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Atomic Alchemy: Thorium–Sodium Alliance for India–EU Energy Security

Vinayaka Y J

Title

Atomic Alchemy: Thorium–Sodium Alliance for India–EU Energy Security

Contributor(s)

Vinayaka Y J, Department of Physics, Nitte Meenakshi Institute of Technology (NMIT)

Abstract

India wants to reach net-zero emissions by 2070. This is a difficult goal for a developing nation trying to lift millions out of poverty while moving towards renewable energy. These challenges require more than political will; it needs trusted partners who invest, invent, and implement together with India.The European Union brings strong technological capabilities and a clear commitment to climate action, making it a natural partner for India. By working together, India and the EU can develop affordable clean energy, produce next-generation technologies such as green hydrogen and thorium-based reactors, and strengthen climate-resilient infrastructure without undermining economic growth. This paper explores how their strategic partnership can turn India's net-zero dream into reality through joint policies, financing models, and knowledge-sharing. The road is tough, but with collaboration, a greener, impartial future is within reach.

1. Introduction

The first time energy security appeared as a policy issue was in the early 20th century when governments were concerned about securing oil for military operations (Yergin, 1991). The first scholarly discussions about energy security happened in the 1960s, and then expanded considerably after the oil shocks of the 1970s (Lubell, 1961). The term energy security has no standard definition. Different countries have different definitions based on the contextual issues they are dealing with (Cherp & Jewell, 2014). For example, in the case of India, energy security means having reliable and affordable access to sustainable energy, and ensuring the country's sovereignty.

There have been changes in the definitions of energy security during this century. It is not simply safe access to coal or oil. It is about growth, climate stability, and geopolitical stability. This is particularly the case for India. According to the International Energy Agency (2021), by 2030, India is predicted to be the third biggest energy consumer. This makes it a challenge to ensure the sustainment of affordable energy access while managing supply chain disruptions (Cherp & Jewell, 2014). This is why partnerships are so important. Policy changes will have to be made to meet India's 2070 net-zero commitments, but strong partnerships will be required as well. In terms of climate and renewables partnerships, the European Union (EU) is the most prominent, given its responsiveness to the climate and the record it carries. This will especially be the case for India and the EU in terms of climate partnerships in the years to come.

Cooperation can be described in simple terms. Who? The EU, as a representative of developed economies, and India, as a representative of the Global South. Where? From Europe's clean-technology hubs to India's expanding cities. When? With the 2030 targets of the Paris Agreement nearly upon us, the time is now. What? The conjunction of energy poverty, clean industrialization and the broader green transition. How? Developing a pilot project together in sodium-ion storage, green hydrogen, and thorium nuclear power, along with knowledge sharing, financing, and demand-side efficiency surrounding overconsumption (European Commission, 2021). This paper places Indo-European cooperation at the crossroads of geopolitics, technology, and the green transition and suggests mechanisms to avoid the repetition of past inequitable practices while securing energy for the future.

2. Current Challenges

India wrestles with a complex set of contradictions and difficulties, as it simultaneously seeks to uplift the millions of people still economically disenfranchised, expand its industrial base to support continued economic growth, and reduce greenhouse gas emissions to meet its climate goals. These competing pressures are now a defining feature of the country's growth prospects. India's population is growing, and with each additional person comes greater demand for energy, while all measures to ensure sustainable development require greater self-restraint and creativity, which are in short supply. To meet India's goals, the challenges of climate equity, the transition in the energy sector, critical minerals, and sustainable living will need to be addressed, as they will provide the greatest obstacles and tensions.

2.1 Balancing Net-zero Goals with Climate Fairness

India is facing extreme challenges finding a middle ground between reality and expectations. As of June 2025, the nation's power sector continues to be thermal. Coal alone contributes 219 GW, gas-based plants add 20 GW, and diesel provides another 589 MW, bringing the total to nearly 240 GW. Thermal energy therefore accounts for **over 50% of the nation's installed capacity**, with coal supplying more than 91% of that share (India's Energy Landscape, 2025). The amount of thermal power shows the amount of transitions that need to be made for the country to reach net-zero. India's net-zero goals are ambitious, but achievable with the right adjustments to the country's primary energy consumption. *Figure 1* shows that as of 2023–2024 the country's primary energy use consists of 60% coal, 29% crude oil, and very little gas, electricity or anything else (Energy Statistics, 2025). With this set up, the true challenges that need to be overcome to eliminate the use of fossil fuels with the replacing of renewables at a pace that the country has never seen before.

