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Decarbonizing Nepal's Cement Industry with Hydropower-Based Hydrogen

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ABSTRACT. The cement industry is a significant global source of CO_2 emissions, with Nepal's clinker production contributing approximately 2.34 million metric tons annually through coal combustion. This study investigates the technical and economic feasibility of decarbonizing Nepal's cement sector by transitioning to green hydrogen fuel, leveraging the country's abundant hydropower resources. Through detailed energy balance calculations and techno-economic modeling, we demonstrate that complete coal replacement would require 227,743 metric tons of green hydrogen annually, necessitating 2,002 MW of dedicated hydropower capacity. Our projections indicate hydrogen production costs could decline to $2.15/kg by 2035, driven by electrolyzer efficiency improvements and Nepal's competitive industrial electricity tariffs. The analysis reveals this transition could eliminate up to 2.57 million metric tons of CO_2 emissions yearly, representing a 98% reduction in fuel combustion emissions. However, implementation challenges include seasonal hydropower variability, requiring 2,000 MW of reservoir projects, and substantial infrastructure investments estimated at $800 million. The study proposes a phased adoption pathway, with 30% hydrogen penetration by 2030 achieving 770,000 metric tons of annual emission reductions. We identify critical policy interventions including a $139/ton carbon price and targeted subsidies to bridge the current cost gap. A $139/ton carbon price and targeted subsidies are identified as key policy interventions to bridge the current cost gap.

Keywords: Cement clinker decarbonization, Green hydrogen, Industrial fuel switching, Nepal hydropower utilization, PEM electrolyzer economics.

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1. Introduction

The global cement industry contributes around 5% to 10% of global carbon emissions, largely due to energy-intensive clinker production that relies heavily on fossil fuels like coal [1, 2, 3, 4]. Emissions range between 0.6 to 0.9 tons of CO_2 per ton of cement produced [5, 6]. Cement demand has surged due to rapid urban development, intensifying emissions. In Nepal, approximately 72 plants emit about 3.6 million metric tons (MT) of CO_2 annually [7].Global emissions from cement reached 1.57 gigatons (Gt) in 2019 [8], underlining the urgency for decarbonization. Nepal has substantial hydropower potential of around 42,000 MW [9] and generates most of its electricity from hydropower, with expansions underway [10]. This hydropower surplus can support green hydrogen production, which offers a carbon-free alternative to fossil fuels in cement manufacturing [7].

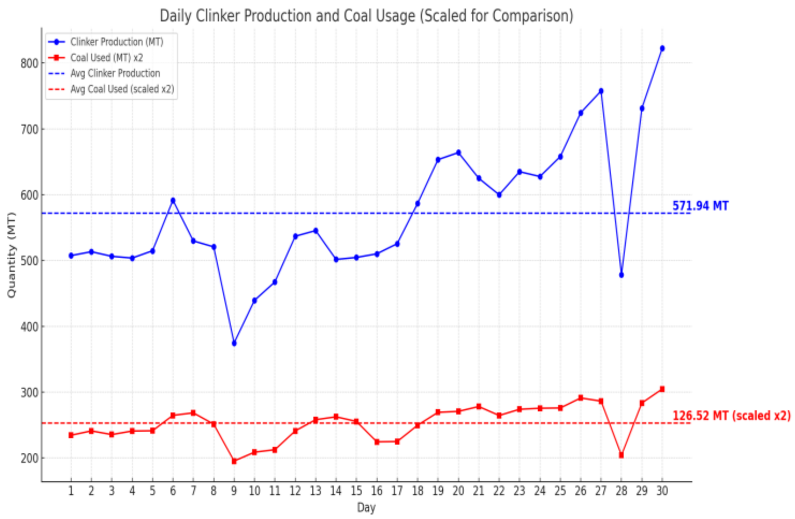

FIGURE 1. Illustration of the coal usage for clinker production in a Nepalese clinker factory.

