



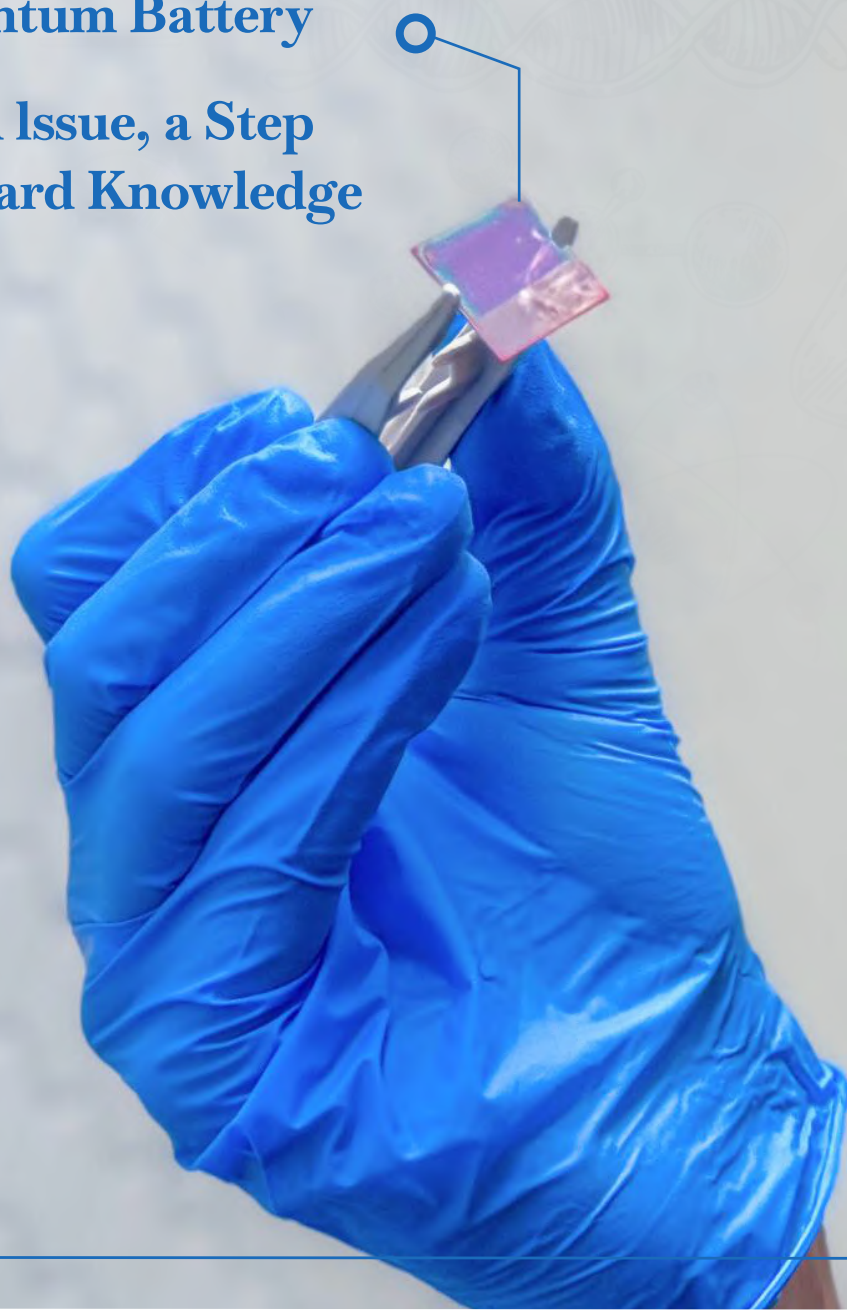
Meta Chem

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Quantum Battery

**Each Issue, a Step
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MetaChem

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Energy and Sustainable Development

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Wonders of Nanoscience



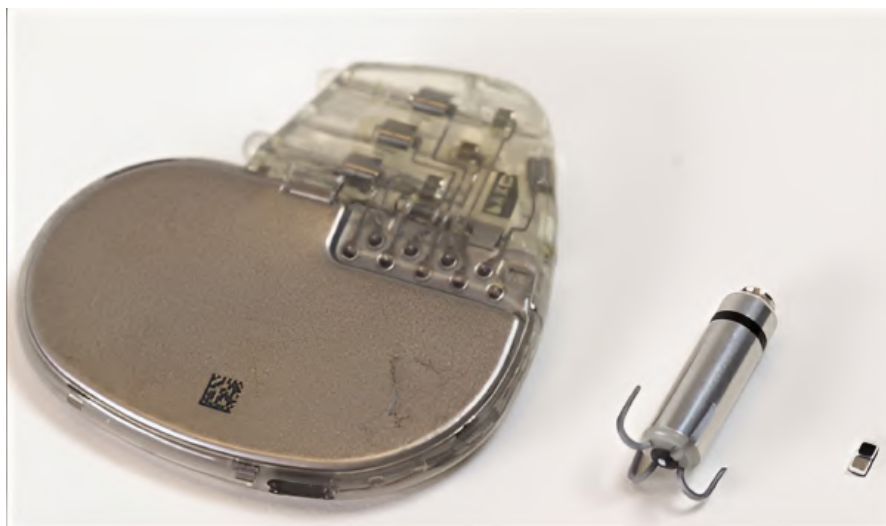
Author: Abdulhamid Dehghani

Fully Bioresorbable, Wireless, Photoelectric Nanoscale Pacemaker: An Injectable, Surgery-Free Innovation for Temporary Treatment of Cardiac Arrhythmia with Spontaneous Self-Elimination

Engineers at Northwestern University have developed a fully bioresorbable nanoscale pacing system (dimensions under 15×4 mm and mass less than 0.2 g) that can be delivered intracardially or epicardially via syringe injection (inner needle diameter ≤ 1 mm).

