacitors do this job wonderfully, handling much higher power levels and quicker charging and discharging. Innovations continue to upgrade the performance of SC, especially in terms of energy density and low manufacturing cost, which will make this technology relevant and sustainable in solving our global energy challenges. Despite its outstanding characteristics, SCs' low specific energy prevents them from being used in various contexts; hence the requirement for developing new cathode materials for SCs maintaining low cost, high specific power, and long life. One promising electrode material is porous hard carbon, as it is expected to enhance the performance of supercapacitors in industrial and consumer applications, such as electric vehicles and portable electronic devices. Biomass-derived porous carbon, along with its abundance, also has advantages like renewability, high specific surface area, huge pore volume, good conductivity, and strong electrolyte interaction. Agricultural byproducts are excellent raw materials for the synthesis of nanoporous bicarbons.

Adsorption:

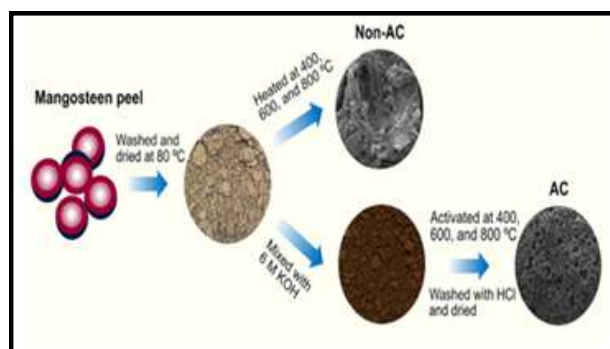
A process in which atoms, ions, or gas and liquid molecules stick to the outside surface of a solid or liquid material, rather than soaking inside it. Supercapacitors (EDLCs) store energy by electrostatically adsorbing electrolyte ions onto the surfaces of porous electrodes, forming an electrical double layer.

Key points:

- **Energy storage:** Ions rapidly accumulate on high-surface-area carbon/graphene electrodes.
- **High power:** Surface-based ion adsorption enables very fast charging and discharging.
- **Surface optimization:** Increasing electrode surface area and optimizing pore size allows more ions to be stored, improving capacitance and overall performance.

Mangosteen peel-derived AC for supercapacitors:

Material synthesis



In this study, mangosteen peels were used for the preparation of AC. The peels underwent thermal treatment at different temperatures of 400, 600, and 800°C under an argon atmosphere for 2 h. The phase formation, morphology, and porosity properties of the prepared materials were investigated using X-ray Diffraction (XRD), scanning electron microscopy (SEM), and N₂ adsorption-desorption techniques, respectively. 3M KOH aqueous electrolyte was the activating agent used.

Results

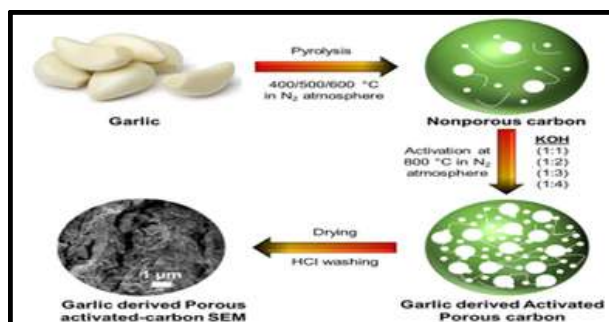
Increasing the activation temperature to 800°C gave the highest specific surface area of 1039 m²g⁻¹ however, it did not produce the highest capacitance. AC prepared at 600 °C delivers the maximum

specific capacitance value of 182 Fg^{-1} at a current density of 0.5 Ag^{-1} in 3M KOH aqueous electrolyte. The activation temperature also changed the type of oxygen-containing surface functional groups, which contributed to improved charge storage at 600°C . Therefore, this study proves that it is important to optimize activation temperature rather than only maximizing surface area to achieve supercapacitor performance, and 600°C is the most favorable activation condition as it balances porosity and surface chemistry, resulting in the highest capacitance.

Almond shell biomass-derived porous carbons for advanced supercapacitors:

Material synthesis

Another recent study regarding biowaste as electrode material was conducted using almond shell waste converted into high-performance porous carbon for supercapacitors using 6M or 12M acid pretreatment, phosphoric acid activation, and high-temperature pyrolysis.



Results

The optimized acid treatment enriched lignin and promoted the formation of locally ordered graphitic nanocrystalline domains. The resulting material had a specific surface area of $1180 \text{ m}^2 \text{ g}^{-1}$ and a highly developed mesoporous structure. Whereas excessive acid treatment produced smaller pores and more oxygen-containing functional groups, showing that the pretreatment concentration strongly affects the final structure. The best material, AC6-600(1000), showed excellent durability, retaining 81.1% of its initial capacitance after 100,000 cycles at 10 Ag^{-1} . DFT calculations confirmed that the locally ordered

carbon structure provides stronger K^+ adsorption, helping explain its improved charge-storage behavior. Overall, this study proposes a “nanocrystalline-domain–pore co-design” strategy, showing that optimizing both graphitic ordering and pore structure together, rather than maximizing surface area alone, is an effective approach for developing biomass-derived carbon electrodes for practical supercapacitors.

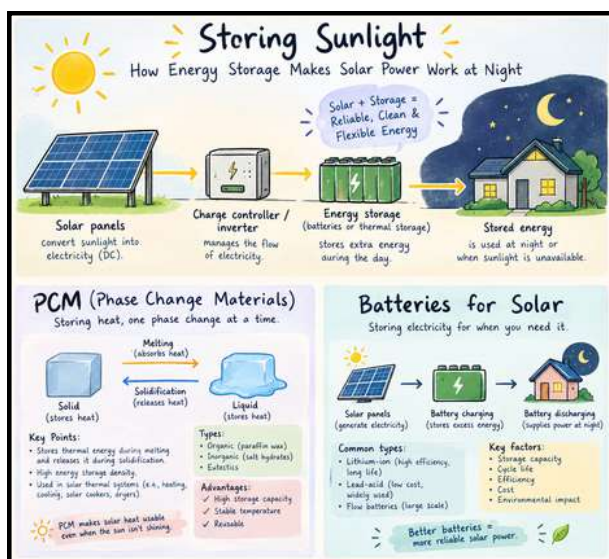
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Strong Sunlight: How Energy Storage Makes Solar Power Work at Night

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1. Introduction

Solar panels are a marvel of physics, converting sunlight into electricity in an instant, silently, and without moving parts. Yet the sun sets every evening, factories run through the night, and hospitals cannot afford a blackout when the sky is dark. This simple contradiction — abundant energy by day, none by night — is the central problem facing the solar transition. Solving it does not require better panels; it requires better storage. Around the world, engineers are pairing photovoltaic systems with technologies that can hold sunlight's energy and release it hours, or even days, later. This coupling of generation and storage is quietly becoming the backbone of a reliable renewable grid.

2. Why Solar Needs a Storage Partner

A solar panel produces power only when photons strike its surface, so its output rises and falls with clouds, seasons, and the rotation of the Earth itself. Without storage, this variability forces grid operators to keep fossil-fuel plants running as backup, undermining the very purpose of switching to renewables. Coupling solar generation with storage changes this equation: excess energy produced at noon, when demand is often low, is captured and released in the evening, when demand peaks.

2.1 Batteries: fast but limited

Batteries have become the most familiar answer to this problem. Lithium-ion systems can charge and discharge within milliseconds, making them ideal for smoothing short fluctuations and shifting a few hours of surplus power into the evening. Their speed makes them indispensable for grid stability, though their cost and finite cycle life still limit how much energy they can economically store.

3. Phase Change Materials: Storing Heat, Not Just Electricity

Batteries are not the only way to store sunlight. Phase change materials, or PCMs, take a different route: rather than storing electrical charge, they store thermal energy in the structure of a substance itself. As a PCM melts, it absorbs a large amount of heat while its temperature stays almost constant; as it later solidifies, it releases that same heat back. Salts, paraffin waxes, and certain metal alloys are common choices, each melting at a temperature suited to a particular application.

In concentrated solar power plants, molten salts store heat collected during the day and release it to generate steam and drive turbines long after sunset. Because PCMs store energy as heat rather than as charge, they avoid the chemical degradation that limits battery lifespans, and they can be far cheaper per unit of energy stored, which makes them attractive for large, stationary installations.