From Figure 1, it is evident that 4.52 MT of clinker is produced from 1 MT of coal. With 5 million MT of clinker produced in Nepal in 2019/20 [11], this equates to 1.11 million MT of coal consumption, emitting 2.34 million MT of CO_2 from coal combustion alone [12]. These emissions are projected to increase with industry expansion. Green hydrogen could drastically reduce these emissions. Coal costs about \$121/MT in Nepal. Matching coal's energy content (7,000 kcal/kg) would require approximately 205.88 kg of hydrogen (LCV $\sim$ 34,000 kcal/kg) [13, 14]. At \$4–\$6/kg [15], equivalent hydrogen energy costs \$1,235/MT-10 times more than coal. However, hydrogen costs are expected to drop due to improved electrolyzers and renewables. Global carbon regulations and rising coal prices (3–5% annually) further diminish coal's cost advantage [16]. Hydrogen, with no direct greenhouse gas emissions, could replace fossil fuels in clinker kilns [17, 18, 19, 20]. Green hydrogen's viability depends on electrolyzer cost and efficiency [21, 22]. Technology advancements are lowering costs, and coupling these systems with Nepal's hydropower could make hydrogen competitive [23].

This study investigates the potential for replacing coal with green hydrogen in Nepal's cement industry. It evaluates energy and cost feasibility, hydropower capacity, and emissions impact through 2035. By integrating carbon pricing and investment planning [24], it offers a practical decarbonization roadmap for Nepal's cement sector.

2. Methodology

This study adopts a comprehensive analytical framework to evaluate the technical and economic feasibility of replacing coal with green hydrogen in Nepal's cement industry, with a specific focus on clinker production. The approach integrates mass and energy balance calculations, hydrogen substitution modeling, hydropower capacity assessment, and techno-economic analysis. A 2035 projection horizon is used to reflect evolving costs of electrolyzers and hydrogen production technologies. The system boundary considers Nepal's grid emissions, local hydropower dynamics, and industry-specific emission factors. Each stage of the methodology is designed to quantify the hydrogen requirements, assess renewable energy integration potential.

2.1. System Boundary and Baseline Establishment.

- Temporal Scope: 2024 (baseline) to 2035 (projection)

- Functional Unit: 1 metric ton (MT) of clinker produced.
- Key Assumptions:
  - Bituminous coal LHV: 7,000 kcal/kg ($\pm 2\%$ variability)
  - Hydrogen LHV: 33.33 kWh/kg (34,000 kcal/kg)
  - Electrolyzer efficiency: 65% (PEM systems)
  - Grid emission factor: 0.012 kg CO_2/kWh (Nepalese grid)

PEM electrolyzers were considered due to their high current density and suitability for variable renewable inputs (reference).

2.2. Core Calculations With Enhanced Detail.

2.2.1. *Energy and Mass Balance Calculations.* Coal-to-Clinker Ratio is derived from plant operational data (Figure 1):

$$\text{Ratio} = \frac{\sum \text{Daily Clinker}}{\sum \text{Daily Coal}} \tag{1}$$

Annual Coal Consumption for 5 million MT clinker (2019/20) is:

$$\text{Coal} = \frac{\text{Clinker Production}}{\text{Clinker to Coal Ratio}} \tag{2}$$

CO_2 Emissions (EPA Tier 2) is:

$$CO_2 = \text{Coal Consumed (MT)} \times \text{Emission Factor} \quad (2.32 \text{ tons } CO_2/\text{ton coal}) \tag{3}$$

2.2.2. *Hydrogen Substitution Framework.* The energy equivalence is:

$$H_2 \text{ Required} = \frac{\text{Calorific Value of Coal (kcal/kg)}}{\text{Calorific Value of Hydrogen (kcal/kg)}} \tag{4}$$

Total Hydrogen Demand for 100% substitution is:

$$= \text{Coal Required} \times \text{Energy Equivalence} \tag{5}$$

2.2.3. *Renewable Energy Integration.* Hydropower Requirement (65% capacity factor):

$$\text{Energy Needed} = \frac{\text{Total Hydrogen needed (kg)} \times \text{Energy required to produce 1 kg of hydrogen (50 kWh/kg)}}{\text{Capacity factor of hydropower (0.65)} \times \text{Hours in a year (8760 hours)}} \quad (6)$$

$$= 2,002 \text{ MW}$$

Surplus Verification: Nepal's Hydropower Capacity vs. Green Hydrogen Requirements (2024) is shown in Table 1.