The implant is free of batteries and connecting wires, drawing its power instead from galvanic reactions induced upon contact with body fluids. Wireless control is achieved through a soft, flexible skin-mounted patch that emits near-infrared (NIR, $\lambda \approx 850\text{--}950$ nm) pulses, which penetrate the skin, sternum, and myocardial tissue to activate the implant's photoelectric receivers. All components including Mg electrodes, GaInP/GaAs semiconductor layers, biodegradable polymer insulators, and a flexible substrate degrade within body fluids over a period of several weeks to a few months into harmless metabolites (such as Mg^{2+} ions and organic acids), thereby completely eliminating the need for surgical extraction. This technology is specifically designed for the treatment of transient arrhythmias following open-heart surgery in

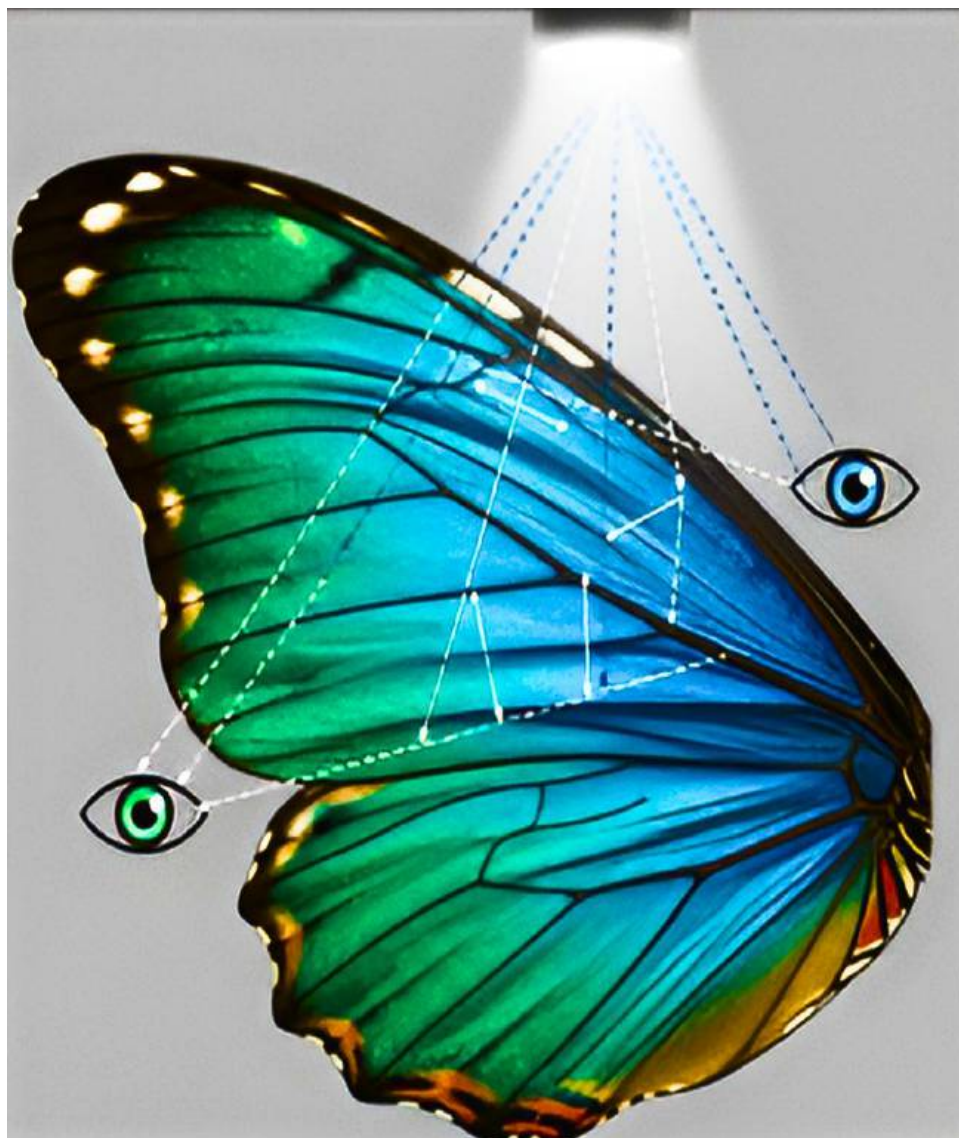
infants and children with congenital heart defects, a population in which the use of conventional permanent pacemakers is unsuitable due to rapid cardiac growth and the burden of repeated surgical interventions. Results published in *Nature* demonstrate the system's successful performance across small and large animal models (mice, rabbits, and dogs), as well as in ex vivo donor human hearts. The device is capable of delivering more than 100,000 pacing pulses with sub-5-millisecond temporal precision, without current leakage or tissue inflammation. This achievement represents the first clinically oriented demonstration of a fully transient, self-eliminating nanoscale pacemaker, marking a paradigm shift in the treatment of temporary arrhythmias from invasive surgical approaches toward minimally invasive, autonomous solutions.



From left: a conventional pacemaker, a leadless pacemaker, and the new pacemaker

References:





Author: Azam Moazeni Bistgani

Nanoscale Applications in the Production of Smart Colors: A New Perspective on Light Reflection and Material Architecture

In a recent study at the University of Cambridge, researchers developed nanoparticles that change color solely with the observer's viewing angle, regardless of the type or intensity of illumination.

This phenomenon is inspired by the nanoscale architecture of the Morpho butterfly's wings, which exhibit angle-dependent structural coloration. The effect originates from the highly ordered arrangement of polymeric nanoparticles. Light is reflected according to the Bragg reflection principle, so changing the viewing angle shifts the reflected wavelength and, consequently, the observed color. The illumination itself remains unchanged throughout this process. Unlike conventional pigments or metallic nanoparticle-based colors, the observed color is

determined by the nanoscale geometry of the material rather than its chemical composition. This structural approach offers new opportunities for designing anti-counterfeit inks, angle-responsive displays, and smart optical coatings. These findings highlight that color can be engineered as a physical property arising from nanoscale structural order. This concept opens new possibilities for the development of advanced photonic materials and next-generation optical technologies based on material architecture.

References:



Energy Systems (CO₂ Emissions)



Author: Pouria Tafreshi

This review article presents a comprehensive and systematic analysis of energy systems carbon dioxide (CO₂) emissions and mitigation policies in three Central Asian countries – Kazakhstan, Uzbekistan and Kyrgyzstan – covering the period from 1990 to 2022. These countries share a common historical legacy as former Soviet republics and similar institutional frameworks; however, they exhibit markedly different energy resource endowments, energy mixes, and emission trajectories. All three nations are parties to the Paris Agreement, making their decarbonization pathways particularly relevant within the context of global climate mitigation efforts.