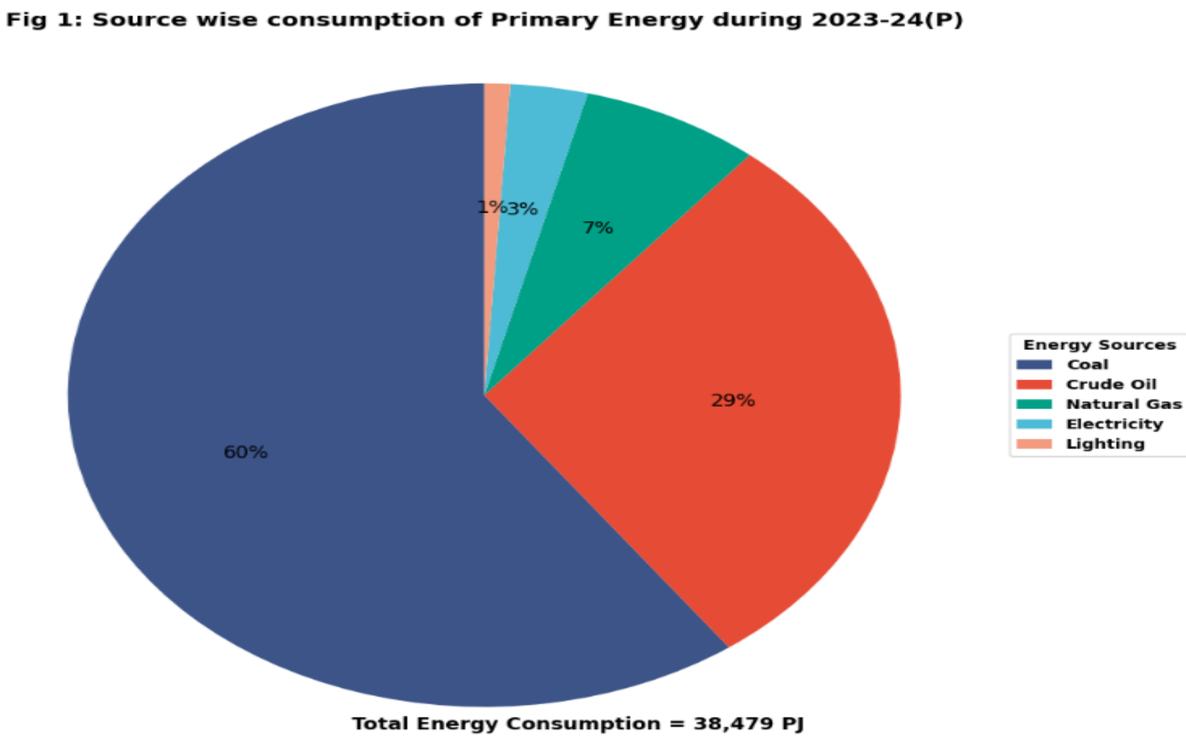


Fig. 1 *Source-wise consumption of primary energy in India during 2023–24 (P) (Data source: Ministry of Statistics and Programme Implementation, Energy Statistics India 2025) Data compiled and chart prepared by the author (2025).*

Various impediments to global climate equity persist. Among several studies, the United States, the European Union, and China are projected to collectively use nearly 45% of the carbon budget for a 1.5°C world by 2030 and close to 91% by 2050. In contrast, India's commitment to achieving net-zero by 2070 will still result in **India having 1850 to 2100 carbon emissions that are 59% less than China, 58% less than the United States, and 49% less than the European Union** (Malyan, A., & Chaturvedi, 2021). Yet, there are little to no global climate negotiations that have any accurate and concrete definitions of equity. These climate negotiations have been educated and researched, so that each state can have an equitable share of the carbon budget. UNFCCC results have yet to be developed so that the allocation of responsibilities are aligned to the various levels of development (Williges, K., Meyer).

2.2 Powering the Great Energy Shift

There are both demand and supply pressures that India must face when seeking a transition. As for demand, most reports project electricity demand will rise significantly, so much so that estimates have it reaching 5,500 - 6,000 TWh by 2050 (Wartsila, 2021). To meet this demand, investments will have to be made and will be unprecedented.

To achieve these goals so as to meet the demands of the solar and wind developments, **$223 billion will be needed just within the 2022 - 2029 time span** (S. Jaiswal, 2022). Additionally, the **National Green Hydrogen Mission** states that there must be 125 GW of renewable energy by 2030, with 60 – 100 GW of those being in electrolyzer capacity, in order to be able to obtain the 5 megaton (MT) goal for hydrogen production annually (National Green Hydrogen, 2023).

Financing large investments of this size will remain a goal of the company. Financial stress remains on the distribution companies (DISCOMs), and that is attributed to inflexible subsidies, poor infrastructure, and cross-subsidization. All of these issues make it more difficult to incorporate intermittent renewables into the grid. Additionally, energy storage is a problem, and so is the scaling of bioenergy because of costs and food security. The demand for cooling is also growing quickly. **By 2037 - 38, air conditioners are expected to be responsible for 50% of total cooling demands, while in 2021 they accounted for just 7 – 9%**. India's unique position of being the only nation currently dealing with a combination of high demand growth and renewable integration will make it particularly difficult to overcome the rapid changes in load curves that it currently faces.