4. Storage for Rural India

Nowhere is the promise of solar-plus-storage more visible than in rural India, where millions of households still live beyond the reach of a stable grid. Small solar-battery microgrids, often no larger than a few kilowatts, now light homes, run water pumps, and charge mobile phones long after dusk. Lead-acid batteries dominated early rural installations because they were cheap and locally serviceable, but lithium-ion batteries are increasingly displacing them,

offering longer life and better performance in India's heat. Battery-swapping stations are also emerging for electric rickshaws and small vehicles, letting a depleted battery be exchanged for a charged one in minutes rather than hours. For a farmer whose irrigation pump once depended on erratic diesel supply, a solar panel and a battery bank can mean an evening's water, a lit room after sunset, or a refrigerator that keeps vaccines cold in a village clinic.

5. Conclusion

Storing sunlight is, at its heart, an exercise in patience: capturing energy when it is abundant and releasing it when it is needed. Whether through the fast electrochemistry of a battery, the quiet melting and freezing of a phase change material, or a modest village microgrid, the coupling of solar generation with storage is what will finally let the sun light our nights, and not merely our days.

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MXenes and MBenes: The Next Frontier Beyond Graphene for Ultrafast Energy Storage

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1. Introduction

The growing demand for energy, together with the environmental problems associated with fossil fuels, has increased the need for sustainable energy-storage technologies. Electrochemical energy storage, particularly rechargeable batteries and supercapacitors, is important because it can provide high energy density, good efficiency and long cycle life¹. However, batteries generally provide higher energy density at the expense of power delivery, which can limit their use in applications requiring rapid charging and discharging. Therefore, developing electrode materials that can transport ions and electrons rapidly while maintaining long-term stability has become an important area of research².

1.1 Beyond Graphene: MXenes and MBenes

Graphene was one of the first two-dimensional (2D) materials to attract major attention for energy storage because of its high electrical conductivity, large surface area and mechanical strength. However, graphene sheets tend to restack during electrode fabrication, reducing the accessible surface area and restricting ion transport. This has encouraged researchers to explore other 2D materials with more controllable surface chemistry and interlayer structures. Among them, MXenes and the more recently developed MBenes have emerged as promising candidates³. Structural evolution and properties of Graphene, MXenes, and MBenes are demonstrated in Figure 1.

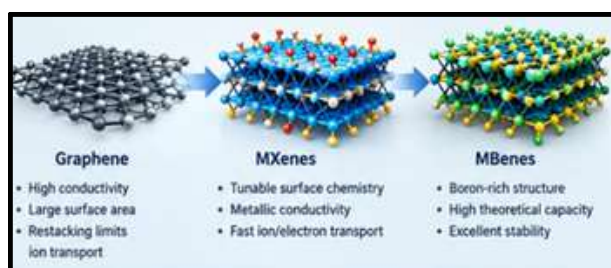


Fig. 1: Structural Evolution of Graphene, MXenes, and MBenes

2. Unique MXene Characteristics

MXenes are a family of 2D transition-metal carbides and nitrides generally obtained by selectively removing the A-layer from layered MAX phases. They are commonly represented by the formula $M_{n+1}X_nT_x$, where M is an early transition metal, X is carbon or nitrogen, and T_x represents surface terminations such as $-O$, $-OH$ and $-F$. Their combination of metallic electrical conductivity, hydrophilicity, tunable surface chemistry and layered structure makes them particularly interesting for electrochemical energy storage⁴. The general chemical formula and structure of MXenes are shown in Figure 2.

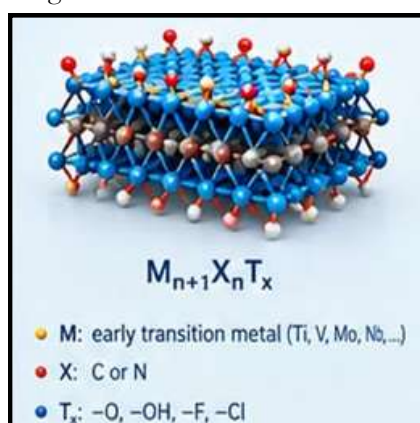


Fig. 2: Chemical Formula and MXene Structure

2.1 MXene Storage Dynamics

One important advantage of MXenes is their ability to support both rapid electron transport and ion storage. Charge storage and Ion transport dynamics are exhibited in figure 3.

In materials such as $Ti_3C_2T_x$, ions can interact with surface functional groups and interlayer spaces, producing pseudocapacitive as well as intercalation-type storage. Unlike conventional battery electrodes where ion diffusion through the bulk can be relatively slow, surface-controlled or near-surface



Fig. 3: Energy Storage Mechanisms in 2D Layers

reactions can occur more rapidly. This helps explain the high rate capability observed in many MXene-based electrodes. $Ti_3C_2T_x$ has therefore been investigated extensively in lithium-, sodium-, potassium-, magnesium-, zinc- and aluminium-ion storage systems as well as supercapacitors.

2.2 The Restacking Challenge

However, MXenes also have an important limitation: restacking. During processing, individual nanosheets can come together and reduce the accessible surface area and the width of ion-transport channels. Figure 4 illustrates, the structural comparison of restacked and modification-protected MXenes.

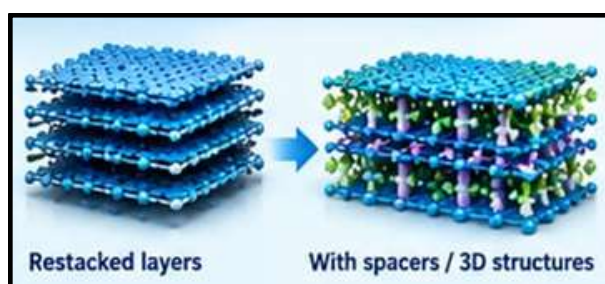


Fig. 4: Restacked vs. Spaced 3D Layers

As a result, a significant fraction of the theoretically available active surface may become inaccessible. Strategies such as introducing spacers, forming 3D architectures, and combining MXenes with graphene or carbon nanotubes have been investigated to reduce this problem. These approaches can maintain more open pathways for electrolyte ions while preserving the high conductivity of the MXene framework.

2.3 The Role of Synthesis

The synthesis method also plays an important role in determining MXene performance. Conventional HF etching and fluoride-salt/HCl methods such as LiF/HCl are widely used to remove the A-layer from MAX phases. These processes can produce different

surface terminations, defects and structural characteristics, which in turn affect ion adsorption and electrochemical behaviour. Thus, improving synthesis and controlling surface chemistry are as important as selecting the MXene composition itself⁵.

3. MBenes: Structure and Properties

MBenes represent a newer class of 2D transition-metal borides and are generally derived from layered MAB phases. Their general structure can be represented as $M_{n+1}B_nT_x$, where boron replaces the carbon or nitrogen found in MXenes. Figure 5 shows the general molecular architecture of MBenes.

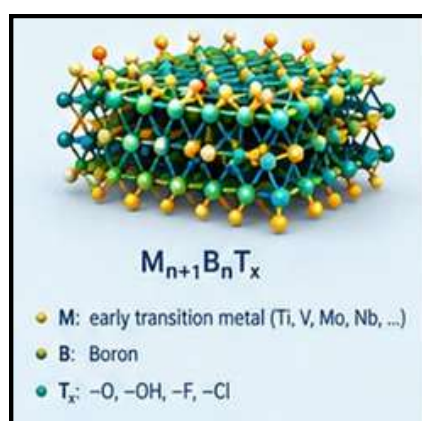


Fig. 5: Schematic Model of a 2D MBene Layer

The presence of boron gives these materials a different bonding environment and electronic structure. Both theoretical calculations and recent experimental studies suggest that some MBenes can combine metallic conductivity, mechanical stability, high theoretical capacity and low ion-diffusion barriers⁶.