The analysis indicates that emission CO₂ intensities in the three countries remain substantially higher than the global average, despite noticeable declines since the early 2000s. This persistent carbon intensity is largely attributed to structural dependence on fossil fuels, inefficient energy conversion technologies, aging power infrastructure, and limited penetration of modern energy efficiency measures.

Kazakhstan exhibits the highest per capita CO₂ emissions due to its coal-dominated electricity and heat generation sectors, which account for a significant share of national emissions. Uzbekistan's emissions profile is shaped primarily by its heavy reliance on natural gas, particularly in power generation and industrial applications. Kyrgyzstan, while characterized by a comparatively low-carbon electricity

mix dominated by hydropower, experiences considerable energy losses and inefficient residential energy consumption, especially during winter heating periods.

Using long-term datasets from the International Energy Agency, the World Bank, and national statistical sources, the study examines trends in total primary energy supply, electricity generation capacity, final energy consumption, and sectoral CO₂ emissions. Particular attention is given to emissions from electricity and heat production, transport, and industry, which together constitute the dominant sources of CO₂ in the region. Although CO₂ emissions per unit of GDP have declined across all three countries—indicating partial decoupling of economic growth from emissions—absolute emission levels have remained high or increased during periods of economic expansion.

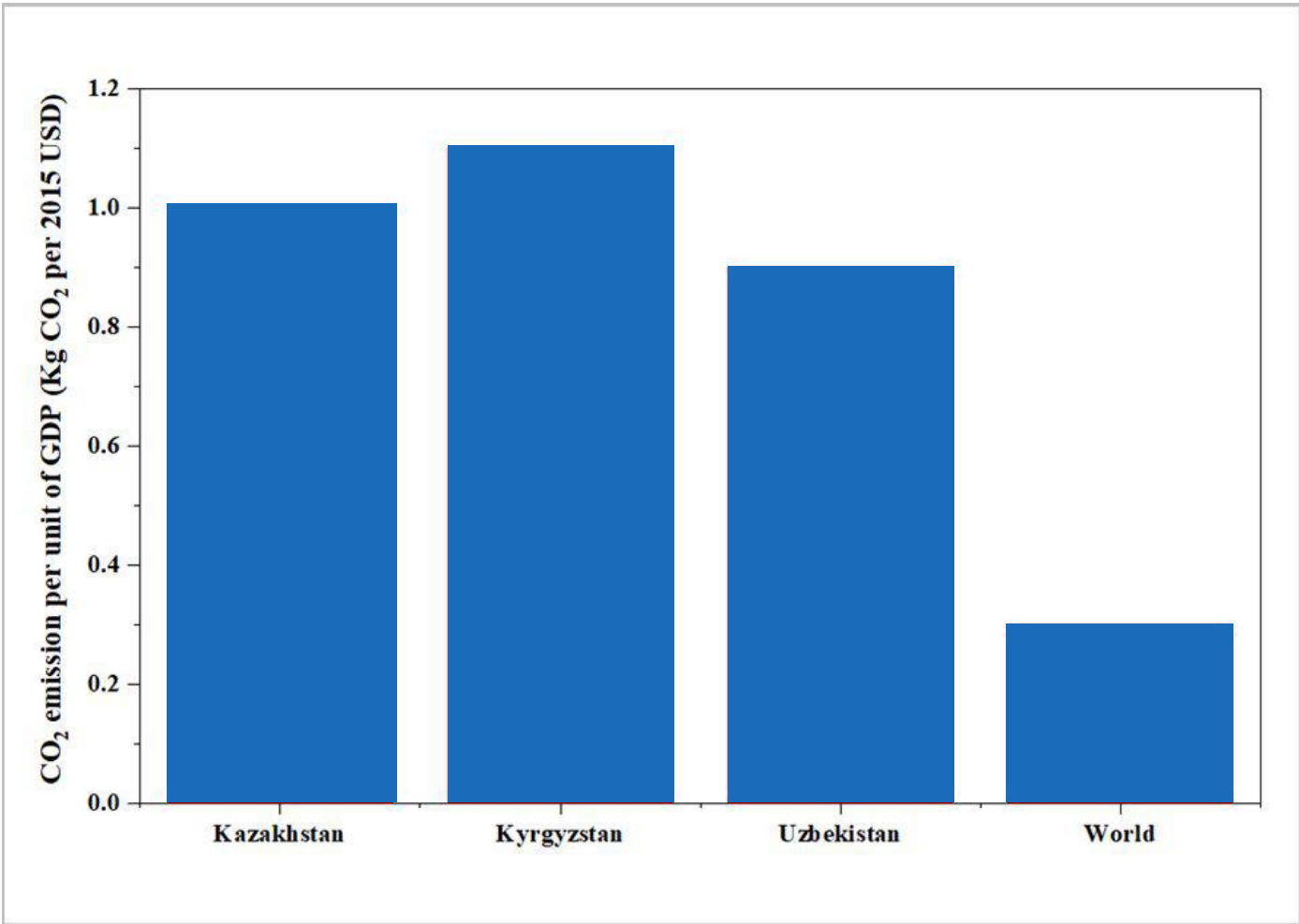
This finding underscores that improvements in economic efficiency alone are insufficient to achieve meaningful emissions reductions without deeper structural transformations of national energy systems.

This article further provides a detailed review of national energy and climate policy frameworks, including renewable energy targets, energy efficiency strategies, and long-term decarbonization plans. Kazakhstan and Uzbekistan have adopted relatively more ambitious policy initiatives, such as competitive renewable energy auctions, large-scale deployment of solar and wind power, and emerging strategies for low-carbon hydrogen production. In contrast, Kyrgyzstan's policy focus remains centered on hydropower development; however, progress is constrained by infrastructure degradation, limited financial resources, and vulnerability to climate-induced hydrological variability.

