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Beyond the Barrel and the Battery: India-EU Pathways to Alternative Green Solutions

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Title

Beyond the Barrel and the Battery: India-EU Pathways to Alternative Green Solutions

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The world is in the midst of an energy transition from reliance on fossil fuels to newer, cleaner energy sources. As India and the European Union (EU) traverse the unending complexities of global energy transitions, a notable irony emerges. As we transition to renewable energy sources, this change could offer freedom from carbon-intensive dependencies. Still, it inadvertently creates new dependencies on critical elements and rare-earth metals whose supply chains are predominantly controlled by China.[1] The emerging situation may lead to renewed dependence and, consequently, new opportunities for geopolitical tensions. Situated within the current geopolitical landscape, the paper argues for a significant shift towards a strengthened partnership between India and the European Union. It emphasises the critical role of nuclear and hydrogen energy as essential 'alternative green solutions' that could enhance renewable energy efforts and also ensure energy security for both partners. By building on existing bilateral mechanisms such as the India-EU Trade and Technology Council (TTC) and the Clean Energy and Climate Partnership (CECP), the paper outlines a comprehensive strategy and a suggestive framework for change across interstate, national, and civil society domains. A proposed phased roadmap calls for reducing mineral dependencies, expanding clean energy capacity, enhancing research and development partnerships, and achieving emissions reductions by 2035. The recommendations put forth in this paper arise from the understanding that renewable energy sources alone may not be sufficient to comprehensively address issues related to intermittency, baseload requirements, or the geopolitical risks associated with clean-energy supply chains. Nuclear and hydrogen offer complementary approaches to facilitate the decarbonization of sectors beyond electricity generation. The combination of India's substantial thorium reserves and its advanced digital capabilities, in congruence with the European Union's rich nuclear heritage and robust R&D infrastructure, has the potential to drive this transformative shift. The paper offers a condensed overview of the current energy landscape, an in-depth rationale for prioritising nuclear and hydrogen, layered policy prescriptions, including suggestions such as energy citizenship, projected outcomes, technical insights, a timeline for the changes, and leverage points. In conclusion, the paper reimagines energy sovereignty transcending the barrel (fossil fuels) and the battery (critical minerals) towards alternative green solutions for a resilient, equitable future.

1. Current energy landscape and policy frameworks

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[1] Sophia Kalantzakos, "The Race for Critical Minerals in an Era of Geopolitical Realignments," The International Spectator 55, no. 3 (2020): 1–16, https://doi.org/10.1080/03932729.2020.1786926

India's current energy basket reflects a dynamic transition while simultaneously grappling with persistent limitations. As of June 2025, the nation had achieved a renewable energy capacity of 226.79 GW[2] which is largely buttressed by advancements in solar and wind energy. However, it is noteworthy that fossil fuels still account for approximately 50 per cent of the electricity supply.[3] Nuclear power currently contributes to an installed capacity of 8.78 GW.[4] which represents approximately 2% of the overall electricity mix. While the figure is relatively modest, the long-term aspirations are significant. India has articulated a vision to increase its nuclear capacity to 100 GW by the year 2047[5] with a focus on the development of small modular reactors and thorium-based systems.[6] Hydrogen is increasingly recognised as a fundamental component of similar strategic initiatives. The National Green Hydrogen Mission (NGHM), initiated in 2023, aims to achieve an annual production of 5 million tonnes by 2030.[7] The recent allocations project a substantial annual output of 8,62,000 tonnes, supported by an impressive electrolyser capacity of 3,000 MW.[8] The scope of this policy support encompasses various initiatives, including the incentive structures established by the NGHM and possibly the implementation of the Sovereign Green Bond framework. India possesses notable comparative advantages in the nuclear sector, particularly in its thorium reserves and the extensive expertise developed at BARC over several decades. However, significant challenges remain, including the high costs of electrolysers and a substantial dependence on mineral imports, the majority of which are sourced from China.