2.3 The Critical Mineral Conundrum

The wide range of technologies that include renewables, electric vehicles, hydrogen systems, and digitalization all depend on critical minerals (CMs). However, India continues to have an underdeveloped domestic supply chain to support this. The Ministry of Mines has classified 30 minerals as critical, and as of now, the country has zero domestic production of lithium, cobalt, nickel, vanadium, niobium, germanium, or tantalum, and **depends 100% on imports for these** (Ministry of Mines, 2023). They also fully import rare earth elements necessary for the permanent magnets found in EVs, while China dominates the global supply of heavy rare earths, controlling 94% of it. India also does not have domestic production of the several PV manufacturing materials such as silicon, silver, indium, gallium or tellurium. The domestic manufacturing capacity is low and is also subject to underdeveloped policy support, high costs, and competitive imports.

India's reliance on critical minerals brings multiple risks. More imports from South Africa, the Congo, and especially China, heighten supply-chain vulnerabilities. India's costs and risks also increase due to global price rises and dollar-denominated trade. Moreover, pollution from e-waste is compounded by a lack of formal recycling. Other than copper, iron, and aluminium, India's critical mineral recycling capabilities are nonexistent, and recycling, especially from e-waste, is done in an informal and energy-wasteful manner (R. Chadha, 2021).

2.4 LiFE: Rethinking Lifestyles for a Sustainable Future

A global initiative that promotes responsible consumption and sustainable way of living **Lifestyles for Environment (LiFE)** has been championed by India (PIB, 2021). LiFE was introduced at the COP26 conference in 2021 and promotes the mindful use of resources through the integration of new and old traditional practices (NITI Aayog, 2022). LiFE at COP26 focused on sustainable practices in the consumption of resources and sustainable production in the market along with supportive policies.

The initiative has several challenges. The concepts of sustainable consumption and sustainable production have no universally accepted common metrics or definitions. The lack of consensus has fragmentation of the world into two opposing viewpoints that has lost contemporary relevance. These metrics also explain the lack sufficient integration into the mainstream global development goals. There are no measures of economic activity that describe sustainable oriented activities, and we will continue to promote an output centric approach to measuring activity and focus on stagnation and waste. In the absence of frameworks of integration to the various levels of society, the political will, and ultimately the energy needed to promote sustainable lifestyles becomes fragmented toward a motion with little or no throughput. Lastly, India requires more scientific and technological inputs that simplify the integration of sustainability into everyday activities, the desire for greener consumption.

3. Innovative Energy Solutions and Sustainable Lifestyles

3.1 Turning Abundance into Advantage: India–EU Sodium-Ion Initiatives

There is great potential for renewable energy in India. It is estimated that solar energy is able to produce 748,990 MW, which is 36% of India's renewable energy capacity. On top of that, wind energy can contribute another 1,163,856 MW, or 55% (Energy Statistics, 2025). However, this will need to be integrated into a strong energy storage system to ensure a reliable energy supply. As it stands, solar energy is only usable when the sun is shining, and wind energy can only be produced when the wind is blowing. Currently, energy storage in India relies heavily on lithium-ion (Li-ion) batteries, and the country must import nearly all of the lithium and other essential battery materials (Ministry of Mines, 2023). This dependence creates economic and strategic threats to the country. On the other hand, **sodium-ion (Na-ion) batteries** can provide an alternative. They require materials that India has in abundance, are able to lessen import dependency, and can be manufactured in current Li-ion factories.

3.1.1 Scaling Sodium-Ion Storage Systems.

a) **Plenty of Available and Nearby Materials:** Sodium can be sourced from seawater and salt deposits. This would help India avoid importing lithium, cobalt, and nickel.

b) **Preparedness:** Na-ion tech can utilize the Li-ion manufacturing lines that already exist, helping to reduce investments and deploy faster.

c) **Suitability of Performance**: The Sodium-ion batteries can store energy at **160-190 Wh/kg** (Bača, 2025). This, combined with Na-ion batteries safety, makes them a good candidate for **stationary energy storage systems (ESS)** (ex. Solar, Wind and EV Charging Stations) and **light electric mobility** where costs are more significant than a high energy density.

d) **Expected Cost Parity:** Na-ion batteries are projected to achieve price-parity with Li-ion batteries within a 40% range of plausible future scenarios by 2030 (Fig. 2). This hedges the market from possible spikes in the price of Li-ion batteries.