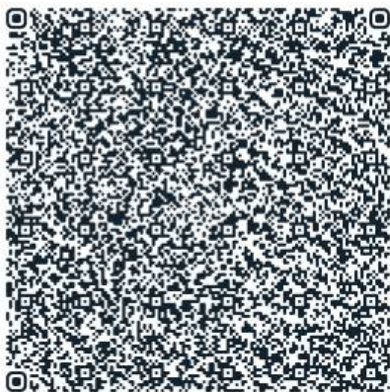
Despite the existence of policy instruments and international climate commitments, the study identifies several persistent structural and institutional barriers that hinder effective emissions mitigation. These barriers include fossil fuel subsidies, limited access to climate finance, regulatory uncertainty, weak institutional capacity, and gaps between policy formulation and implementation.

Moreover, regional energy cooperation remains underdeveloped, despite its significant potential to enhance energy security and support low-carbon transitions through cross-border electricity trade. The article concludes that accelerating decarbonization in Central Asia requires integrated and coordinated policy approaches. These approaches should combine large-scale renewable

energy deployment, systematic energy efficiency improvements, gradual reform of fossil fuel subsidies, strengthened institutional capacity, and enhanced regional cooperation. Overall, the review provides valuable insights for policymakers, researchers, and international stakeholders seeking to design effective climate mitigation strategies tailored to resource-rich transition economies.



References:



Green Ammonia Synthesis Using Heterogeneous Catalysts: From Nitrogen Activation to Sustainable Production



Authors: Yasin Sarpeleh, Zahra Jamali

Ammonia is one of the most fundamental chemicals in the world, playing a vital role not only in the production of nitrogen-based fertilizers but also, more recently, as a hydrogen carrier and a promising energy storage medium. Although the ammonia molecule itself is carbon-free, its conventional production process is not inherently sustainable. The Haber-Bosch process, which converts nitrogen and hydrogen into ammonia, is typically carried out at temperatures of approximately 400–600 °C and pressures of 15–30 MPa. In addition to its high energy consumption, the hydrogen required for this process is predominantly produced through natural gas reforming or coal gasification. Consequently, ammonia production accounts for a significant share of global energy consumption and carbon dioxide (CO₂) emissions [1,2].

In the concept of green ammonia, hydrogen is produced through water electrolysis powered by solar, wind, or other renewable energy sources, while the energy required for the ammonia synthesis unit is supplied from low carbon energy resources. However, replacing fossil derived hydrogen with green hydrogen alone is insufficient to reduce production costs and energy consumption. The key challenge lies in the development of catalysts capable of

promoting ammonia synthesis at lower temperatures and pressures while maintaining satisfactory reaction rates. As illustrated in Figure 1, green ammonia synthesis encompasses a range of nitrogen sources, energy conversion pathways, and catalytic systems. Electrocatalytic, photocatalytic, and photoelectrocatalytic approaches can utilize renewable energy to convert various nitrogen species into ammonia under much milder reaction conditions [1,2].

Why Is Nitrogen Activation Difficult?

The greatest challenge in ammonia synthesis is the exceptional stability of the nitrogen molecule. The bond dissociation energy of the N≡N triple bond is approximately 941 kJ mol⁻¹, and nitrogen also exhibits low solubility in aqueous media. In thermocatalytic systems, the adsorption and dissociation of molecular nitrogen are often among the slowest steps of the reaction. In electrochemical systems, the competing hydrogen evolution reaction (HER) can consume electrons and protons before they are utilized for nitrogen reduction, thereby decreasing the efficiency of ammonia synthesis [1,3].

Heterogeneous catalysts facilitate nitrogen adsorption and electron transfer to its antibonding orbitals by providing active surface sites. Following nitrogen activation, stepwise hydrogenation occurs on the catalyst surface, leading to the sequential formation of NH*, NH₂*, and ultimately NH₃ intermediates. Therefore, catalyst performance depends on the number of active sites,

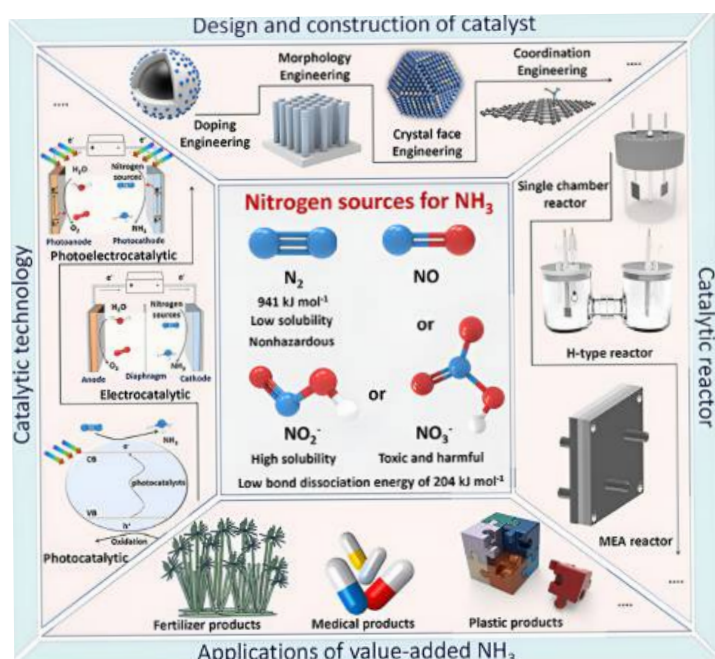


Figure 1. Schematic illustration of nitrogen sources, catalytic pathways, catalyst engineering strategies, and reactor systems employed in green ammonia synthesis. Adapted from Ref [3].

electronic structure, particle size, crystal defects, and the interaction between the active phase and the support [3,4].

Next Generation Heterogeneous Catalysts

Iron based catalysts remain the foundation of the industrial Haber Bosch process; however, ruthenium and cobalt have also attracted considerable attention because of their high capability for nitrogen activation. Supporting these metals on basic supports, hydrides, nitrides, and electrides can increase the electron density of the metal, thereby facilitating the dissociation of the nitrogen molecule. Some of these materials have demonstrated remarkable catalytic activity even at temperatures of approximately 250–300 °C. Nevertheless, the high cost of ruthenium and the long-term stability of the supports remain major limitations [1].