On the other hand, Europe's trajectory presents a distinctly different landscape. In 2025, renewable energy sources accounted for 42.5 per cent of electricity generated in the European Union, with a target set for 2030 to achieve 45 per cent of generation capacity as part of its REPowerEU initiative. [9] Nuclear energy plays a significantly more pivotal role in the energy landscape of individual EU countries, such as France, where 70%

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[2] Government of India, Press Information Bureau, “India’s Energy Landscape,” June 2025, https://static.pib.gov.in/WriteReadData/specificdocs/documents/2025/jun/doc2025622575501.pdf

[3] NITI Aayog, “Electricity Generation,” India Climate & Energy Dashboard (ICED), https://iced.niti.gov.in/energy/electricity/generation

[4] NITI Aayog, “Electricity Generation,” India Climate & Energy Dashboard (ICED), https://iced.niti.gov.in/energy/electricity/generation

[5] Press Information Bureau, Government of India, “Nuclear Power in Union Budget 2025–26,” February 3, 2025, https://www.pib.gov.in/PressReleasePage.aspx?PRID=2099244

[6] P.K. Vijayan, V. Shivakumar, S. Basu, and R.K. Sinha, “Role of Thorium in the Indian Nuclear Power Programme,” Progress in Nuclear Energy 101, pt. A (2017): 43–52, https://doi.org/10.1016/j.pnucene.2017.02.005

[7] Ministry of New and Renewable Energy (MNRE), Government of India, “National Green Hydrogen Mission,” http://mnre.gov.in/en/national-green-hydrogen-mission

[8] Press Information Bureau, Government of India, “Unlocking India’s Green Hydrogen Production Potential,” 2025, https://www.pib.gov.in/PressReleasePage.aspx?PRID=2129952

[9] European Commission, “REPowerEU,” May 18, 2022, https://commission.europa.eu/topics/energy/repowereu_en

of electricity is generated by nuclear power.[10] In a similar vein, the aspirations surrounding hydrogen are notably ambitious, with the EU aiming for a target of 20 million tonnes of capacity by 2030.[11] This goal is designed to be evenly divided between domestic production and imports, supported by initiatives such as the EU hydrogen bank. The key policy drivers include the European Green Deal, the Critical Raw Materials Act (2023), and specific funding mechanisms from the European Investment Bank and Horizon Europe. In addition, Europe grappled with significant dependencies, particularly its reliance on rare-earth element imports, which currently stand at 95 per cent.[12] alongside persistent political scepticism regarding the expansion of nuclear energy.[13]

In light of these circumstances, China's dominance becomes increasingly significant. China accounts for 70 per cent of the global wind components market and 80 per cent of solar module production, thereby establishing itself as a critical intermediary within the clean energy supply chain. India has been affected by Beijing's restrictions on graphite exports, while Europe has faced significant price volatility. These vulnerabilities have reinforced the logic of bilateral cooperation and furthered a partnership between India and the EU on energy matters. Frameworks such as the TTC, with its focus on green technologies for 2025, the CECP’s 82 projects and the 2021 connectivity partnership, and the Mineral Security partnership have become critical anchors for diversification.

2. . Nuclear and Hydrogen as ‘Alternative Green Solutions’

The exploration of alternatives that complement and extend beyond the fossil-to-renewables frameworks transcends a purely technical discussion, as it embodies a fundamental existential enquiry. Renewable energy sources have demonstrated significant advancements in both scale and cost efficiency. An example of this is the 90 per cent decline in solar photovoltaic prices since 2010.[14] However, these technologies continue to face challenges related to variability and the need for substantial energy storage solutions reliant on mineral-intensive battery systems. Despite their ability to be dispatched as needed, fossil fuels reintroduce historical

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[10] World Nuclear Association, “Nuclear Power in France”, https://world-nuclear.org/information-library/country-profiles/countries-a-f/france

[11] European Commission, “Hydrogen,” https://energy.ec.europa.eu/topics/eus-energy-system/hydrogen_en