3.1 Theoretical Battery Performance

A major area of interest is the use of MBenes as anodes for lithium- and sodium-ion batteries. Theoretical studies of MB_3 monolayers, for example, have predicted high lithium-storage capacities together with relatively low diffusion barriers and suitable open-circuit voltages. The boron-rich surface can provide sites for metal-ion adsorption, while the 2D structure provides short diffusion pathways. These characteristics make MBenes interesting candidates for fast ion storage. However, theoretical predictions should be distinguished from experimental performance because the number of

experimentally demonstrated MBene systems is still much smaller than that of MXenes⁷.

3.2 Experimental Milestones and Variations

Experimental progress is beginning to demonstrate this potential. Different transition-metal borides have been investigated as MBene-type electrodes, with reported examples showing reversible capacity and cycling stability in lithium- and sodium-ion storage. However, the performance varies strongly with composition, structure, surface termination and electrode architecture. Therefore, it is too early to consider MBenes as a direct replacement for MXenes; rather, they represent an emerging platform that could provide additional possibilities for electrode design⁸.

3.3 MBene Synthesis Hurdles

The main challenge for MBenes is their synthesis. Although many MAB precursors can be produced through methods such as solid-state sintering and spark plasma sintering, selectively extracting the appropriate atomic layer is more difficult than the conversion of MAX phases into MXenes. Strong metal-boron bonding and the limited number of experimentally established synthesis routes make the preparation of high-quality MBenes challenging. Scalable synthesis, control over defects and surface terminations, and long-term stability in practical electrolytes therefore remain important research problems.

2. Conclusion and Future Outlook

Overall, MXenes and MBenes demonstrate how the structure and surface chemistry of 2D materials can be used to improve energy-storage performance. MXenes are currently more experimentally developed and offer high conductivity, tunable surface chemistry and rapid pseudocapacitive ion storage, while MBenes provide a newer family of materials with promising theoretical capacities and ion-transport properties. Their practical use will depend on solving problems such as restacking, oxidation, synthesis scalability and electrode stability. Rather than simply replacing conventional materials, these 2D boride, carbide and nitride systems provide new ways to control the movement and storage of ions and electrons, making them promising

candidates for the development of high-power and fast-charging energy-storage devices.

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The Second Life of Batteries: Recycling, Reuse and Ethical Responsibility

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1. Introduction

Battery technology is an essential component of our modern world. In search of renewable energy source we are becoming more reliable on electric devices. Batteries are used in energy storage system, portable rechargeable devices, electric vehicles, mobiles and laptops. The demand of batteries has surge in recent years due to growth of electric devices and electric vehicles.

1.2 Types of Batteries:

On the basis of their charge capacity batteries can be divided into two types:

Primary Batteries: The primary batteries can only

used once until their energy is finished, they cannot be recharge.

Secondary batteries: The secondary batteries are chargeable and can be used many times. There are so many examples of secondary batteries such as Lithium-ion batteries, Lead acid batteries, Nickel-metal hydride batteries, Nickel cadmium batteries. Of them all the Lithium-ion batteries are relatively small and lightweight with high capacity of energy storage and widely used in electronic gadgets and electric vehicles. And the lead acid batteries are economical and reliable. They are found in backup power systems and vehicles.

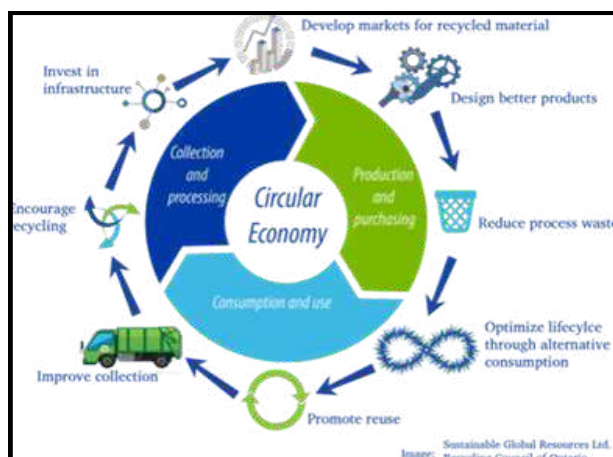
2 .The need for second life of batteries:

The second life of batteries is very important aspect to control e waste and conserve natural resources. The reasons for recycling batteries are as follows:

Impact on environment: E-waste contain harmful chemicals like lead, mercury, cadmium, etc. improper dispose of e-waste creates serious environmental and health problems. Exposure to these harmful chemicals may cause diseases related to respiratory system, nervous system and other organs. Polluted air, water and soil can negatively affect animals, plants and aquatic organisms and can cause damage to ecosystem.

Resource conservation: Batteries contain important and valuable materials like copper, lead, lithium and lead. By recycling we can reduce the need for mining new materials. We can reuse the materials extracted from old batteries and conserve the natural resources.

Sustainability: Battery recycling crucially help in sustainable development because it reduce environmental pollution, conserve natural resources, reduce greenhouse gas emission, protection of human health and supports sustainable electric mobility. It promotes circular economy.



3. Recycling Methods:

To recycle batteries we can use different methodologies such as:

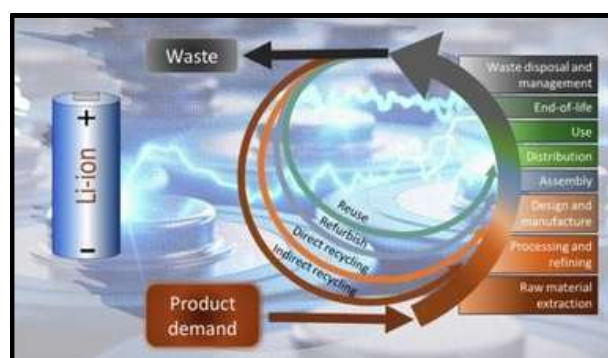
Mechanical recycling: In this method the collected batteries get mechanically crushed into smaller pieces. After separating the components the recovered

materials used in manufacturing new materials.

Pyrometallurgical recycling: In this process batteries are heated in a furnace, metals like cobalt, copper, nickel can be recovered. This process commonly used for lithium-ion batteries.

Hydrometallurgical Recycling: In this method chemical solutions are used to extract valuable materials. It can provide high recovery rate for certain materials.

Direct recycling: Direct recycling helps to recover battery materials without breaking them.



4. Current initiatives for recycling batteries in India:

India is rapidly growing its recycling ecosystem through financial incentive schemes, bilateral technological partnership and different regulations like, India's battery recycling is governed by Battery Waste management Rules (BMWR) - 2022, The hazardous and other waste rules-2016.

India is formalizing the informal recycling sector through:

- 1) EPR linked revenue through certificates.
- 2) MSME cluster development programs.
- 3) Technology transfer under mission LIFE.

Financial and policy Incentives:

- 1) Critical mineral Financial incentives
- 2) Budgetary import exemptions
- 3) EU-India green partnership
- 4) 3000 crore Lithium scheme.

5. Conclusion and future outlook:

The second life of batteries is very important step towards reducing e-waste and support circular

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Photo-Rechargeable Batteries is the combination of solar energy harvesting and electrochemical storage in one device. We used solar energy which requires two separate devices connected by wires. First one is, Solar panel which catches sunlight and converts it into electricity. Second one is battery which takes the electricity through a cable and stores in the battery[1].

In this solar setup electricity travels across wires and power controllers. Some energy turns into heat and gets lost during travel. This wastes a portion of the captured power before it can run light and tools. The entire setup is also heavy and bulky.

2. Photo-Rechargeable batteries

2.1. Why we use Photo-Rechargeable batteries

We use Photo-Rechargeable batteries because it combines the light harvesting and storage in one small battery. And it does not require any separate panels and external charge controller only require minimal wiring and because of this specific factor, photo rechargeable battery almost takes no space and weighs very little and is more suitable for small electronics that need to be lightweight, like smartwatches, fitness trackers, tiny internet sensors and small medical devices.

2.2. Working of Photo-Rechargeable Batteries

Photo rechargeable batteries work like standard battery, but they contain a light absorber that acts like a built-in solar panel. When light shines on the battery, it creates an internal electric charge that directly drives the charging process, eliminating the need for external solar panel or charger[3].