TABLE 1. Current Hydropower Status

Parameter	**Values**	**Notes**
Total Installed Hydropower	3,329.54 MW [25]	90.4% of Nepal's grid capacity
Peak Domestic Demand (2024)	2,316 MW [26]	10% annual growth
Monsoon Export (2023)	1.7B units [27]	≈ 1,940 MW continuous for 4 months
Dry Season Generation	≈ 1,085 MW	Drops to 1/3 of installed capacity [28]
Under Construction	7,000 MW [29]	Phased completion through 2030

Green Hydrogen Requirement

- Required Capacity: 2,000 MW (continuous, 65% capacity factor)
- Equivalent to: 61.4% of current hydropower capacity

TABLE 2. Feasibility Analysis

Scenario	**2024 Reality**	**2030 Projections**
Monsoon Availability	Total: ≈ 3,300 MW After demand: 984 MW surplus	Total: ≈ 10,255 MW After demand: 6,155 MW surplus
Dry Season Availability	Total: ≈ 1,085 MW Deficit: 917 MW	Total: ≈ 3,418 MW Marginal surplus: 18 MW
Hydrogen Feasibility	Impossible	Possible with new capacity

Critical Requirements

- Reservoir Projects: Minimum 2,000 MW needed for dry-season reliability
- Investment: $4–5 billion for dedicated hydrogen infrastructure
- Policy: Fast-track approvals for hydrogen-dedicated projects

TABLE 3. Cost Projections (2024 vs. 2035)

Parameter	**2024 Value**	**2035 Projection**	**Calculation Basis**
Electrolyzer CAPEX	$1,200/kW	$400/kW	12% annual reduction (Yang et al., 2023)
H_2 Production Cost	$5.00/kg	$2.15/kg	Learning curve (18% reduction/year)

2.2.4. *Techno-Economic Assessment.* These cost projections are primarily based on global learning curves; however, in the Nepalese context, electricity tariffs for industrial hydropower are lower. According to Nepal Electricity Authority (NEA), off-peak industrial tariffs range from 4.74 to 7.14 NPR/kWh, which equals $0.035 to $0.053 per kWh at 135 NPR/USD, depending on voltage level and time-of-use pricing [30]. To validate global hydrogen cost projections under Nepal-specific conditions, a Levelized Cost of Hydrogen (LCOH) calculation was performed based on domestic electricity pricing and electrolyzer characteristics.

As previously noted, Nepal's industrial tariffs provide a competitive electricity cost advantage for hydrogen production. Green hydrogen production via PEM electrolyzers requires approximately 50 kWh of electricity per kilogram of hydrogen, assuming 65% efficiency. Using these values, the electricity input cost per kg of hydrogen is calculated as follows:

TABLE 4. Input Cost per kg of Hydrogen

Electricity Price (USD/kWh)	**Electricity Cost per kg H_2 (USD)**
0.035	1.75
0.040	2.00
0.045	2.25
0.050	2.50
0.053	2.65

The Levelized Cost of Hydrogen (LCOH) is given by:

$$\begin{aligned} \text{LCOH} &= \text{Electricity Cost} + \text{CAPEX Recovery} + \text{O\&M Cost} \\ &= (C_e \times E) + \left(\frac{C_{\text{capex}} \times \text{CRF}}{8760 \times \text{CF} \times \eta}\right) + \left(\frac{C_{\text{O\&M}}}{8760 \times \text{CF} \times \eta}\right) \end{aligned} \tag{7}$$

Where:

- C_e = Electricity price (USD/kWh)
- E = Energy per kg H_2 = 50 kWh
- C_{capex} = Electrolyzer cost (USD/kW)
- CRF = Capital Recovery Factor
- CF = Capacity Factor
- η = Efficiency (kg H_2/kWh input)
- $C_{\text{O\&M}}$ = Annual O&M cost (USD/kW/year)

TABLE 5. Input Parameters (2035 Projections)

Parameter	**Value**	**Unit**	**Notes**
Electrolyzer CAPEX	\$400	/kW	PEM electrolyzer, 2035 projection
Electricity consumption	50	kWh/kg H_2	Industry standard for PEM electrolysis
Capacity factor (CF)	65%	–	Based on Nepal's hydropower variability
Fixed O&M cost	\$15	/kW-year	3.75% of CAPEX
Discount rate	8%	–	Standard project financing rate
System lifetime	20	years	Typical electrolyzer lifespan

Using a simplified LCOH model (based on IEA/IRENA methodology):

$$\text{CAPEX Recovery} = \frac{\text{Electrolyzer CAPEX} \times \text{CRF}}{\text{Capacity factor (CF)} \times \text{hours in a year}} \tag{8}$$