[12] European Commission (Eurostat), “International Trade in Critical Raw Materials,” 2023, https://ec.europa.eu/eurostat/statistics-explained/index.php?title=International_trade_in_critical_raw_materials

[13] Gaston Meskens, “The Trouble with Justification – Getting Straight on the Science and Politics of Nuclear Energy,” Energy Strategy Reviews 1, no. 4 (2013): 233–242, https://doi.org/10.1016/j.esr.2013.01.004

[14] Hannah Ritchie, “Solar Panel Prices Have Fallen by Around 20% Every Time Global Capacity Doubled,” Our World in Data, June 13, 2024, https://ourworldindata.org/data-insights/solar-panel-prices-have-fallen-by-around-20-every-time-global-capacity-doubled

vulnerabilities, ranging from OPEC+'s manipulation of fuel supplies to the escalating challenges posed by the climate crisis. In this context, the paper suggests that combining nuclear and hydrogen energy offers a viable solution to this predicament. Nuclear energy provides a reliable baseload power source with zero carbon emissions. At the same time, hydrogen offers flexibility and plays a crucial role in decarbonising challenging sectors such as steel production, transportation, and chemical manufacturing. But most importantly, both sources reduce mineral needs and exposure: the nuclear method uses uranium cycles that circumvent the need for critical minerals like lithium, while the hydrogen approach employs electrolysis, thus eliminating the need for rare-earth-intensive battery storage. The export restriction imposed by China in 2023 highlights the pressing need for diversification in this context. [15]

The Conference of the Parties 28 (COP 28) recognises that achieving a limit of 1.5 °C in global warming necessitates a threefold increase in nuclear capacity worldwide by the middle of this century.[16] Hydrogen could account for as much as 20 per cent of total final energy demand.[17] The geopolitical and environmental stakes are high for both India and the European Union. Net-zero pledges--2070 for India and 2050 for the EU--cannot be met without these two pillars. Neither region can insulate itself from mineral leverage that China could potentially use, as Russia did with gas as a weapon before 2022.

The example of hydrogen clearly demonstrated its significant potential. The production of hydrogen in its grey, blue and green variants highlights the latter as a crucial element in facilitating low-carbon transitions. India has already begun piloting projects such as GAIL's 4.3-tonne-per-day facility (Madhya Pradesh)[18]. The NGHM is experimenting with hydrogen derived from biomass, including agricultural residues.[19] Costs remain steep, at $4.1-5.0 per kilogram. However, India's manufacturing capacity, coupled with the Production-Linked Incentive schemes for electrolysers, offers a promising impetus for growth. The contribution of Europe is characterised by the development of advanced Proton Exchange Membrane (PEM) and high-temperature

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[15] Gracelin Baskaran and Meredith Schwartz, "The Consequences of China's New Rare Earths Export Restrictions," Center for Strategic and International Studies (CSIS), April 14, 2025, https://www.csis.org/analysis/consequences-chinas-new-rare-earths-export-restrictions

[16] U.S. Department of Energy, "At COP28, Countries Launch Declaration to Triple Nuclear Energy Capacity by 2050, Recognizing the Key Role of Nuclear Energy in Reaching Net Zero," December 1, 2023, https://www.energy.gov/articles/cop28-countries-launch-declaration-triple-nuclear-energy-capacity-2050-recognizing-key

[17] Hydrogen Council and McKinsey & Company, Hydrogen for Net Zero, November 2021, https://hydrogencouncil.com/wp-content/uploads/2021/11/Hydrogen-for-Net-Zero.pdf

[18] Press Trust of India, "GAIL's 10 MW Green Hydrogen Plant in Madhya Pradesh Inaugurated," The Economic Times, May 26, 2024, https://economictimes.indiatimes.com/industry/renewables/gails-10-mw-green-hydrogen-plant-in-madhya-pradesh-inaugurated/articleshow/110436499.cms