2.3. Core components of photo rechargeable batteries:

i. **Photocathode:** This is the positive side of the battery also known as cathode. The main job of this part is to catch the sunlight when it falls on the battery. It absorbs the light rays deeply to create energy inside the system. By absorbing this light, it starts the whole process of generating power without needing any external plug.

ii. **Anode:** This is the negative side of the battery. Its primary role comes into the play during the charging process. When the battery is charging up, this negative side acts as a storage compartment. It saves the energy particles safely inside its structure, holding onto them until you are ready to use the battery.

iii. **Electrolyte:** This is the liquid or gel substance which allows the energy particle to move between both sides of the battery. It blocks electricity so that it forces to travel outside to power the devices.

iv. **External circuit:** The path of the battery which carries the electricity out to power the gadget or device.

v. **Separator:** A thin layer of porous separator is used to prevent electrical shorting.

3. Types of photo rechargeable batteries

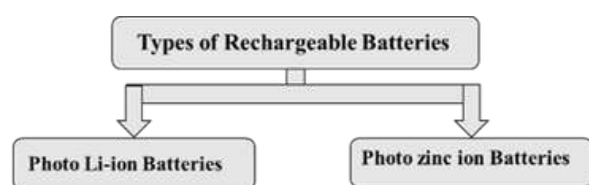


Fig. 1: Types of photo rechargeable batteries

Just like traditional batteries, photo rechargeable batteries are available in various materials composition with photo zinc ion and photo lithium ion which represents two main general researched types. In both structures use of a light sensitive photocathode to move the ion and charge the battery.

3.1. Photo zinc ion battery

Photo zinc ion battery with built-in solar panel which

captures the light. Three important parts in this are:

i. **Photocathode:** This is the front side of the battery it is composed of a mixture of vanadium pentoxide (this has microscopic fiber to catch the light) P3HT (It is the plastic like material that conduct electricity) rGO (It is the sheet of carbon which transport energy quickly)

ii. **Anode:** This is the back side that has the zinc metal foil and act like a storage vault.

iii. **Electrolyte:** The liquid that has the zinc sulfate solution acting like a path for a particle to travel.

Importance:

The zinc ion battery is important because it is safe to use and has rechargeable water-based battery that can store huge amount of energy. And it is highly capable and won't catch fire.

3.2. Photo Li-ion battery

This is the special type of lithium-ion battery.

i. **Photocathode:** This is the front side of the battery and it is composed of mixture of vanadium pentoxide (this has microscopic fiber to catch the light) P3HT (It is the plastic like material that conduct electricity) rGO (It is the sheet of carbon which transport energy quickly)

ii. **Anode:** This is the back side that has the lithium metal foil and act like a storage vault.

iii. **Electrolyte:** The liquid that has the organic lithium solution and act like a path for a particle to travel.

Importance:

It has high energy density. It Can recharged anytime. It is lightweight. It has long lifespan.

Limitation

Photo Li-ion batteries uses flammable organic liquids which can catch fire at extreme temperature.

4. What is a 2D Perovskite

Perovskite are group of material that is known for superior light absorber and for good performance in solar cells. 2D perovskite is the thin layer of this

material.

2D Perovskite photocathode acts like a sponge that naturally absorbs sunlight and traps lithium particle at the same time[2].

4.1. How it works in photo Li-ion battery:

Battery has three main layers

- i. *Photocathode*: 2D perovskite which is often combined with another material MoS₂ molybdenum disulfide.
- ii. *Anode*: Store the material of lithium.
- iii. *Electrolyte*: Is the liquid or gel which allows the ion to move smoothly.

4.2. Working:

- Light hits to photocathode: Sunlight hit directly on 2D perovskite layers causing it to release the electrons.
- Charge gets separated: The generated electrons flow away, creating an internal electrical force.
- Charge drives lithium movement: Lithium-ion slides into the empty space between the perovskite sheets to follow the electrons and to maintain the neutrality.
- Energy is stored in the battery: The lithium ions and electrons are simultaneously stored in 2D perovskite structure itself converting the light into stored chemical energy.

Importance:

- They make the battery more stable.
- They waste less energy.
- They act like a waterproof shield.
- They don't crack under high heat.

- They charge fast using sunlight.
- They help to work solar and battery smoothly together.
- It is used in the tiny devices

Conclusion:

Photo rechargeable batteries combine a solar panel and a battery into a single device that captures light and stores energy. It is compact and self-charging and wire free and supports more sustainable, and low energy use.

Charging process	Discharging process
Photocathode absorbs light.	Stored chemical energy drives ion motion.
Charges are separated.	Electrons flow from anode to cathode.
Increase in the battery charge.	Battery loses stored energy.

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Micro to Mega: How the Same Electrochemical Physics Powers Smartwatches and Power Grids

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Introduction

On the flexible surface of a medical skin patch, a sub-millimeter micro-supercapacitor stores fractions of a milli-joule to record a patient's heart rate. A thousand miles away, a 100 MW / 400 MWh containerized battery facility injects megawatts of

power into an electrical grid to stabilize frequency drops. Though separated by nine to twelve orders of magnitude in spatial footprint and energy capacity, both devices share a fundamental reality: they are governed by the exact same laws of interfacial electrochemistry. Whether shuffling ions across a

nanometer-scale double layer or driving bulk phase transitions inside a multi-ton battery module, the engineering challenges at both extremes reflect the same core trade-offs.

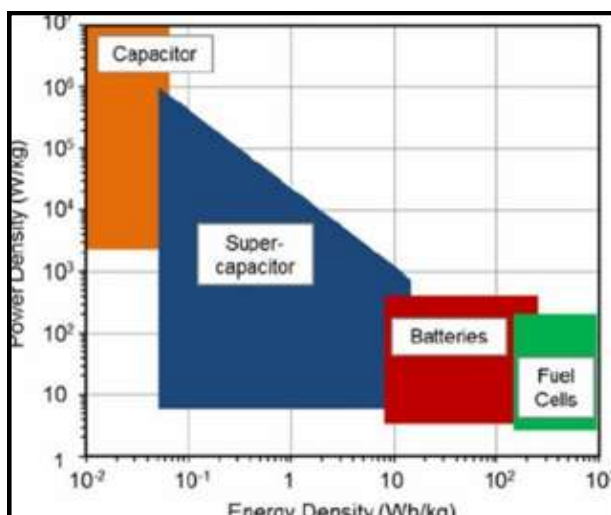
1. The Common Physics: Electrostatics, Redox, and the Ragone Trade-Off

At its core, electrochemical energy storage operates via two fundamental mechanisms:

1.1 Electrochemical Double-Layer Capacitance (EDLC): Non-faradaic electrostatic charge accumulation at the electrode-electrolyte interface. Because no chemical bonds are broken or formed, EDLC devices offer near-instantaneous charge/discharge capability and exceptional cycle stability (>100,000 cycles).

1.2 Faradaic Redox Reactions:

Charge transfer driven by oxidation and reduction states within bulk material structures. Faradaic processes yield significantly higher energy storage capacity at the cost of slower kinetics and mechanical degradation over time. The balance between these mechanisms defines a system's position on the Ragone Plot —the universal metric balancing energy density (ϵ) and power density (P).



Stored Energy: $E = 1/2 CV^2$

Maximum Power output: $P_{max} = V^2/4.ESR$

Where C represents capacitance, V is the perational voltage window, and ESR is the Equivalent Series Resistance.

Whether optimizing an on-chip micro-device or a high-voltage grid storage bank, energy storage design centers on two primary goals: maximizing V without triggering electrolyte breakdown, and minimizing ESR across all material interfaces.

The Micro Scale: Micro-Supercapacitors & Flexible Wearables

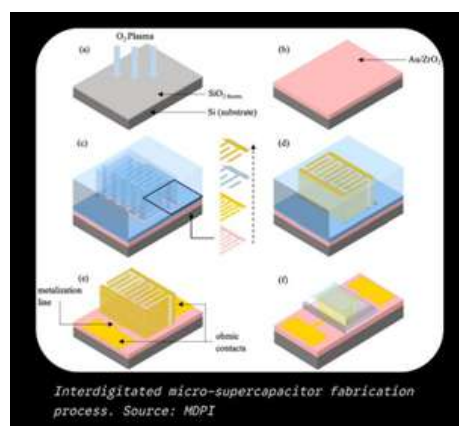
At the micro scale, energy storage systems power autonomous Internet of Things (IoT) nodes, wearable sensors, and implantable medical monitors. These applications demand micro-scale footprints, rapid pulse response, long operational life, and seamless integration with energy harvesting sources (such as piezoelectric or thermoelectric generators).