Where:

$$\text{CRF (Capital Recovery Factor at 8\% for 20 years)} \approx 0.1019$$

$$\text{CAPEX contribution per kg } H_2 = \text{CAPEX Recovery} \times 50 \text{ kWh}$$

$$\text{Fixed O\&M contribution per kg H}_2 = \frac{\text{Fixed O\&M cost}}{\text{CF} \times \text{hours in a year}} \times 50 \tag{9}$$

TABLE 6. Total LCOH Range

Electricity Price (USD/kWh)	Electricity	CAPEX	O&M	Total LCOH (USD/kg)
0.035	1.75	0.36	0.13	2.24
0.040	2.00	0.36	0.13	2.49
0.045	2.25	0.36	0.13	2.74
0.050	2.50	0.36	0.13	2.99
0.053	2.65	0.36	0.13	3.14

These values show that, under Nepal's industrial electricity tariffs and projected electrolyzer costs by 2035, the levelized cost of green hydrogen could fall within the range of $2.24 to $3.14 per kg. This aligns closely with the IEA's global LCOH forecast for green hydrogen and demonstrates competitive feasibility in Nepal's context [23, 30, 31].

2.2.5. *Break-Even Analysis.*

(1) **Cost Comparison:**

$$\text{Coal Energy Cost} = \text{Cost of coal in Nepal/MT} + (\text{CO}_2 \text{ Emission Factor} \times \$50 \text{ carbon tax}) \tag{10}$$

$$\text{H}_2 \text{ Energy Cost} = \text{H}_2 \text{ required} \times \text{H}_2 \text{ Production Cost} \tag{11}$$

(2) **Subsidy Requirement:**

$$\text{Gap} = \text{H}_2 \text{ Energy Cost} - \text{Coal Energy Cost} \tag{12}$$

2.2.6. *Emission Reduction Potential.*

(1) **Direct Fuel Combustion:**

$$\Delta\text{CO}_2 = \text{CO}_2 \text{ Emissions MT/year} \times \text{Substitution Ratio} \tag{13}$$

(2) **Process Emissions (Le Chatelier's principle):**

$$\text{CaCO}_3 \rightarrow \text{CaO} + \text{CO}_2 \implies 0.52 \text{ MT CO}_2/\text{MT clinker} \tag{14}$$

(3) **Net Reduction (100% H_2** scenario):

$$= \text{CO}_2 \text{ Emissions MT/year} - \big(5 \text{ million MT clinker} \times \text{Process Emissions}\big) \tag{15}$$

2.2.7. *Validation Protocol.*

(1) **Cross-Method Verification:**
- Coal calculations compared with CSI Cement CO_2 Protocol
- Hydrogen yields verified against IEA H_2 Technical Report (2023)

(2) **Sensitivity Testing:**
Key Variable: Electrolyzer efficiency (±5%)

$$\text{Revised H}_2 = \frac{\text{Total Hydrogen Demand for 100\% substitution}}{0.60} \text{ to } \frac{\text{Total Hydrogen Demand for 100\% substitution}}{0.70} \tag{16}$$

(3) **Uncertainty Propagation:**

$$\text{Total Uncertainty} = \sqrt{(\text{Operational Cost}_{\text{Coal}})^2 + (\text{Operational Cost}_{\text{H}_2})^2} \tag{17}$$

2.2.8. *Policy Implications Framework.*

(1) **Incentive Structures:**

$$\text{Required Carbon Price} = \frac{\text{H}_2\text{ Energy Cost} - \text{Coal Energy Cost}}{\text{Emission Factor}} \tag{18}$$

(2) **Infrastructure Investment:**

$$\text{Investment} = \frac{\text{Energy Needed (MW)}}{\text{2035 Projected Electrolyzer Cost}} \tag{19}$$

3. Results and Discussions

This section presents the core findings of the study by quantitatively analyzing the technical, environmental, and economic implications of replacing coal with green hydrogen in Nepal's cement industry. Key outcomes are derived from the previously discussed methodology and supported by real-world plant data, techno-economic assumptions, and national hydropower capacity insights.