Perovskites with the general formula ABO₃ are among the most promising families of catalytic materials. Substituting elements at the A and B sites enables the tuning of electrical conductivity, redox properties, oxygen

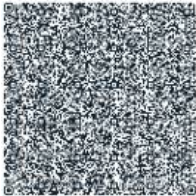
vacancy concentration, and the adsorption strength of nitrogen-containing species. For example, in the oxynitride–hydride perovskite BaCeO_{3-x}N_yH_z, lattice nitride and hydride ions directly participate in ammonia formation. This pathway, which resembles the Mars–van Krevelen mechanism, can reduce the activation energy compared with the conventional surface reaction pathway [2].

In addition to perovskites, low dimensional materials including zero-dimensional nanoparticles, one-dimensional nanorods and nanowires, and two-dimensional nanosheets have also gained significant attention. Their high specific surface area, large number of edge atoms, and tunable electronic structure make them highly suitable for photocatalytic and electrocatalytic processes. The introduction of controlled defects, doping, and the construction of heterostructures can enhance charge separation, facilitate electron transfer, and improve the selective adsorption of nitrogen or nitrate species [4].

Comparison of Major Catalyst Families

Main Limitation	Main Advantage	Representative Catalysts	Synthesis Method
Requires hydrogen and generally operates at higher temperatures and pressures than emerging routes	Closest to industrial technology with relatively high ammonia production rates	Fe, Ru, and Co supported on oxide, hydride, nitride, and electride supports	Thermocatalytic
Competition from the hydrogen evolution reaction (HER), low N ₂ solubility, low ammonia production rates and current densities, and limited long-term stability	Direct utilization of renewable electricity, modular reactor design, and operation at atmospheric pressure under milder conditions	Perovskites, single atom catalysts, metals and metal oxides, and two dimensional materials	Electrocatalytic
Rapid electron hole recombination, limited visible light absorption, difficult N ₂ activation, and low quantum efficiency	Direct utilization of solar energy and the ability to operate under near ambient conditions	TiO ₂ , graphitic carbon nitride (g-C ₃ N ₄), and S scheme and Z scheme heterostructures	Photocatalytic
Power consumption for plasma generation, limited energy efficiency, and challenges in designing continuous and scalable reactors	Nitrogen activation at lower temperatures,electrical controllability,and compatibility with decentralized systems powered by renewable energy	Metals and metal oxides, particularly Ru , Ni , Co , and Fe based systems	Plasma-Catalytic

References:



Smart Supercapacitors: From Engineered Nanomaterials to the Next Generation of Energy Storage Systems



Author: Hadis Akbari

Rapid advances in portable electronics, electric vehicles, and renewable energy technologies have significantly increased the demand for high-performance electrochemical energy storage systems. Imagine a smartphone or an electric vehicle that can be fully charged within seconds, withstand millions of charge-discharge cycles with negligible performance degradation, and maintain reliable operation under harsh environmental conditions. Although lithium-ion batteries currently dominate the energy storage market because of their high energy density, they still suffer from several inherent limitations, including relatively slow charging rates, limited cycle life, safety concerns associated with thermal runaway, and gradual capacity fading during long-term operation.

These challenges have stimulated extensive research into complementary energy storage technologies capable of delivering both high power and long-term durability.

Among these technologies, supercapacitors have emerged as one of the most promising candidates owing to their exceptionally high power density, ultrafast charging and discharging capability, excellent cycling stability, and superior operational reliability. Consequently, supercapacitors have attracted considerable attention for applications ranging from consumer electronics and hybrid/electric vehicles to renewable energy integration and smart power management systems.

Despite these remarkable advantages, conventional supercapacitors still face a critical challenge: their energy density remains considerably lower than that of lithium-ion batteries. As a result, recent research has shifted beyond merely increasing specific capacitance toward the rational design of advanced electrode materials, hierarchical porous architectures, and innovative electrolyte systems that can simultaneously enhance energy density without sacrificing power capability or cycling stability. In particular, emerging materials such as MXenes, metal-organic frameworks (MOFs), covalent organic frameworks (COFs), and various hybrid nanocomposites have opened new opportunities for constructing high-performance supercapacitor electrodes with enhanced electrical conductivity, abundant electrochemically active sites, and efficient ion transport pathways.

Recent research has increasingly focused on advanced electrolyte engineering, as the electrochemical performance of supercapacitors is governed by the synergistic interaction between electrodes and electrolytes. Emerging electrolyte systems, including Water-in-Salt Electrolytes (WiSEs), Deep Eutectic Solvents (DESSs), and gel/solid-state electrolytes, have significantly expanded the electrochemical stability window, enhanced device safety, and enabled the development of flexible and wearable energy storage devices. These advances highlight that future high-performance supercapacitors will rely not only on engineered electrode materials but also on the integrated optimization of electrolyte chemistry and device architecture.

Are Supercapacitors More Than Energy Storage Devices?

Recent advances in nanotechnology, materials science, and intelligent energy systems have transformed the role of supercapacitors from conventional energy storage devices into multifunctional components of integrated energy management systems. Beyond rapid energy storage and delivery, modern supercapacitors are increasingly designed to harvest ambient energy, monitor their operational status, and interact with surrounding electronic systems, enabling the development of self-powered and autonomous technologies. A major breakthrough in this field is the development of integrated energy harvesting-storage systems, where supercapacitors are directly coupled with energy harvesters such as photovoltaic cells, piezoelectric nanogenerators, and thermoelectric devices to capture and store solar, mechanical, or thermal energy in real time.

. These integrated platforms provide sustainable power for wireless sensors, Internet of Things (IoT) devices, environmental monitoring systems, and smart infrastructure. Another emerging direction involves structural supercapacitors, in which load-bearing components simultaneously function as energy storage units, offering significant reductions in system weight and volume for applications in transportation, aerospace, and robotics. Similarly, photo-supercapacitors integrate solar energy conversion and electrochemical storage into a single device, minimizing energy losses while enabling self-powered wearable and portable electronics.