2. Core Architectures & Materials

2.1 Micro-Electrodes: Traditional stacked planar geometries create long ion-diffusion pathways. Modern micro-supercapacitors (MSCs) utilize interdigitated, finger-like electrode arrays. This design reduces ionic transport distances down to the sub-micron scale, driving ESR down significantly.

2.2 2D Nanomaterials & MXenes: Graphene, transition metal carbides/nitrides (MXenes), and conducting polymers enable high surface area and fast surface pseudocapacitance bridging the gap between high power and functional energy density.

2.3 Solid-State Gel Electrolytes: Liquid electrolytes pose leakage risks in wearable devices. Hydrogel or polymer-based gel electrolytes offer mechanical flexibility and biocompatibility while maintaining high ionic conductivity.



3. Bottlenecks at the Micro Scale

3.1 Energy Density (mWh/cm²): Because planar space on flexible substrates or silicon chips is limited, volumetric and areal capacities dictate feasibility.

3.2 Micro-Fabrication Costs: Integrating active energy materials alongside CMOS circuitry requires precise photolithography, inkjet printing, or laser scribing, which present scaling challenges.

The Mega Scale: Grid Storage & Renewable Integration

At the macro extreme, grid-scale Energy Storage Systems (ESS) stabilize power grids reliant on intermittent renewable sources like solar and wind. These installations perform critical functions including peak shaving, load leveling, and fast frequency response.

Core Architectures & Materials

1.1 Lithium Iron Phosphate (LFP) & Sodium-Ion: Lithium-ion chemistry—specifically LFP—dominates modern grid storage due to its balance of thermal stability, cycle life, and cost-effectiveness. Sodium-ion is emerging as a lower-cost alternative for stationary storage where gravimetric density is less critical.

1.2 Flow Batteries: Vanadium redox flow batteries separate energy capacity (tank volume) from power capability (stack size), providing long-duration storage without rapid electrode degradation.

1.3 Grid Supercapacitors: For ultra-fast frequency regulation (responding within milliseconds to sudden load shifts), large supercapacitor banks buffer short-duration power spikes before chemical batteries ramp up.

Bottlenecks at the Mega Scale

Levelized Cost of Storage (LCOS): The primary metric for grid viability is the total cost per kilowatt-hour delivered over a multi-decade operational lifespan.

Thermal Management & Safety: Large-scale energy containment introduces thermal runaway

risks. Heat dissipation across dense battery racks requires liquid cooling channels and active HVAC controls.

4. Comparing Extremes: Micro vs. Meg

Engineering Parameter	Micro Scale (Sensors & Wearables)	Mega Scale (Power Grids)
Primary Objective	Spatial efficiency & uninterrupted power pulses	Lowest levelized cost (LCOS) & high round-trip efficiency
Dominant Form Factor	On-chip interdigitated arrays, thin films	Modular rack containers, mega-liter electrolyte tanks
Dominant Bottleneck	Areal energy density (mWh/cm ²)	Thermal management, raw material supply chains
Cycle Life Requirement	>100,000 cycles (low maintenance)	5,000 – 15,000 cycles (10–20 year lifetime)
Limiting Resistance (ESR)	Micro-electrode geometry & interface impedance	Busbars, interconnects, & power electronics

5. Cross-Pollination: How Micro and Mega Inform Each Other

The boundary between micro and mega engineering is far from impermeable. Innovations developed at one end of the spectrum frequently solve bottlenecks at the other:

Nanostructured Electrode Architecture: The 3D porous structures and interdigitated networks created for micro-supercapacitors are inspiring 3D-structured thick electrodes in grid batteries, improving ion diffusion rates in heavy battery packs.

Distributed Battery Management Systems (BMS): Architectures designed to manage multi-megawatt grid arrays—monitoring cell health, thermal gradients, and state-of-charge balancing—are being miniaturized into ultra-low-power micro-BMS chips for wearable energy harvesting units.

Conclusion

Energy storage engineering spans vast orders of magnitude, yet it remains bound by the same physical laws. Whether optimizing ion diffusion across a micro-supercapacitor finger or managing heat transfer through a megawatt battery rack, success relies on controlling charge movement at the atomic scale.

As material science advances—from novel 2D MXenes to low-cost sodium chemistry—the principles refined at the micro level will continue to shape the resilience of our global energy grid.

Future scope

Micro-Scale Scope (Wearables, IoT & Medical)

Energy Harvesting Integration: Combining micro-storage directly with kinetic, thermal, or solar energy harvesting for battery-free, self-powered devices.

Advanced Form Factors: Fabrication of flexible, printable, and ultra-thin storage embedded into smart textiles, wearables, and system-on-chip (SoC) architectures.

Biocompatible Electronics: Expanding transient, non-toxic micro-storage solutions for transient medical implants and continuous health-monitoring patches.

Mega-Scale Scope (Grids & Heavy Industry)

Renewable Integration: Buffering intermittent power generation from solar and wind farms to ensure consistent baseline delivery.

Grid Resilience & Microgrids: Providing fast frequency regulation, voltage stabilization, and island-mode operation during severe weather or outage events.

Data Center & Industrial Power Buffering: Absorbing peak load spikes and delivering rapid power backup for critical infrastructure like AI data centers.

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When Light Turns a Semiconductor into a Topological Insulator

What if light could temporarily change the fundamental electronic properties of a material? Researchers have demonstrated that carefully controlled **ultrashort pulses** of light can transform a semiconductor into a **topological insulator**—a material whose interior behaves as an insulator while its surface can support conducting electronic states.

The technique is based on **Floquet engineering**, a quantum approach in which periodic driving modifies the electronic structure of a material. Instead of permanently altering the material through chemical modification or fabrication, scientists can use light to dynamically reshape how electrons behave. Such topological states could offer new possibilities for **low-power electronics, spin-based devices, and quantum technologies**, where controlling electronic behaviour at ultrafast timescales is essential.

The demonstration highlights a powerful idea in modern condensed-matter physics: **light is not merely something that reveals the properties of matter—it can be used to control and create new phases of matter**. By manipulating materials with precisely controlled light pulses, researchers are moving toward a future where electronic properties can be actively engineered on demand.

From University of Poona to the TWAS Prize: The Impactful Journey of Prof. S.B. Ogale

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Department of Physics, MES's Nowrosjee Wadia College, Pune 411 001



Introduction:

Dr. Satishchandra Ogale is a distinguished scientist and materials expert with a career spanning over four decades. He has made significant contributions to advanced functional materials, energy storage, and sustainable technologies. His research focuses on developing new materials for clean energy and sustainability, and he has received numerous national and international honours, including the prestigious TWAS (The World Academy of Sciences) award in Physics. Dr. Ogale is also known for his work in energy harvesting and storage, as well as his involvement in mentoring young scientists and engineers.

Early life and Education:

Dr. Ogale was born on 24th July, 1953. Dr. Ogale stood first in the entire state of Maharashtra in the SSC examination in 1969 and ranked first in all school, college and university examinations. His educational background is marked by his PhD from the University of Pune in 1980. He has served as a faculty member for many years and has been a visiting faculty/scientist at several prestigious institutions, including the University of Southern California, University of Maryland, and FOM Institute, Netherlands. His research spans Solar Energy, Energy Storage, Graphene and Functional Carbon, Oxide Electronics and Spintronics, and

Pattern Formation.

Research Focus:

Dr. Ogale has worked extensively in the field of Advanced Materials; especially on High Temperature Superconductivity, CMR Manganites, Diluted Magnetic Semiconductors and Spintronics. His current research interests are in the field of Clean and Renewable Energy; especially Battery technologies and Green Hydrogen/Clean Fuels. He has over 550 research publications in reputed international peer-reviewed journals, 12 US Patents granted based on research done entirely in India, and three books co-edited for Springer, Wiley and Elsevier. His h-index is 93 with about 41700 citations. Dr. Ogale's research has been centred around clean energy, with a particular emphasis on energy harvesting and storage technologies. His work has led to the establishment of the Centre for Energy Science at IISER Pune and the RISE at TCG-CREST.