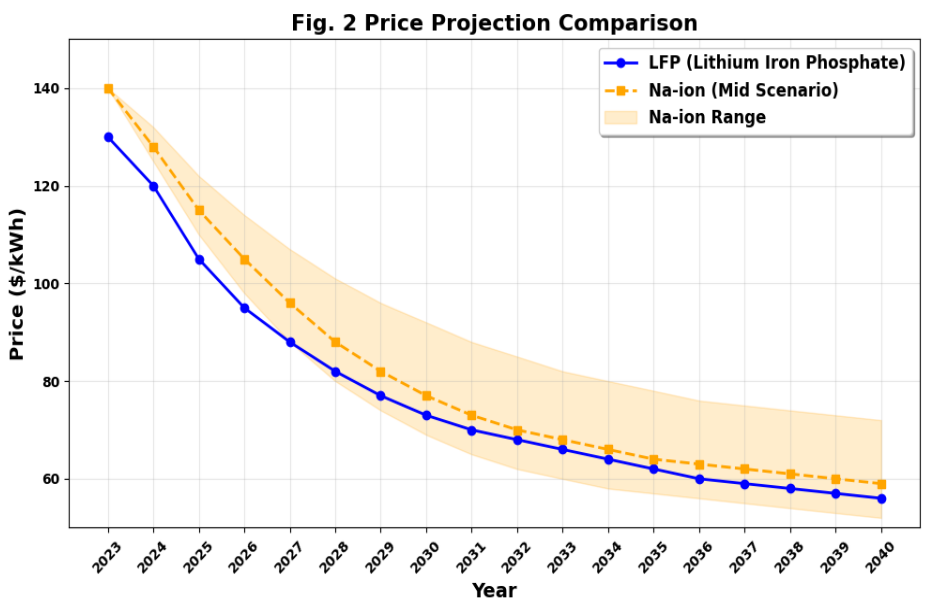


*Fig. 2 Price Projection Comparison: The graph shows how sodium-ion and **Lithium Iron Phosphate batteries** (LFP) battery prices may change over time. Na-ion could reach cost parity with LFP in the early 2030s. The shaded area shows possible variations. It makes clear that R&D can make Na-ion competitive (Data source: Yao et al., 2025)*

3.1.2 Strategic Actions for India and Europe

a) **Reduce Import Dependence by Diversifying Supply Chains:** Na-ion may build reliance barriers and protect India's energy system from external shocks.

b) **Expand R&D:** Partnership of India and the EU may suit this need. While Europe has more advanced technology and machinery, India has skilled and cheaper operational labor.

c) **Establish Early Demand:** Government procurement of Na-ion batteries for renewable energy parks or light vehicles, accompanied by early adoption subsidies and tax breaks, may facilitate early demand.

d) **Local Supply and Standard Setting:** Local production of strategic materials such as hard carbon. Stated safety regulations should be in place to ensure production scale up.

e) **Smart Technology Mixing:** Na-ion and Li-ion can be used together, each serving its purpose.

f) **Develop India-EU Relations:** Establish innovation centers, subsidize pilot production, and implement cross-training and knowledge/standards sharing. With projects such as SIMBA, NAIMA, ENTISE, and ALTRIS the EU has been the main driver of sodium-ion R&D and will continue to be so for solid-state sodium-ion devices. Given this context, India should engage with these initiatives to combine Europe's technology leadership with India's affordable and skilled workforce in order to bolster the development of sodium-ion technology.