[19] Press Information Bureau, EY, "India's Green Hydrogen Revolution: An ambitious Approach", PIB Compilation May 2024, https://static.pib.gov.in/WriteReadData/specificdocs/documents/2024/may/doc2024510336301.pdf

electrolysis technologies, in conjunction with innovative underground storage solutions.[20] The potential for synergy is evident: EU certification standards, such as CertifHy, can facilitate access of Indian green hydrogen to the European market, thereby supporting the EU's import objective of 10 million tonnes.[21]

The argument regarding nuclear issues is similarly compelling. Nuclear energy effectively addresses the intermittency challenges associated with renewable sources, such as capacity factors exceeding 90 per cent and lifecycle emissions comparable to those of wind energy. India's three-stage thorium program, supported by its substantial reserves of 5,30,000 tonnes, seeks to transition progressively from Pressurised Heavy Water Reactors (PHWRs) to Fast Breeder Reactors (FBRs), ultimately culminating in the adoption of thorium reactors. The Kalpakkam Prototype Fast Breeder Reactor, which has been operational since 2024, represents a noteworthy achievement for India and has set the stage for advancing the third stage of the three-stage nuclear program by the 2030s.

Europe possesses significant expertise in Pressurised Water Reactors (PWR) and Generation IV reactors, complemented by its collaborative efforts with India in the International Thermonuclear Experimental Reactor (ITER) project.[22] Small Modular Reactors (SMRs), currently under deliberation by India and France, offer a more adaptable option than conventional, capital-intensive power plants. Similarly, the European Union is discussing the potential reactivation of inactive plants. An example is Belgium's 2022 decision to postpone the decommissioning of its reactors, as well as evaluations indicating that Germany's units that were closed in 2023 should be brought back online.[23]

The alignment in strategic terms presents a persuasive case. Nuclear energy and hydrogen technologies complement one another, reduce reliance on external sources, and align seamlessly with the frameworks of cooperation between India and the EU. Their commitment extends beyond reducing emissions by hundreds of millions of tonnes. It also encompasses creating employment opportunities and establishing a new era of industrial growth. Crucially, they foster resilience to external shocks, thereby safeguarding both India and the EU from a recurrence of previous vulnerabilities in an emerging, mineral-driven era. A few policy recommendations are suggested below.

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[20] Clean Hydrogen Joint Undertaking, Clean Hydrogen JU Annual Work Programme 2024, January 16, 2024, https://www.clean-hydrogen.europa.eu/system/files/2024-01/Clean%20Hydrogen%20JU%20AWP%202024%20-%20all%20chapters_Final_For_Publication.pdf

[21] CertifHy, "CertifHy – Renewable Hydrogen Certification Schemes," https://www.certifhy.eu/

[22] Prachi Lokhande, "Nuclear Energy Breakthroughs and India's Contributions," Centre for Air Power Studies (CAPS), May 14, 2022, https://capsindia.org/nuclear-energy-breakthroughs-and-indias-contributions/

[23] Chris Gattringer, "Germany's CDU Mulls Reactivation of Nuclear Power Plants," Brussels Signal, April 2, 2025, https://brusselssignal.eu/2025/04/germanys-cdu-mulls-reactivation-of-nuclear-power-plants/

3. Policy Recommendations

3.1 Level of the India-EU Inter-State Joint Commission

India and the EU must work to enhance existing frameworks, specifically the TTC and the CECP, to strengthen collaboration on nuclear and hydrogen as alternative green solutions. The emphasis should be on innovation, diversification of supply chains, and enhancement of bilateral energy security.

A) A dedicated nuclear-hydrogen subgroup within the TTC's working group 2 could integrate efforts of SMRs, High-temperature electrolysis (HTE) and thorium-based research.[24] Funding from Horizon Europe and India's Department of Science and Technology would support collaborative research and development, workshops and testing facilities.[25] Insights gained from India's role in ITER could guide future research in thorium and fusion technologies.