Honours and Awards:

Dr. Ogale's academic achievements include winning numerous national and international awards such as the INSA Young Scientist Medal, Dr. N. S. Sathyamurthy Award, and the Sir C.V. Raman Prize. He is also an elected fellow of the Indian Academy of Science, National Academy of Science, and Maharashtra Academy of Science. Dr. Ogale's contributions to science are recognized with multiple honours, including the first Ramanujan fellowship of DST in 2006 and the Raja Ramanna fellowship in 2018. He has been a key figure in building interdisciplinary programs and mentoring over 65 PhD scholars.

Global Recognition:

Dr. Ogale has been honored with the International Newton Prize by the British Council for excellence in international research collaboration and the Best

Physicist's Spotlight

International Collaboration Award by Times Higher Education for the UK-India SUNRISE program.

About Research Institute for Sustainable Energy (RISE):

Research in RISE focuses on the Development of Novel Materials and Device Technologies in the Area of Sustainable Energy Storage. There is an ongoing PhD program in RISE starting 2023 and the Ph.D. degree is awarded by the Academy of Scientific and Innovative Research (AcSIR). RISE also plans to start two-year MTech courses in "Battery Technologies" and "Green Technologies and Sustainability" in future. In addition to the coursework, this will have a strong component of hands-on laboratory work providing useful training for individuals employed in academia as well as industries. The RISE Laboratory of Energy Materials and Devices occupies an area of 10,000 square feet. This space is compartmentalized into a materials synthesis lab and a device characterization lab, all conforming to the highest safety standards. Besides this the facility has classrooms for both conducting academic lectures for both in-house and online classes. Dr. Ogale is the Director of RISE.



Device Fabrication Lab (Fig. Above)



Material Synthesis Lab (Fig. Above)

Dr. Ogale's dedication to advancing science and technology for sustainable development has made him a respected and influential figure in the global scientific community. His work continues to inspire and drive innovation in the fields of materials science and energy research.

Photos of Prof. S. B. Ogale

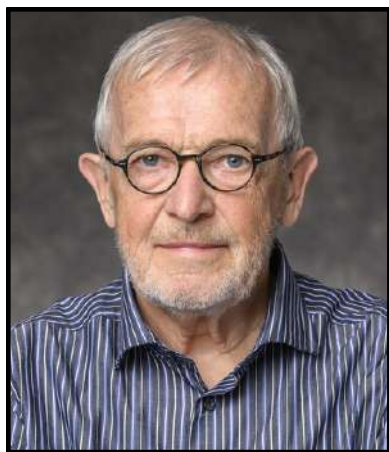


Image Courtesy: Respective Owners

Francis Halzen and the Neutrinos from the South Pole – Nobel Prize Physics 2026

Yash Bundile

Department of Physics, MES's Nowrosjee Wadia College, Pune 411 001



Professor Francis Halzen of the **University of Wisconsin–Madison** has been awarded the **Nobel Prize in Physics 2026** “for decisive contributions to the IceCube Neutrino Observatory and the discovery of high-energy neutrinos of astrophysical origin”. His achievement is a remarkable mix of particle physics, astrophysics, technology and scientific perseverance. Halzen helped open a whole new way of observing the Universe by turning a huge volume of ice in Antarctica into a giant detector.

Neutrinos are among the most elusive of the particles known to physics. They are electrically neutral, have a very small mass and interact only very weakly with matter. They go through the Earth, they go through our bodies, in huge numbers every second, with no apparent effect. But because they can travel through matter almost without absorption or deflection, they are unique cosmic messengers. Matter and magnetic fields may absorb or scatter photons, but neutrinos can carry information directly from the extreme environments where they are produced.

Halzen had an idea for catching these ultra-rare particles using something already in place on a massive scale: the ice below the South Pole. It was a contraption known as the IceCube Neutrino

Observatory, a particle detector unlike any standard laboratory instrument. Its main detector covers an area of about one cubic kilometer of Antarctic ice, with 5,160 digital optical modules buried deep below the surface. These sensors are strung on cables from some 1,450 to 2,450 meters below the ice.

The principle behind IceCube is both elegant and fascinating. When a high-energy neutrino happens to interact with an atomic nucleus in the Antarctic ice, it can produce a charged secondary particle. If this particle travels faster than light can travel through the ice, it produces a faint cone of blue Cherenkov radiation. The optical sensors embedded in the ice detect this tiny flash. By measuring when the light reaches different sensors and analysing the overall pattern, scientists can reconstruct the direction and energy of the original neutrino, effectively tracing it back toward its cosmic source.

Halzen conceived of a way to catch these ultra-rare particles with something already in place on a massive scale—the ice below the South Pole. It was a device called the IceCube Neutrino Observatory, a particle detector unlike any conventional laboratory instrument. Its main detector covers an area of roughly one cubic kilometer of Antarctic ice, with 5,160 digital optical modules deployed deep below the surface. These sensors are strung on cables from about 1,450 to 2,450 meters below the ice.

The scientific reward was enormous. IceCube has detected high-energy neutrinos from beyond our Solar System. This is direct evidence that the Universe contains very powerful natural particle accelerators that can produce particles at enormous energies. Additional observations have linked neutrino emission to distant cosmic sources, and have even detected neutrinos associated with our own Milky Way galaxy. These discoveries established neutrinos as a new astronomical messenger and

Physicist's Spotlight

helped to boost the nascent field of multi-messenger astronomy, where scientists can probe the Universe using different kinds of information, such as electromagnetic radiation, gravitational waves and high-energy particles.

Halzen's work is important for reasons that go far beyond the discovery of a hard-to-detect particle. Some of the most violent environments in the cosmos can generate high-energy neutrinos, where matter, magnetic fields and radiation reach extraordinary conditions. Neutrinos can escape these environments and travel enormous distances with little effect, and so they can offer clues about cosmic accelerators that conventional telescopes cannot reveal on their own. So IceCube has made a frozen landscape at the bottom of the world into a window on the most energetic processes in the Universe.

Francis Halzen's Nobel Prize is ultimately a recognition of scientific vision and persistence. He looked at the nearly transparent ice beneath

Antarctica not simply as frozen water, but as a potential telescope capable of detecting particles arriving from the depths of space. Decades later, that idea has become a functioning observatory that continues to uncover new information about our cosmic surroundings. Even today, IceCube is being upgraded with additional sensors and improved instrumentation, allowing scientists to study neutrinos with greater precision and search for new sources and phenomena.

By transforming Antarctic ice into a telescope, Francis Halzen and the IceCube collaboration have opened a new window on the Universe—one in which nearly invisible particles can reveal some of the most powerful events in existence. His story is a reminder that some of the greatest advances in physics begin with an unusual question: What if we could use the world around us in a completely different way? At the South Pole, that question turned ice into an observatory and elusive neutrinos into messengers from the cosmic frontier.

Photos of Francis Halzen



Image Courtesy: Respective Owners

Centre for Materials for Electronics Technology (CMET)

Vidhi Baldota

Department of Physics, MES's Nowrosjee Wadia College, Pune 411 001

Centre for Materials for Electronics Technology (C-MET), established in 1990 is an Autonomous Scientific Society under Ministry of Electronics and Information Technology (MeitY), Govt. of India dedicated to R&D on Electronic Materials. It has three laboratories located in Pune, Hyderabad and Thrissur.

C-MET stands as a premier autonomous R&D institution dedicated to bridging the critical gap between indigenous raw materials and advanced electronic devices.

C-MET works diligently with the mission To develop knowledge base in electronic materials and their processing technology for Indian industries and to become a source of critical electronic materials, know-how and services for the industry and other sectors of economy.

The institution is exceptionally well-equipped with state-of-the-art instrumentation and advanced laboratory infrastructure to support precision-grade research. Notable facilities include Class 10000 clean rooms for microfabrication, sophisticated thin-film deposition units, advanced characterization tools for material analysis, and specialized prototyping setups for integrated electronics packaging. These advanced systems allow researchers to conduct high-precision work right from synthesis to testing.