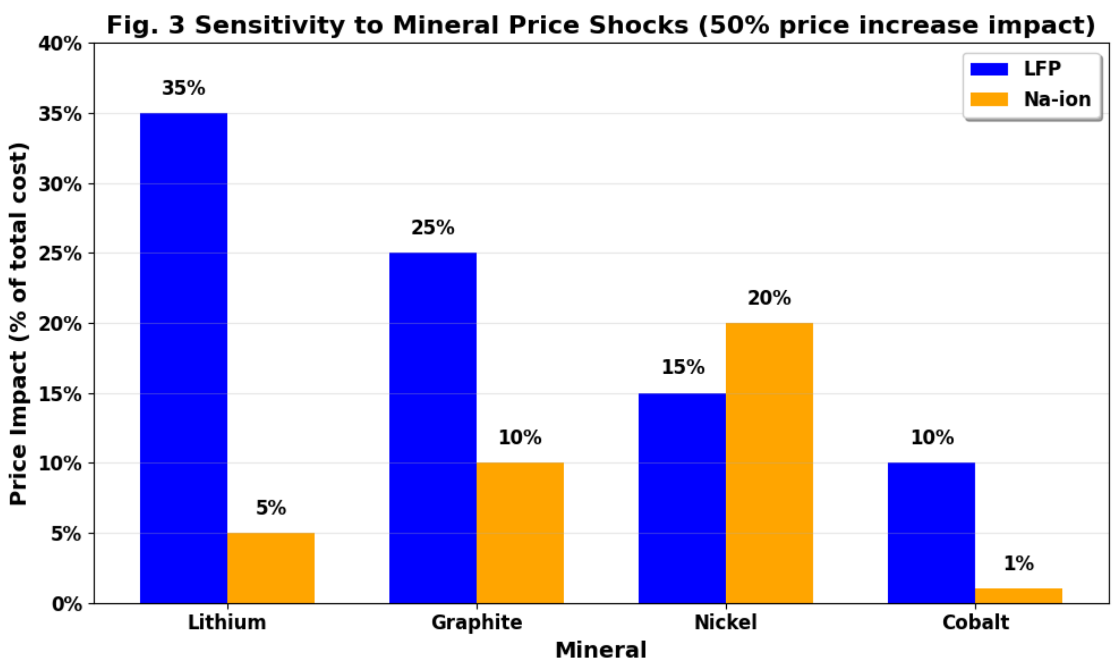


Fig.3 *Sensitivity to Mineral Price Shocks: The graph shows how Li-ion and Na-ion respond to supply chain changes. LFP batteries react strongly to lithium price jumps (35% impact from a 50% rise). Na-ion stays mostly stable. Both types are slightly affected by graphite. Na-ion with nickel cathodes is somewhat sensitive to nickel prices. This highlights why Na-ion helps diversify supply chains and reduce risk (Data source: Yao et al., 2025)*

3.1.3 Expected Benefits

Sodium-ion batteries (NIBs) rely on commonplace sodium found in 2.8% of the Earth's crust. This allows India and Europe (Imports 100% of its CRMs) to lessen reliance on scarce, geopolitically sensitive materials like cobalt, graphite, and nickel, which are dominantly controlled by China. NIBs also help contain costs for Li-ion batteries, improve safety, and reduce costs for thermal management, insurance, and transport. Also, NIB Tech can drive domestic production, increase employment, and enhance partnerships. NIBs coupled with solar and wind make the firming of renewables more reliable and promote the industrialing of resilient, low-carbon energy systems.

3.2 From Sand to Power: Unlocking India's Thorium Advantage

While solar panels and wind turbines are vital for a clean energy future, they cannot alone guarantee reliable supply. Their output is tied to the weather, and even at massive scale they fall short during peak hours unless backed by huge storage systems. To put this in perspective, replacing the steady output of a **900 megawatt nuclear reactor** would require nearly **800 average wind turbines** or around **8.5 million solar panels** (MIT Climate Portal) and still, reliability would be an issue. Add to this the environmental cost of manufacturing solar panels, and the case becomes clear: nuclear energy, particularly thorium-based reactors, is not just an option, but a necessity for uninterrupted, zero-carbon power.

3.2.1 Thorium as a Strategic Asset for Energy Independence

India sits on nearly **1.07 million tonnes of thorium** (pib.gov.in), about **25% of the world's total reserves**. This resource provides a unique opportunity to achieve energy independence, unlike uranium which India must largely import. The three-stage nuclear program was designed precisely to unlock this potential (barc.gov.in):

- **Stage 1:** Pressurized Heavy Water Reactors (PHWRs) use natural uranium and generate plutonium.
- **Stage 2:** Fast Breeder Reactors (FBRs) use plutonium to breed uranium-233 from thorium.
- **Stage 3:** Advanced Heavy Water Reactors (AHWRs) close the cycle by running on a self-sustaining thorium–U-233 fuel.

The **500 MW Prototype Fast Breeder Reactor (PFBR)** at Kalpakkam, now in the commissioning phase, represents the gateway to India's thorium era. Meanwhile, KAMINI, the only operating reactor in the world fuelled by U-233 bred from thorium, already proves the cycle's viability.

3.2.2 Thorium: Why It Matters Now

- **Energy sovereignty:** With some of the world's largest reserves (pib.gov.in), thorium allows India to reduce dependence on imported uranium and shield itself from volatile global fuel markets.

- **Safer and cleaner cycles:** The Th–U-233 fuel cycle produces fewer long-lived actinides. Combined with molten salt reactor (MSR) designs, this adds inherent safety, lowers accident risks, and cuts long-term waste (Kannan, U. 2014).
- **Fuel efficiency:** A uranium-based Light Water Reactor generates ~35 GW-hr per MT of natural uranium, while thorium can deliver up to 11,000 GW-hr per MT (Fig. 4) an enormous leap in resource utilization (Selvan, 2025).
- **Reduced waste:** With burn-up rates as high as 20,000 MWd/tonne, thorium produces much less spent fuel (*MOX Fuel)*. The waste that remains decays faster and is less toxic over the long term.