3.1. **Clinker-to-Coal Dependency and Baseline Emissions.** Nepal's clinker production is heavily reliant on coal as its primary thermal energy source. Based on the operational clinker-to-coal ratio of 4.52 (from Figure 1), the annual production of 5 million metric tons (MT) of clinker requires approximately 1.106 million MT of coal. Using the Tier 2 emission factor of 2.32 tons CO_2 per ton of bituminous coal [12], the corresponding CO_2 emissions from coal combustion total approximately 2.57 million tons/year. This emission estimate establishes the baseline fossil carbon footprint for thermal energy input in the cement manufacturing process and provides the foundation for assessing hydrogen-based decarbonization.

3.2. **Hydrogen Substitution Requirement.** To replace coal with green hydrogen thermally, energy equivalence must be ensured. Given a hydrogen lower heating value (LHV) of 33.33 kWh/kg and bituminous coal LHV of 7,000 kcal/kg ($\approx$ 8.14 kWh/kg), the thermal equivalence factor becomes 205.88 kg of H_2 per ton of coal. For 1.106 million tons of annual coal consumption, the total hydrogen requirement is calculated to be 227,743 MT per year. Assuming 65% electrolyzer efficiency (based on the average performance of modern PEM systems, IEA, 2023), the electrical energy required for hydrogen production amounts to approximately 11.39 billion kWh/year, translating to a continuous power requirement of 2,002 MW. This forms the cornerstone for integrating hydropower and hydrogen strategies in Nepal.

3.3. **Hydropower Feasibility in Nepal and Capacity Factor Justification.** Nepal's total installed hydropower capacity as of 2024 stands at 3,255.8 MW, with over 7,000 MW under construction. The average net capacity factor for hydropower projects in Nepal is approximately 65%, supported by operational reports of peaking run-of-river and reservoir plants [32]. This figure was adopted as a representative national average to estimate annual usable energy for hydrogen production. Based on this assumption, the continuous demand of 2,002 MW for hydrogen production exceeds dry-season generation, which falls to 1,085 MW. During monsoon months, however, surplus capacity of nearly 1,884 MW becomes available. Nepal's dry season hydropower generation drops to one-third of installed capacity ($\approx 1,085$ MW), creating a seasonal deficit. During the monsoon, however, up to 1,884 MW of surplus capacity is available. By 2030, this gap is expected to narrow significantly due to ongoing hydropower expansions. A summary of seasonal capacity and hydrogen demand alignment is provided in Figure 2.

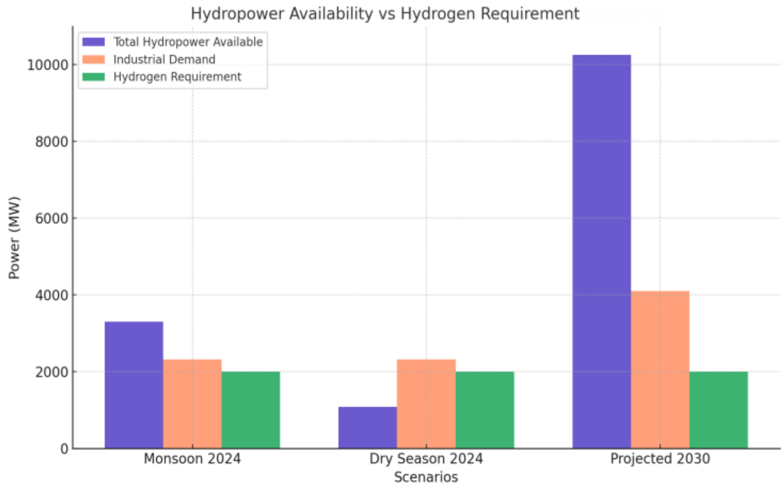

FIGURE 2. Seasonal Hydropower Availability vs. Hydrogen Demand.

3.4. **Emission Reduction Potential.** Full substitution of coal with green hydrogen would eliminate the 2.57 million tons of CO_2 emissions arising from fossil fuel combustion. However, process emissions from calcination of limestone ($CaCO_3 \rightarrow CaO + CO_2$) remain a challenge. With a process emission rate of 0.52 tons CO_2 per ton of clinker, total non-combustion emissions from producing 5 million tons of clinker amount to 2.6 million tons CO_2/year. Thus, net emissions under a 100% hydrogen scenario reduce to 66,370 tons/year, representing a 97.4% reduction in total CO_2 emissions from the cement plant. These values are summarized in Figure 2, which also compares partial substitution under a 30% hydrogen adoption scenario.