Objectives and Core Functions

C-MET operates with the primary objective of establishing technologies up to the pilot-plant scale for a wide range of critical electronic materials and successfully transferring these technologies to industries for commercialization. The center undertakes advanced applied research, sets up state-of-the-art analytical facilities, and serves Indian industries and research organizations by providing comprehensive material characterization and

technical consultancy services.

Core Research Areas, Instrumentation, and Technologies

CMET operates specialized laboratories across India, each driving critical technological advancements. The Hyderabad Laboratory specializes in high-purity materials and advanced electronics, producing critical compounds like TANTALUM NIOBIUM CARBIDE, HIGH PURITY CADMIUM, HIGH PURITY GALLIUM, and HIGH PURITY TELLURIUM, alongside Capacitor and Structural grade Tantalum powder, Tantalum pentoxide & Tantalum-Niobium carbide.

Meanwhile, the Thrissur Laboratory focuses on advanced functional materials, spearheading innovations such as AEROGELS and SUPERCAPACITORS, FLEXIBLE MICROWAVE SUBSTRATES, PIEZOCERAMIC ACTUATORS AND LTCC MATERIALS, PIEZOELECTRIC COMPOSITIONS AND PIEZOCERAMIC COMPONENTS, NTC CHIP THERMISTORS AND CHIP IN GLASS THERMAL SENSORS, GRAPHENE SUPERCAPACITORS, GRAPHENE BASED TRANSPARENT ELECTRODES FOR THIN FILM ACOUSTIC ACTUATORS AND SENSORS, and KESTERITE ABSORBER FOR THIN FILM SOLAR CELLS.

Key Innovations and Industrial Transfers

The institute is equipped with advanced characterization and processing instrumentation to support breakthrough developments. Key material classes and technologies researched and developed at CMET include COLOURED GLASSES, NANOCRYSTALLINE and NANO SIZE PRODUCTS, PHOTOIMAGEABLE THICK FILM MATERIALS, POLYMER SENSOR

Inside the Institute

MATERIALS, SOLDER PASTE FOR SURFACE MOUNT TECHNOLOGY, Barium Magnesium Tantalate (BMT) dielectric resonators, Flexible Microwave Substrates, Negative Temperature Coefficient (NTC) Thermal Sensors, and specialized chemical processes like the conversion of 3N (99.9%) to 6N (99.9999%) pure Cadmium metal. Many of these cutting-edge technologies are successfully developed and actively transferred to Indian industries to foster self-reliance in electronic component manufacturing.

Advanced Instrumentation and Facilities

To support cutting-edge R&D, C-MET houses sophisticated instrumentation capable of micro- and nano-level analysis. These facilities include high-resolution electron microscopes, X-ray diffraction systems, surface characterization tools, and precision electrical testing equipment, enabling precise quality control and advanced characterization of electronic materials. Candidates holding a Bachelor's, Master's, or Doctoral degree find exceptional opportunities here to bridge fundamental science with industrial application.

Institute Images



Institute Logo



Main Building



Lab Images



Event Images



Image Courtesy: Respective Owners

Guest Lecture - Dr. Bhooshan Gadre

BHOUTIKI Physics Club

Department of Physics, MES's Nowrosjee Wadia College, Pune 411 001



The **BHOUTIKI Physics Club** recently hosted an inspiring and intellectually stimulating guest lecture on gravitational waves delivered by the esteemed physicist **Dr. Bhooshan Gadre**.

Dr. Gadre captivated the audience with profound insights into the detection, theoretical mechanics, and cosmic significance of spacetime ripples, breaking down complex astrophysical concepts into engaging, accessible ideas for undergraduate students and physics enthusiasts alike.

Complementing the core lecture, the club premiered a specially curated short video tribute inspired by **Carl Sagan's iconic Cosmos: A Personal Voyage**, setting an awe-inspiring tone for the exploration of the universe. The event concluded on an energetic note with an **interactive physics quiz** that tested participants' knowledge and sparked lively discussions, making it a resounding success for everyone involved.

Beyond the lecture itself, the event served as a meaningful platform for students to engage with contemporary physics beyond the boundaries of the classroom. The discussions encouraged curiosity, critical thinking, and a deeper appreciation of how fundamental physics connects mathematical ideas with observations of the universe. Through such initiatives, the **BHOUTIKI Physics Club** continues to foster a vibrant scientific community where students can learn, question, and explore the frontiers of physics together.

The Stories Behind the Science

Arjun Apte, FYBSc.

MES's Nowrosjee Wadia College, Pune 411 001



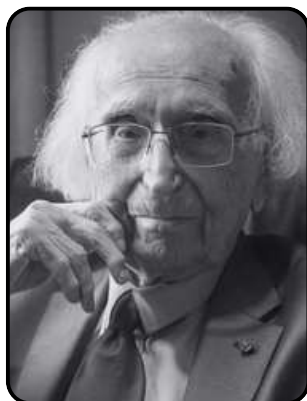
M.P. Parameswaran

M. P. Parameswaran was an Indian nuclear engineer, educationist, science communicator, and one of the key figures in the movement of public science in India. In 1965, Parameswaran earned a Doctorate in Nuclear Engineering from the Moscow Power Engineering Institute. Until 1975, he worked at the Bhabha Atomic Research Centre (BARC).

Thereafter, M.P. Parameswaran had been working for the Kerala Sasthra Sahithya Parishad (KSSP), helping it develop into a public science organization and increasing awareness and literacy of people regarding science in India. He was involved in such organizations as Bharat Jan Vigyan Jatha, All India People's

Science Network, and Bharat Gyan Vigyan Samiti. Being an extremely productive writer, M. P. Parameswaran authored 29 books on various scientific topics in Malayalam and two in English. These books ranged from nuclear science and astronomy to mathematics and ecology.

Additionally, he was involved in developing the keyboard layout for the Malayalam language used in typewriters and later in computers. For his contributions to science popularization and literacy, Parameswaran received numerous national awards, including Kerala Sree in 2022.



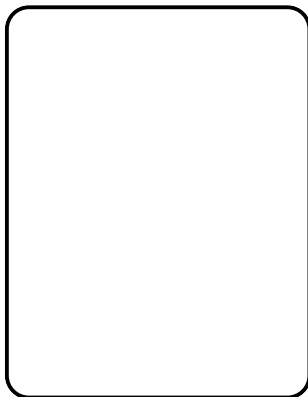
Cyril Hilsum

Cyril Hilsum was a British physicist who made a major contribution to the fields of semiconductors and liquid-crystals. Having graduated from the University of College London in physics, Hilsum worked most of his life in research laboratories of the British government, eventually reaching the post of Chief Scientific Officer.

He made a significant contribution to the advancement of the technology of III-V semiconductors, especially gallium arsenide, and created the first semiconductor laser in Great Britain. Besides, he was co-author of the Ridley–Watkins–Hilsum theory that laid the basis of the Gunn diode – a special semiconductor device. His work was vital for the progress of the technology of liquid-crystal displays (LCDs).

The research at the Royal Radar Establishment revealed early technology of LCDs that became the basis of modern display devices. Cyril Hilsum received numerous awards for his achievements, including Faraday Medal, Max Born Prize, Richard Glazebrook Medal and Prize, and Royal Medal of the Royal Society.

He was elected to be a Fellow of the Royal Society and president of the Institute of Physics in 1988-1990. In his long-lasting career, Hilsum collaborated with industry, government and academic institutions giving advice and making contributions to research of new technologies till very old age.



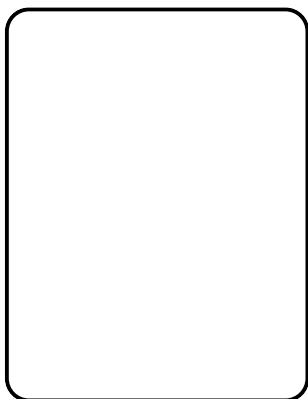
Torstein Jøssang

Torstein Jøssang was a physicist of Norwegian origin, the professor of the University of Oslo. The Cand.Real. and Dr.Philos. degrees were obtained in 1962 and 1968 respectively from the University of Oslo after research done in Ohio State University during 1963-1966.

The early career of Torstein Kristen included guest professorships in China, Israel, and the USA. Since 1969, Torstein had been an associate professor of physics of the University of Oslo, and he achieved the rank of Professor in 1987. He had the fruitful cooperation with the physicist Jens Feder that was demonstrated by the numerous joint researches. Besides doing the research work.