B) A joint SMR program could combine India's thorium and FBR expertise with Europe's advanced reactor designs, including Frances EPR 2.[26] Pilot deployment should commence by 2035, as India focuses on rural energy needs and the EU enhances grid stability in the Northern EU. Establishing shared design standards and alignment across manufacturing and regulatory processes would reduce costs and expedite current timelines.

C) Collaboration on low-cost electrolysers and THE systems has the potential to enhance the economic viability of green hydrogen significantly.[27] India can utilise its scale via PLI.[28] For Europe, it can rely on its expertise in PEM and advanced research and development capabilities. Joint centres in India and the EU can also prototype integrated high-temperature electrolysis systems. Mineral supply risks, especially regarding China's dominance in rare earths, can be mitigated through coordinated sourcing within the Mineral Security Partnership, utilising India's thorium reserves and EU-connected uranium suppliers.

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[24] Office of the Principal Scientific Adviser to the Government of India, "India–EU Trade and Technology Council (TTC)," https://www.psa.gov.in/india-eu-ttc

[25] European Commission, "Horizon Europe," https://research-and-innovation.ec.europa.eu/funding/funding-opportunities/funding-programmes-and-open-calls/horizon-europe_en

[26] FBR (Fast breeder reactor) is a type of nuclear reactor that produces more fissile fuel than it consumes by converting fertile material such as uranium-238 into plutonium; France's EPR-2 (European Pressurized Reactor-2) is a next-generation nuclear reactor design developed to improve safety, simplify construction, and reduce costs compared to earlier EPR models.

[27] Lorenzo Mario Pastore, Antonio Sgaramella, Giulia Bruno, Gianluigi Lo Basso, and Livio de Santoli, "Coupling High-Temperature Electrolysis and Industrial Waste Heat for On-Site Green Hydrogen Production: Energy, Economic and Environmental Analysis," International Journal of Hydrogen Energy 126 (2025): 87–98, https://doi.org/10.1016/j.ijhydene.2025.04.069

[28] Tanya Aggarwal, "Transforming Manufacturing Dynamics: A Look into India's PLI Scheme," Observer Research Foundation (ORF), April 22, 2024, https://www.orfonline.org/expert-speak/transforming-manufacturing-dynamics-a-look-into-indias-pli-scheme

D) Under the CECP, knowledge sharing and management should transition into a formal knowledge hub, consolidating expertise in hydrogen infrastructure, biomass-derived hydrogen, SMR pilots, and certification standards. Collaborations between BARC and Euratom would integrate technical expertise into both frameworks while synchronising India's NGHM with the EU's hydrogen import objectives.

E) Ultimately, both partners must address technical and regulatory challenges. India's subsequent action involves expanding its thorium-based fast-breeder program, whereas the European Union continues with Generation-IV reactors. Joint audits conducted by AERB and ENSREG may facilitate the harmonisation of safety standards and the integration of post-Fukushima insights into SMR designs. Cost reduction can be achieved through the dissemination of procurement strategies and the utilisation of economies of scale. TTC can coordinate funding and standards, CECP can expedite pilot projects, and Horizon Europe can support long-term research and development.

These steps would integrate India's resource advantages and cost-effective manufacturing with Europe's technological capabilities, establishing a robust nuclear-hydrogen ecosystem. Furthermore, they could enable both parties to mitigate external supply shocks, strengthen their climate commitments, and establish a global model of green collaboration amid energy insecurity.

3.2 At the National Level.

Domestic reforms must complement interstate collaboration if nuclear and hydrogen are to take root as viable green alternatives. India and the EU encounter distinct structural challenges, including financing, regulation, infrastructure, and supply chains. Their success hinges on aligning internal strategies with overarching international frameworks, such as India's National Green Hydrogen Mission (NGHM) and the EU's REPowerEU plan.