These developments demonstrate that the future of supercapacitors extends well beyond improving energy density or specific capacitance. Instead, next-generation supercapacitors are expected to evolve into intelligent, multifunctional, and self-sustaining energy systems through the integration of advanced nanomaterials, innovative electrolytes, artificial intelligence, and energy harvesting technologies.

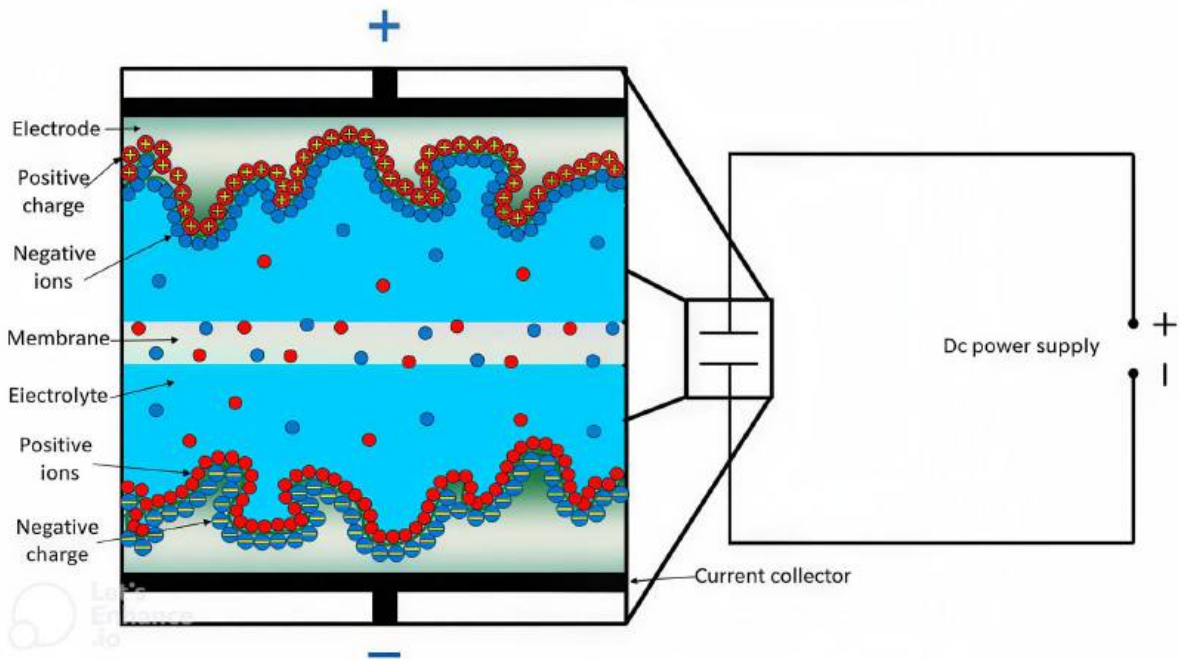
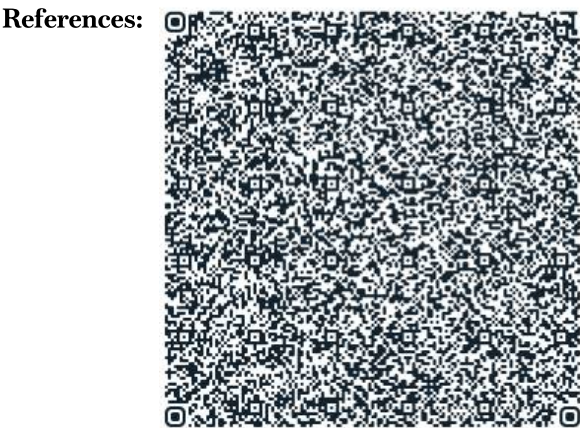


Figure.1. General schematic of a supercapacitor cell illustrating the electrical double-layer capacitance (EDLC) charge storage mechanism

Future Perspectives: Supercapacitors at the Threshold of a New Era

The future of supercapacitor technology extends far beyond the development of advanced electrode materials. Instead, its evolution will be driven by the convergence of nanotechnology, materials engineering, advanced electrolytes, artificial intelligence, and integrated energy harvesting systems. Future supercapacitors are expected to function not only as high-performance energy storage devices but also as intelligent platforms capable of harvesting ambient energy, monitoring their operational status, and seamlessly interacting with next-generation energy networks. Although significant challenges remain—including enhancing energy density, reducing manufacturing costs, and enabling large-scale commercialization—recent advances indicate that supercapacitors are approaching a transformative stage. Their unique combination of high power capability, exceptional cycling stability, and multifunctionality positions them as key components for future electric vehicles, wearable and biomedical electronics, smart cities, aerospace technologies, and the Internet of Things (IoT).

Ultimately, the future of supercapacitors will depend not on the discovery of a single breakthrough material, but on the intelligent integration of advanced materials, innovative device architectures, digital technologies, and data-driven design strategies. This multidisciplinary approach is expected to blur the boundaries between energy generation, storage, and management, paving the way toward autonomous, sustainable, and highly efficient energy systems.



Techno-Economic and Environmental Assessment of a Hybrid Bioenergy System Optimized via NSGA-II: Biomass Pyrolysis, Fischer-Tropsch Synthesis, and Solar-Enhanced Power Generation

1. Introduction

Growing concerns over climate change and the depletion of fossil resources have intensified interest in renewable, low-carbon pathways for producing liquid fuels and electricity. Biomass gasification coupled with Fischer-Tropsch (FT) synthesis is among the most promising routes for converting a widely available renewable feedstock into synthetic diesel-range hydrocarbons, yet conventional biomass-to-fuel systems still suffer from limited exergy efficiency, high production costs, and considerable CO₂ emissions. Prior studies have generally examined isolated subsystems gasification, FT synthesis, power cycles, or carbon capture without a fully integrated, simultaneously optimized framework.