Torstein held the leading positions in the scientific community.

He was the head of the Centre for Advanced Study of the Norwegian Academy of Science and Letters between 1993 and 2000 and the editor of *Physica Scripta* – the journal published by the Royal Swedish Academy of Sciences.



Rafael Sorkin

Rafael Sorkin was an American theoretical physicist. He was professor emeritus of physics at Syracuse University and also Perimeter Institute for Theoretical Physics. Rafael Sorkin is a fellow of the American Physical Society. He is known for his work on the causal set program of quantum gravity which aims at describing the structure of spacetime.

He was born in Chicago in 1945. Rafael Sorkin was the valedictorian of New Trier Township High School in 1963. Later on, he joined Harvard University and obtained his B.A. in 1966. In addition, he received his Ph.D. from California Institute of Technology in 1974. The major areas of study were quantum mechanics, gravity, and spacetime. According to the causal set theory postulated by Rafael Sorkin, spacetime is not essentially a continuum as stated by general relativity but is made up of a set of elementary events causally related to each other. It means that the spacetime appears to be a continuum when viewed at macroscopic scale due to an underlying discrete structure.

Moreover, he contributed to the field of black hole entropy. He studied the possibility of explaining black hole entropy by the mechanism of quantum entanglement across the horizon of a black hole. It showed that the entanglement is very important for the understanding of black holes and quantum gravity. Other researches of his include spacetime topology and quantum geons.

Along with Steven Johnston, he came up with the Sorkin-Johnston Vacuum which is a distinguished vacuum for quantum fields on curved spacetimes. In addition, he invented quantum measure theory and higher order interference theory which result in so-called Sorkin parameters.

Rafael Sorkin died on 12 September 2026 in Kitchener, Ontario, Canada at the age of 80.

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“I Crossed the International Borders and Found a World of Connections in Germany”

Ms. Sayali Neelima Rajesh Atkare

DST-INSPIRE-SRF, Department of Physics, Savitribai Phule Pune University

There are some journeys that take you from one place to another, and there are others that change the way you look at the world. My journey from the classrooms and laboratories of M.E.S. Nowrosjee Wadia College, Pune, to the shores of Lake Constance in Lindau, Germany was one such journey. In June 2026, I had the extraordinary privilege of representing India as one of the Young Scientists at the 75th Lindau Nobel Laureate Meeting for Interdisciplinary Science in Germany. More than 600 young researchers from around the world came together to interact with Nobel Laureates, exchange ideas, and celebrate science beyond disciplinary and geographical boundaries. This privilege came out of extensive selection process through two major selection committees, one where the Department of Science and Technology (DST), Government of India nominated a few selected young scientists based on our work, publications, collaborations and efficiency to represent India on a global level and further the Council for Nobel Laureates Meeting, Lindau shortlisted us based on our calibre to be a part of this prestigious scientific meeting. For me, however, Lindau was much more than a prestigious scientific meeting. It was a deeply personal reminder of how far curiosity, perseverance, education and the encouragement of the right people can take you.

My association with Nowrosjee Wadia College remains an important chapter of my scientific journey. I completed my M.Sc. in Physics here, and it was during these formative years that my interest in materials and their fascinating physical properties began taking a more definite shape. At that stage, I could never have imagined that one day I would be standing in Lindau, surrounded by young scientists from more than a hundred countries and listening to scientists whose discoveries had fundamentally changed our understanding of nature. One of the most surreal experiences at Lindau was realizing how accessible the Nobel Laureates were.

Scientists whose names I had encountered in textbooks and research literature were sitting among us, walking with us, having lunch with us and engaging in remarkably ordinary conversations. What surprised me most was their simplicity. I could ask a complicated scientific question and receive an answer that was surprisingly straightforward. Their ability to distil years of knowledge into a few clear thoughts was itself a lesson in scientific thinking. And sometimes, the conversation had nothing to do with science at all. Sitting beside a Nobel Laureate at lunch and discussing travel, life, cultures or everyday experiences made me realize that scientific brilliance does not require distance or formality. Behind every major discovery is simply a curious human being who kept asking questions. The interactions also reminded me that every scientific journey is different. Each Nobel Laureate had travelled a unique path, faced different challenges and developed different perspectives. Yet their stories had one common thread i.e. curiosity, persistence and the courage to continue when the answers were not obvious. The most valuable lesson was perhaps that scientific excellence and humility can coexist. That ambition and kindness need not be opposites. That different perspectives can strengthen rather than weaken scientific thinking. And that the future of science depends not only on discoveries, but also on how well we communicate, collaborate and support one another.

For a young researcher, opportunities such as Lindau can sometimes feel almost unreal. But experiences like these also reinforce an important belief: the journey matters. My mother, Dr. Neelima Atkare has always told me to believe in myself, be confident in my efforts and that confidence matters. Every classroom matters. Every mentor matters. Every failed experiment teaches something. Every encouraging teacher can alter the trajectory of a student's life.

Student Achievements

In my life, one such teacher is Dr. Shashikant Shinde from our very own alma mater. And every institution that gives a young person the freedom to explore can become part of a much larger story.

I wish everyone who reads this to reach for their goals and achieve extraordinary recognition in their lives as big as they have never thought before.

Author's Introduction:

Author, Ms. Sayali is working as a material scientist in the “Advanced Electronic Materials and Sensors Laboratory” in the Department of Instrumentation, SPPU. She has received one of the most prestigious DST-INSPIRE Fellowship in India for her proposed doctoral thesis. She has represented her institute at various international conferences all over India heading towards her Indian delegative journey to Germany.



Physics Riddles

Team BHOUTIKI

Department of Physics, MES's Nowrosjee Wadia College, Pune 411 001

1. I store charge in an electric field between two plates, letting out a sudden burst of power when you need a quick release. What am I?
2. Wind me up or press me down, I store potential without a sound. Let me go, and watch me spring into kinetic motion, fit for a king! What am I?
3. I hold power in a portable shell, letting ions travel from cell to cell. Lithium is my favorite fuel to ride. What am I?
4. Lift me up against gravity's pull, and my invisible reserve becomes full. Drop me down a turbine chute to yield the fruit. What am I?
5. Spin me fast in a vacuum tight, keeping angular momentum right. I store your energy in rotational speed, ready to discharge whenever you plead. What am I?
6. Cool me down to zero resistance, and I'll keep a current looping in the distance, trapping magnetic fields inside my coil. What am I?
7. Rocks or molten salt are my cozy bed, soaking up the heat until it's time to be spread. What am I?
8. Compress me deep into a cavern vast, under heavy pressure I hold fast, waiting for a turbine blast. What am I?
9. When a speeding car hits the brakes hard, I don't let that motion go discard. I capture the momentum on the fly and boost you back up to the sky. What am I?
10. Einstein wrote my famous rule ($E=mc^2$), locking up colossal energy within a tiny atomic fuel. What am I?
11. I wrap myself in a tight coil around a core, storing energy in a magnetic field and blocking any sudden current shifts with a heavy chore. What am I?
12. Feed me electricity to split water apart, store my gas in a tank to make power start, and exhaust only water when we're through. What am I?
13. I track the desert sun all day long, trapping solar heat in graphite pools so the grid stays strong when the night is cool. What am I?
14. I bridge the gap between a battery and a plate, using an electric double-layer to store charge at a massive rate. What am I?
15. Combine light nuclei or split a heavy one apart, I am the most intense energy storage known to the universe's heart. What am I?

ANSWERS

1. A Capacitor
2. A Spring (Elastic Potential Energy)
3. A Battery
4. Gravitational Potential Energy (or Pumped-Storage Hydro)
5. A Flywheel
6. Superconducting Magnetic Energy Storage (SMES)
7. Thermal Energy Storage
8. Compressed Air Energy Storage (CAES)
9. Regenerative Braking / KEBS (Kinetic Energy Recovery System)
10. Mass-Energy Equivalence / Nuclear Binding Energy.
11. An Inductor
12. Hydrogen Fuel Cell Storage
13. Concentrated Solar Power (CSP) Thermal Storage
14. A Supercapacitor (Ultracapacitor)
15. Nuclear Energy

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