A) In India, the priority must be to broaden the NGHM to include nuclear-linked hydrogen. [29] Funding should focus on pilot projects that integrate Advanced Heavy Water Reactors (AHWRs) and Small Modular Reactors (SMRs) with high-temperature electrolysis (HTE). This will augment the current expenditure of ₹19,744 crore through 2029–30, of which ₹17,490 crore has already been allocated to the Strategic Interventions for Green Hydrogen Transition (SIGHT) programme. Rounds of R&D proposals targeting nuclear–hydrogen synergies would facilitate the scaling of pathways for decarbonising heavy industries such as steel and chemicals, while also leveraging India's developing expertise in biomass-derived hydrogen.

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[29] OECD Nuclear Energy Agency (NEA), "Nuclear Energy in the Hydrogen Economy," https://www.oecd-nea.org/jcms/pl_20492/nuclear-energy-in-the-hydrogen-economy

B) India ought to expand its PLI scheme to include SMR manufacturing. The objective should be to reduce costs, lowering the current unit cost from $2–5 billion. This initiative would leverage the achievements of the broader PLI framework, which, by July 2025, had secured $21 billion in investments across 14 sectors, including advanced chemistry cell (ACC) storage.[30] The initiative must aim to achieve domestic production of 100–300 MW small modular reactors (SMRs) by incorporating thorium-based designs from BARC and promoting collaborations with private industry for deployment in rural and industrial settings. Disbursements linked to performance may promote innovation in modular construction, while requiring technology transfer in PLI approvals would support India's interim goal of achieving 22.5 GW of nuclear capacity by 2032.[31]

C) This initiative may be executed via institutions like the IITs and NITI Aayog, which should aim to utilise predictive analytics for forecasting hydrogen demand, stabilising grids, and optimising the integration of nuclear and hydrogen energy. Open-source simulation tools can model expansion scenarios. Leveraging India's established digital public infrastructure expertise, such tools would lay the groundwork for more cost-effective and secure system planning.

D) The primary focus in Europe is the expansion of hydrogen infrastructure. The EU Hydrogen Bank should be increased in part by reallocating funds from inactive projects, including the 1.3 GW withdrawn in mid-2025 due to regulatory obstacles.[32] This expansion may facilitate pipeline financing, aligning with REPowerEU's objective of establishing a hydrogen-ready backbone. The forthcoming EHB auction, scheduled for the end of 2025, allocates €1 billion for the production of renewable hydrogen.[33] This initiative should be supplemented by investments to retrofit gas networks, especially along critical industrial corridors extending from North Sea ports to inland hubs. To achieve its target of 10 million tonnes of domestic hydrogen by 2030, the EU must streamline application processes and address funding gaps.

E) Nuclear energy should be reintegrated into the core of EU energy policy. Licensing for small modular reactors (SMRs) should be standardised across member states through the European Nuclear Safety Regulators Group (ENSREG) to reduce deployment timelines. Feasibility studies should assess the potential to restart idled reactors, with a specific focus on Germany. Independent studies, including the December 2024 report by Radiant Energy Group, indicate that facilities like Brokdorf may be able to

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[30] Sudhanshu Singh, “India’s PLI Schemes Bring in US$21 Billion in Investment in 2025,” India Briefing, July 23, 2025, https://www.india-briefing.com/news/indias-pli-schemes-bring-in-us21-billion-in-investment-in-2025-38796.html/

[31] Government of India, “Rajya Sabha starred question number-289, answered on 27.03.2025,” April 2025, https://cdnbbsr.s3waas.gov.in/s35b8e4fd39d9786228649a8a8bec4e008/uploads/2025/04/202504011320114536.pdf

[32] FuelCellsWorks, “Largest European Hydrogen Bank Funding Winner Pulls Out,” August 12, 2025, https://fuelcellsworks.com/2025/08/12/energy-policy/largest-european-hydrogen-bank-funding-winner-pulls-out

[33] European Commission, “Competitive Bidding under the Innovation Fund,” https://climate.ec.europa.eu/eu-action/eu-funding-climate-action/innovation-fund/competitive-bidding_en

restart within nine months, potentially restoring 20–30 GW of capacity.[34] Belgium's 2022 decision to prolong reactor lifespans establishes an additional precedent.