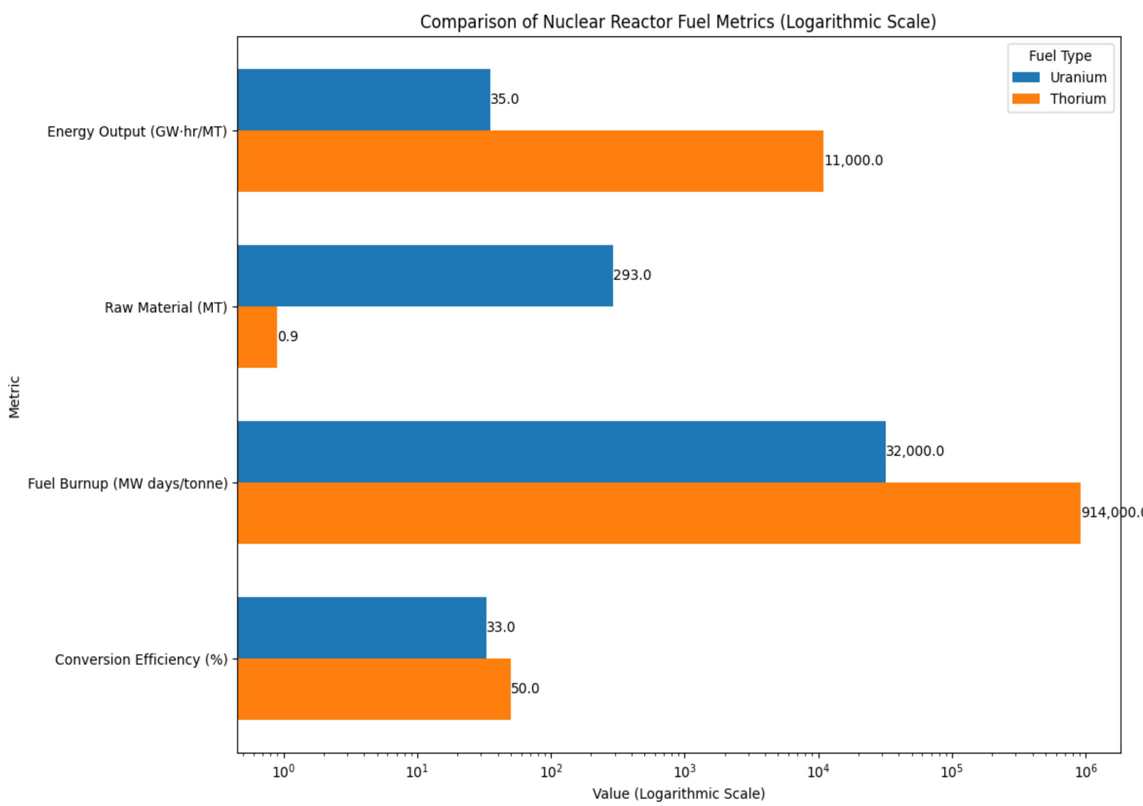


***Fig. 4** presents a comparative analysis of uranium-fueled light-water reactors and thorium-fueled reactors, highlighting thorium's advantages in terms of higher energy output, enhanced resource utilization, and reduced radioactive waste generation. (Data source: Selvan, 2025)*

- **Passive safety:** Advanced designs like the AHWR use gravity-driven cooling and natural convection, allowing safe shutdowns even without external power (Thangamani, 2019).
- **Support for renewables:** Thorium reactors provide reliable, carbon-free baseload, balancing solar and wind variability.

3.2.3 Strategic Actions for India and Europe

- **Launch joint pilot projects:** Europe launched the *Industrial Alliance on SMRs (Small modular reactors)* in February 2024 to speed up research, development, and deployment of the first SMR projects by the early 2030s. India, in turn, allocated **USD 2.4 billion** in its Union Budget 2025–26 to design and commission at least five indigenous SMRs by 2033 (PIB, 2025). With both programs already moving forward, this is the right moment to join forces and co-develop **thorium-based SMRs** (Gonçalves, 2025).
- **Drive fuel-cycle innovation:** India and Europe can jointly advance Thorium to U-233 fuel fabrication, molten-salt reprocessing, and safeguard systems under IAEA and Euratom supervision **(**Belles, 2020**)** .
- **Mobilize finance and share risk:** Both sides can draw on EU climate funds, blended finance tools, and the *SMR Industrial Alliance* to spread investment risk and support the first thorium projects.
- **Coordinate regulatory standards:** Regulators can establish shared India–EU frameworks on safety, emergency response, and waste management, making licensing smoother and building mutual confidence.
- **Build public confidence:** Governments and industry should open transparency portals with real-time safety data and lead local engagement campaigns to counter misinformation and strengthen social acceptance.
- **India-Specific Policy Recommendations**
  India's nuclear growth has been slowed by long approvals - Kudankulam, for instance, faced years of delay. One way to fix this is a single-window system where safety, environmental, and regulatory checks happen at the same time, not one after the other. If we back it with digital records, virtual consultations, and AI monitoring, it could cut delays by up to 40% (Thoom, S. R. 2025). Right now, India spends less than 1% of GDP on research way below countries like the US or South Korea. Boosting this to around 2% would really speed up thorium reactors and SMRs, making the 2030 pilot goal more doable. NPCIL and BARC would still lead, but private firms could help in non-sensitive areas like fuel handling , maintenance and decrease costs by approximately 15–20 %, and improve operational efficiency by 25-30% (Marwah, P. 2022). With smart incentives and partnerships, India could save costs, build reactors faster, and strengthen its energy security.