Prepared by: Mehdi Amini

This study addresses that gap by proposing an innovative, solar-assisted autothermal biomass gasification system fully integrated with Fischer-Tropsch synthesis, a Rankine steam power cycle, and an MDEA-based post-combustion carbon capture unit. Concentrated solar heat is combined with autothermal gasification to supply thermal energy for the process and to preheat feed streams, improving syngas quality and overall thermal management. The entire flowsheet was designed and simulated in ASPEN Plus, while a multi-objective NSGA-II optimization (implemented in MATLAB and coupled with ASPEN Plus through a COM interface) was used to simultaneously maximize energy and exergy efficiency, improve economic return, and minimize CO₂ emissions an integration and optimization strategy not previously documented for this class of hybrid biomass-solar systems. The analysis spans energy, exergy, and economic (3E) assessment together with a full life-cycle assessment (LCA), offering a comprehensive picture of the technical, financial, and environmental performance of the proposed cogeneration concept.

2. Results and Discussion

Energy and exergy performance

In the base configuration, the gasification unit converted biomass into syngas with 58.26% energy efficiency and 53.5% exergy efficiency, while the Fischer-Tropsch synthesis unit achieved 49.61% energy and 47.25% exergy efficiency with the lowest exergy destruction (19.2%) among the major sections. The post-combustion carbon capture unit was the weakest link, with only 33.18% energy and 32.6% exergy efficiency and the highest exergy destruction (48.8%), pointing to solvent regeneration and absorption column irreversibilities as priority targets for improvement. Auxiliary equipment heat exchangers and compressors performed comparatively well, reaching energy/exergy efficiencies of about 67.6%/62.4% and 73.2%/69.8%, respectively.

Economic performance

Using a biodiesel sale price of 1490 \$/ton and an electricity price of 0.085 \$/kWh, the base-case system required a capital cost (CAPEX) of 0.734 M\$/ton biomass and an annual operating cost (OPEX) of 633,600 \$/(year-ton biomass). The resulting economics were favorable: a net present value (NPV) of 0.588 M\$/ton biomass, an internal rate of return (IRR) of 19.12%, and a payback period (PBP) of 3.74 years. Sensitivity analysis showed that rising interest rates and steam costs erode profitability (e.g., PBP lengthening to 4.42 years as steam cost increases), whereas a longer plant lifetime substantially improves all financial indicators, with NPV rising from 0.382 to 0.588 M\$/ton biomass as the operating horizon extends from 15 to 20 years.

Effect of solar input and operating parameters

Increasing solar radiation from 0.4 to 1.2 kW/m² raised total generated power from 0.468 to 1.404 MW, improved Rankine cycle efficiency from 21.8% to 24.9%, cut the electricity cost from 0.1275 to 0.0485 \$/kWh, and reduced CO₂ emissions from 0.224 to 0.093 ton/MW, confirming the strong economic and environmental value of the solar contribution. Parametric studies further revealed clear optimum operating windows: an air/biomass ratio of 1.4–1.6 maximizes syngas quality and thermodynamic efficiency; a Fischer–Tropsch reactor length of about 7–8 m maximizes biodiesel yield with diminishing returns beyond that; biomass moisture should be kept below ~20% to avoid efficiency losses; and a gasification temperature near 1000 °C gives the best trade-off between syngas/biodiesel yield and CO₂ emissions.