F) Technical and policy challenges persist in both India and the EU. India must implement small modular reactors (SMRs) in rural grids within a timeframe, leveraging their modularity for off-grid electrification. The European Union should integrate high-temperature electrolysis with existing nuclear facilities and increase salt-cavern hydrogen storage capacity. Regulatory delays pose a significant challenge; India should digitise its approval processes, whereas the EU could implement unified directives to expedite licensing. The elevated costs of PEM electrolysers necessitate the implementation of subsidies and collaborative procurement strategies to reduce these expenses. Existing policy mechanisms, such as India's ₹17,490 crore SIGHT budget[35] and the EU's Critical Raw Materials Act (CRMA), should be utilised to ensure diversified sourcing and enhance supply chain resilience.[36]

Collectively, these national-level reforms could enable India and the EU to convert their interstate partnerships into measurable results effectively.

3.3 People/Society level

The viability of nuclear and hydrogen as foundational elements of the energy revolution depends on public trust. Despite the potential of these technologies, widespread scepticism persists. Concerns persist due to the legacies of Chornobyl and Fukushima, apprehensions about potential accidents, and insufficient transparency in decision-making. There are indications that attitudes may shift when benefits and risks are communicated effectively.

A) The Green Future Initiative: India and the EU should collaborate to initiate a multilingual communication campaign endorsed by the TTC to enhance acceptability. This campaign should utilise television, social media, and influencers to elucidate the role of nuclear and hydrogen in achieving net-zero emissions. Public town halls situated near project locations may effectively localise the message by illustrating to residents how initiatives lead to job creation and improved access to electricity.

B) Resources for Instruction and Immersion: Education should be integrated into awareness initiatives. Partnerships among organisations such as IITs, TU Delft, and other technical universities should

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[34] Radiant Energy Group, "Restart of Germany's Reactors: Can It Be Done?," July 18, 2023 (updated November 28, 2024), https://www.radiantenergygroup.com/reports/restart-of-germany-reactors-can-it-be-done

[35] Ministry of New and Renewable Energy (MNRE), Government of India, "National Green Hydrogen Mission," https://mnre.gov.in/en/national-green-hydrogen-mission/

[36] Ministry of New and Renewable Energy (MNRE), Government of India, "National Green Hydrogen Mission," https://mnre.gov.in/en/national-green-hydrogen-mission/

facilitate the introduction of modules focused on nuclear and hydrogen technologies, emphasising safety, environmental impact, and innovation. Immersive VR/AR technologies facilitate the transformation of abstract anxieties into relatable realities, enabling students and community leaders to engage with simulated environments such as SMRs or hydrogen hubs. Funding for exchanges and capacity-building initiatives may be sourced from programs such as Erasmus+ and SERB in India. The broad distribution of the knowledge base should be facilitated by open-access digital content tailored to local languages.

C) Collaborations within the community: Collaboration with civil society organisations is essential for building trust. Non-governmental organisations that facilitate connections among communities, businesses, and governments must be incorporated. These organisations can ensure that new energy projects are co-designed with local involvement, rather than imposed from above, through open benefit-sharing agreements, participatory planning, and public consultations. The establishment of advisory boards comprising community representatives, technical specialists, and non-governmental organisations would introduce an additional level of responsibility.

D) Energy Citizenship: The long-term objective should be to promote "energy citizenship," wherein individuals actively participate in the energy system rather than merely consuming it. Existing models include rooftop and field leasing programs in Karnataka, India. Citizens have several options, including direct investments, reduced tariffs, and participation in governance systems. The EU and India should establish citizen forums that contribute directly to national and TTC-level regulatory processes.