3.2.4 Key Benefits of Thorium Collaboration

Cooperation on thorium is mutually beneficial for India and Europe. For India, it reduces the need for imported uranium. For Europe, it broadens their fuel diversification. European and Indian thorium reactors provide steady, carbon-free power, and help stabilize solar-wind grids. They also produce less long-lived waste, and their passive, low-pressure designs lower accident risks. Europe provides advanced designs for small modular reactors (SMRs), regulatory experience, and climate financing. India provides thorium, its own SMR designs, and a plentiful supply of trained engineers. They also strengthen their bilateral partnership, and resilient supply chains and collaboration on fuels, molten salts, components, and workforce training, building a comprehensive India-EU nuclear ecosystem.

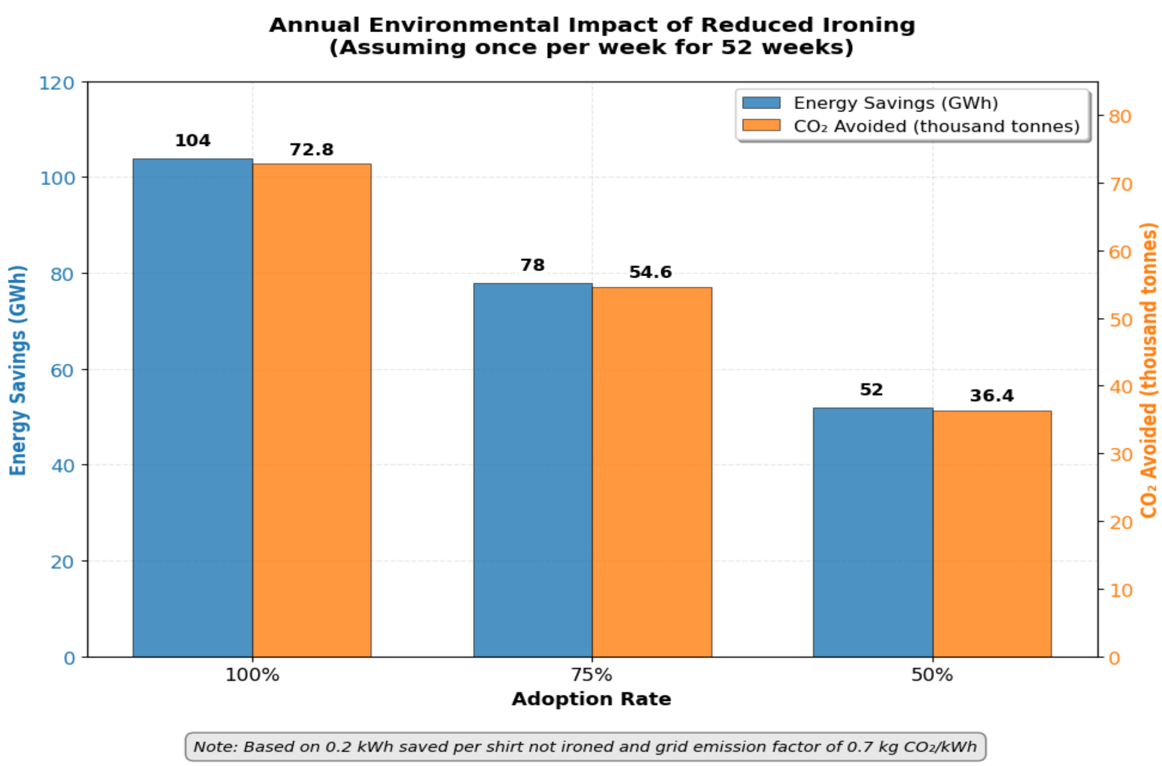
3.3 Feasibility, Global Adoption, and Financing of Sodium-Ion and Thorium Technologies

The more restricted deployment of sodium-ion batteries and thorium-based reactors in China and the United States is more a function of differing system priorities, legacy infrastructure, and resource endowments than techno-immaturity. In fact, sodium-ion batteries are not designed to supplant lithium-ion systems in high-energy electric vehicles (EVs). Rather, they are more cost effective and safer alternatives to be deployed in stationary (as opposed to mobile) systems. In stationary systems, other than the sodium-ion batteries' lower energy density, material availability and supply security will outweigh the energy density of lithium-ion systems (IRENA, 2023; Peters et al., 2022). China's consistent reliance on Lithium-ion battery technology, despite the increasing popularity of sodium-ion battery technology, is primarily due to the significant sunk investments it DC made in the technology, the established supply chain for it, and the reliance on sodium-ion systems as a complementary hedge against lithium trade prices.