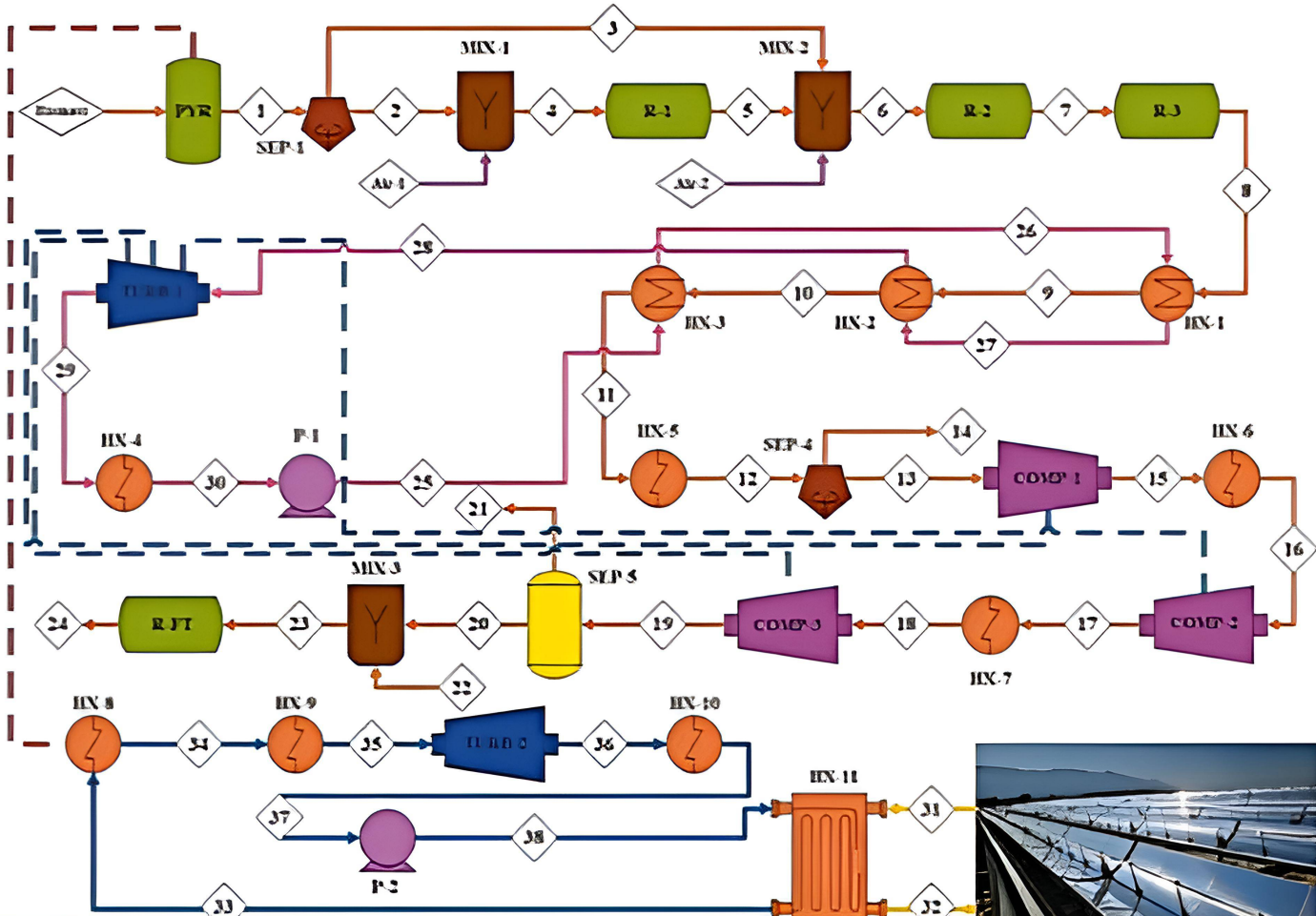


Fig. 1. Schematic of the proposed process: biodiesel production and power generation loop (gasification, Fischer–Tropsch synthesis, Rankine cycle, and solar collector field). Source: Amini et al., Energy Conversion and Management: X 28 (2025) 101408.



Life-cycle assessment

Compared with a conventional fossil-fuel power plant and a stand-alone solar parabolic-trough (PTC) system, the biodiesel-based cogeneration system showed clearly lower impacts on global warming, acidification, and fossil-resource depletion. Its main drawbacks were slightly higher water consumption and toxicity-related impacts, indicating that solvent and water management remain areas for future improvement.

NSGA-II multi-objective optimization

Applying NSGA-II (population of 100, 246 generations, crossover rate 0.92, mutation rate 0.05) with TOPSIS-based decision-making identified an optimal operating point that improved total energy efficiency from 55.91% to 57.08% and exergy efficiency from 51.77% to 53.21%, mainly through better heat integration and lower total exergy destruction (from 3484 to 3157 kW). The optimized design also reduced CO₂ emissions from 0.50 to 0.468 ton/MW, lowered the electricity cost from 0.0543 to 0.0526 \$/kWh, shortened the payback period from 3.74 to 3.49 years, and raised NPV from 0.5877 to 0.6078 M\$/ton biomass with only a modest rise in biodiesel unit cost (1350 to 1386.2 \$/ton) and a small increase in biodiesel output (43.84 to 44.68 kg/h). These results demonstrate that multi-objective optimization can reconcile thermodynamic, economic, and environmental objectives without sacrificing overall system performance.

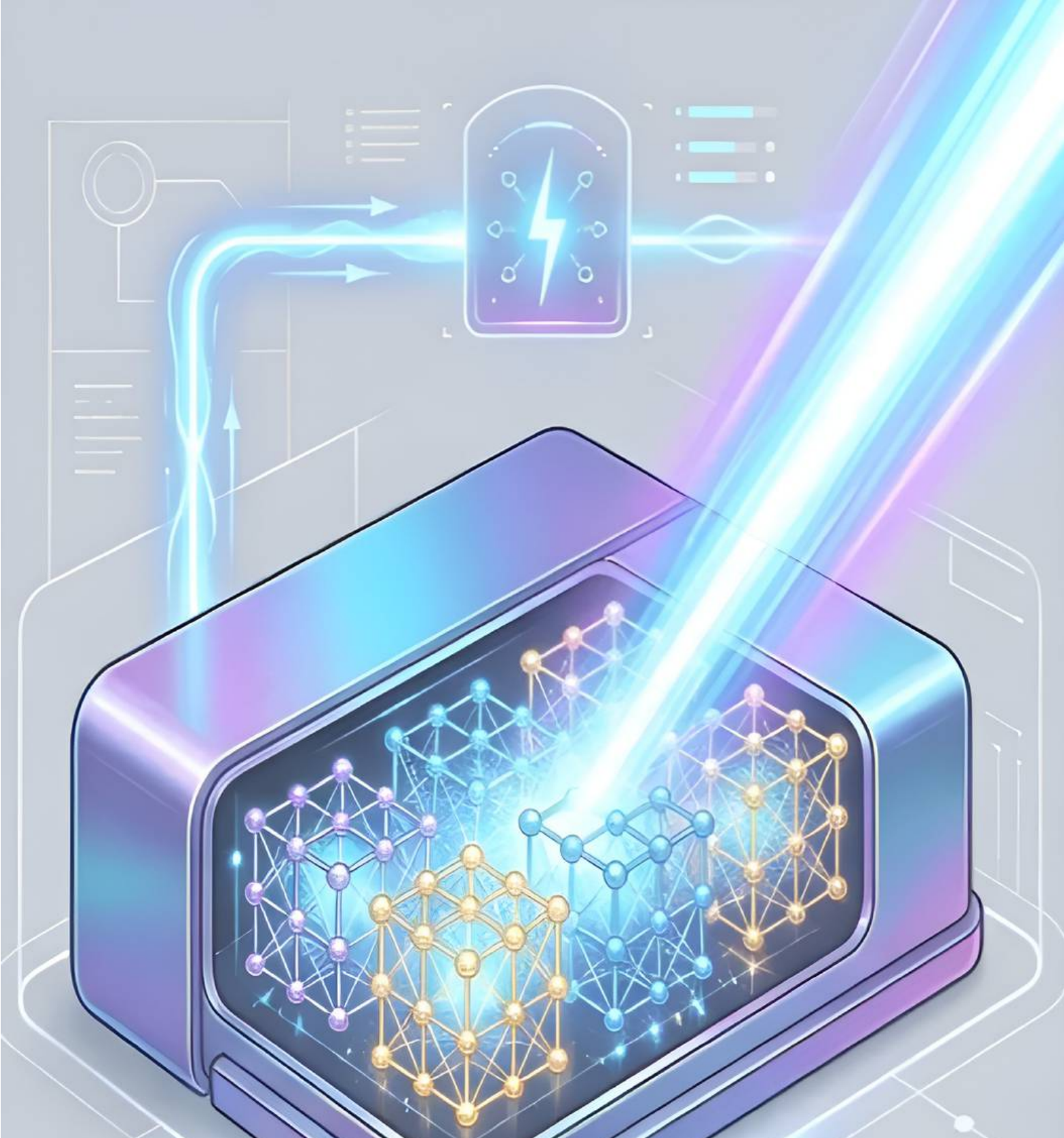
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