E) Addressing Disparities and Anxieties: Scepticism encompasses both social and technical dimensions. In regions characterised by historical displacement or uneven development, communities' express concerns regarding potential marginalisation. Simplified explanatory texts and annual safety reports released collaboratively by Europe's ENSREG and India's AERB can help address knowledge gaps. Tailored communication is essential, as European audiences may respond more positively to discussions on emissions reduction and climate leadership, whereas Indian populations may prioritise employment and energy accessibility. Regular workshops led by credible civil society actors can ensure that these issues are acknowledged and integrated into the planning phase. Achieving acceptability requires not only promoting safety but also demonstrating equity, transparency, and tangible local benefits.

4. Roadmap for Implementation

A) Phase 1--Foundations (2025-2028):

- SMRs: Site selection + licensing in 1-2 EU countries and 1-2 Indian sites; complete safety submissions. No grid-connected SMRs yet.
- Conventional nuclear: Life-extension and uprate decisions; PFBR/large reactor construction continues.
- Hydrogen: Commission approx. 1-1.5 GW electrolysers (EU + India); approx. 0.2-0.4 Mt/yr supply under contract. HTE: R&D test loops only.

B) Phase 2 --First Builds (2029-2033)

- SMRs: First EU SMR starts construction; India's project advances to procurement.
- Conventional nuclear: +4-8 GW via large reactors/life-extensions.
- Hydrogen: EU reaches approx. 1-2 Mt/yr; India 0.5-1 Mt/yr (5-10 GW electrolysers)
- Pipelines: Pilot corridors, not full backbones.

C) Phase 3 -- First Operations (2034-2038)

- SMRs: 1 EU SMR online (2034-36); India's first SMR 2036-38
- Conventional nuclear: +8-12 GW combined capacity since 2025.
- Hydrogen: EU 2-3 Mt/yr; India 1-1.5 Mt/yr; initial storage + pipeline retrofits.
- Milestones: 1-2 SMRs in service; 3-4 Mt/yr low-emissions Hydrogen; integrated storage and corridors begin.

D) Phase 4 -- Scale & Impact (2039-2045)

- SMRs: Replication reduces costs; 5-7 total across EU+India.
- Conventional nuclear: Life-extensions + select large builds.
- Hydrogen: 5-6 Mt/yr output across EU+India by early-2040s.
- Infrastructure: Expanded EU corridors; India develops multiple nuclear+renewable H_2 hubs.
- Milestones: +15-20 GW nuclear vs 2025 baseline; approx. 5-6 Mt/yr sustainable Hydrogen.

Conclusion

India and the EU's collaboration on nuclear and hydrogen technology should be seen as laying the foundation for a long-term marathon rather than a sprint towards 2045. The partnership contributes distinct but complementary strengths. Europe's expertise in regulatory frameworks, Generation-IV designs, and hydrogen research aligns with India's advanced nuclear research, thorium utilisation goals, and cost-effective energy strategies. The integration of these capabilities offers a unique opportunity to shift from transactional energy relationships to strategic collaboration.

Balancing ambition with practicality is challenging. Nuclear deployment is inherently politically sensitive, capital-intensive, and slow. High costs and technological unpredictability constrain hydrogen's potential. Expecting significant results within 10 years may undermine credibility. A realistic course offers a sustainable trajectory: pilots in the late 2020s, initial commercial builds in the 2030s, and gradual scaling into the 2040s. Previous transitions highlight the need for public legitimacy, financial innovation, and regulatory harmonisation to align with technological advancements. India and the EU can enhance energy system resilience by diversifying mineral supply chains, aligning safety and certification standards, and jointly investing in infrastructure. Short-term profits may be minimal, but long-term gains would be substantial.

The India-EU framework extends beyond a bilateral initiative and illustrates how large democracies can establish technical collaboration while pursuing strategic goals amid geopolitical competition and climate challenges. Crucially, if advanced through the TTC, the MSP, and forums like the G20, this partnership has the potential to shape the rules and norms of a new energy order. By demonstrating that democracies can collaborate on hard technologies, balance sustainability with security, and align innovation with public accountability, India and the EU can extend their influence well beyond their bilateral horizon. In the end, the greatest achievement of this partnership may not be the technologies it builds, but the trust it sustains.

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