Just as with China and the US, the absence of commercial thorium reactors is a result of institutional lock-in relating to uranium-based fuel cycles and a set of regulations geared towards light-water reactors in the US. On the other hand, India's domestic nuclear fuel cycle options were fully mapped to the use of thorium because of the country's uranium scarcity and considerable thorium stocks, which made thorium a strategic necessity rather than an experimental option. Financing these pathways can be based on approaches other than new fiscal outlays. Research from the World Bank and NIPFP illustrates how politically motivated "freebies" and subsidy controls tend to create a large fiscally unproductive investment gap, and the focus on spending can also alleviate some of the fiscal constraints on strategic investments. Even with such spending focus, **India would also benefit from an increase in R&D expenditure from <1% of GDP towards 1.5–2%** in order to create a more sustained funding orbit for sodium-ion manufacturing, pilot deployments, and thorium-based reactors via blended model PPPs (OECD-NEA, 2022).

3.4 Rethinking Consumption for Sustainable Futures

Technological advancement alone cannot help us as a nation solve our energy crisis if our consumption continues to grow. Our way of life shows that we live as if there are no limits to the resources we have. All the hidden energy that was used to create and transport every vehicle we drive, every phone we upgrade, and every shirt we buy. If we do not slow down our rate of overconsumption, sustainability is just a good concept that we are not using. India's growth is phenomenal. Millions of people are living better lives than they have in the past. But this growth comes with lots of malls, gadgets, AC units, and cars on our roads. Europe is at a standstill in terms of consumption, but India is developing rapidly. The critical issue at hand is whether we can evolve using a model that does not emphasize consumption. Perhaps we can if we change our concept of what being successful really means. Simple everyday activities. Is it really necessary to iron every shirt? Enough people skipping ironing shirts one time keeps more than 100 GWh of energy and avoids 73,000 tons of CO_2 from being made (Fig. 5). That's like taking 15,000 petrol cars off the road. School, college, and office rules like that would have big impacts for small choices. Consider emails. How often do we just delete the junk? Data centers use power to do their work, while we do this small act of power saving. Same with repairing shoes instead of buying new, cycling short distances, or planting. This is the spirit of India's LiFE (Lifestyle for Environment) mission thoughtful living, not thoughtless consuming. It is not about sacrifice; it is about smart use of what is available. Redefining growth like this, India can do all the things people want to do and more - all while cutting back on mistakes of the past.



4. Future Pathways

To realize this alliance, both India and the EU must immediately follow a clear, action-oriented roadmap.

Phase 1: Foundational Pilots (2024-2026)

In the next twelve months, establish a joint India-EU Task Force to initiate two flagship projects: a 100 MWh sodium-ion battery storage pilot at a Indian renewable park, and a thorium fuel fabrication research program with BARC and Euratom. At the same time, finalize a Critical Minerals Partnership to ensure lithium and nickel supply chain availability.

Phase 2: Scaling and Integration (2027-2033)

Scale successful pilots into commercial ventures. This entails constructing giga-scale Na-ion battery factories through joint ventures and launching the first collaborative thorium SMR project. For this, an Indo-EU Green Transition Fund will be created to provide blended finance and to mitigate the risk for private investors the funding will finance these technologies.

Phase 3: System-Wide Transformation (Post-2033)

Focus on integration and global leadership. Create "Green Hydrogen Corridors" using nuclear and renewable energy for electrolysis. Export the integrated "SMR-Storage-Hydrogen" model globally. Incorporate the principles of LiFE into national education curricula and corporate ESG standards to fundamentally lower energy demand.

5. Conclusion

As India's energy needs grow and its climate commitments solidify, nuclear energy and sodium-ion batteries will be critical in ensuring secure low-carbon pathways for the country. This paper highlighted numerous avenues for India and Europe to collaborate on thorium reactors, SMRs, and pilot projects, among other sustainable initiatives. However, while the opportunities are plenty, trust remains a critical issue. India must be seen by Europe as a responsible partner who is willing to collaborate, and not compromise, its sovereignty. India, however, possesses the means to take unilateral actions. While such actions will likely be in India’s best interests, collaborative initiatives will be even more beneficial, especially considering the costly and time-sensitive nature of the initiatives. To turn plans into reality, more relaxed timeframes on compliance and approval, as well as limited but well established partnerships, are essential. India and Europe’s collaboration, in whatever form it takes, will contribute to all stakeholders, and most importantly, to the planet, by striving for progress in sustainable energy, protecting the environment, and working under the principle that cooperation is not an option, but rather, a responsibility to the future.

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