Figure 3 shows the stark contrast between current coal-based emissions and the near-zero emissions scenario with hydrogen adoption, while highlighting persistent process emissions from limestone calcination. The geographical concentration of clinker plants in specific regions (notably Province Koshi, Bagmati, and Lumbini) could enable targeted hydrogen infrastructure development.

3.5. **Economic Assessment and Break-Even Analysis.** The cost comparison indicates that the effective cost of coal, including a projected carbon tax of \$50/ton CO_2, amounts to \$237 per MT coal equivalent. On the other hand, with hydrogen projected at \$2.15/kg by 2035 (based on cost learning curves), the energy-equivalent cost reaches \$443 per MT-resulting in a cost premium of \$206 per MT. This would still represent an 87% cost premium compared to coal on an energy-equivalent basis, even with a \$50/ton carbon tax on coal.

Figure 4 demonstrates the sensitivity of hydrogen costs to electricity prices, showing how Nepal's low industrial tariffs (\$0.035–\$0.053/kWh) could make green hydrogen more competitive by 2035. Globally, hydrogen costs are projected to reach \$2–\$3/kg in Europe and the Middle East by 2035, with India aiming for sub-\$2/kg hydrogen through solar-based electrolysis. Compared to these benchmarks, Nepal's hydropower advantage and low industrial tariffs position it competitively, though seasonal generation challenges must be addressed through reservoir-backed capacity and grid management strategies.

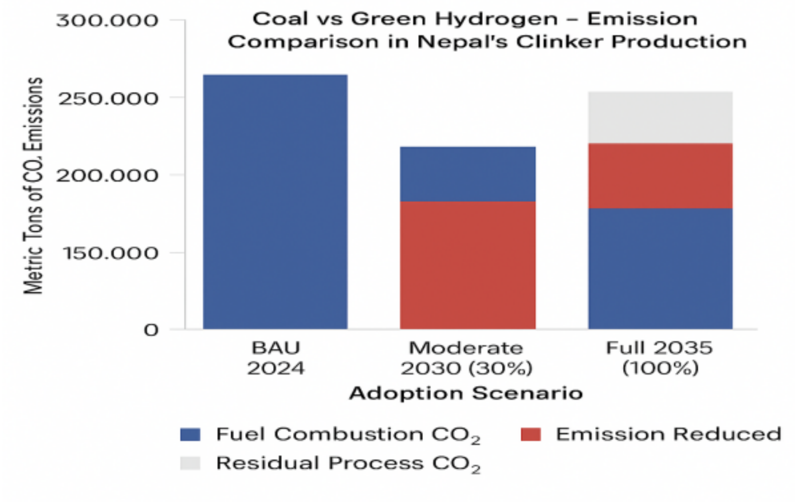

FIGURE 3. CO_2 Emission Comparison - Coal vs. Green Hydrogen

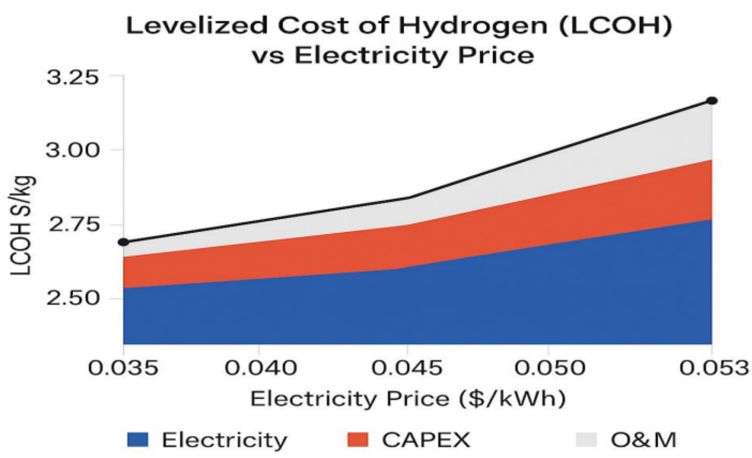

FIGURE 4. Levelized Cost of Hydrogen (LCOH) vs. Electricity Price.

3.6. **Strategic Adoption Pathways and Policy Recommendations.** A phased adoption strategy offers the most pragmatic approach to balancing environmental goals with infrastructure and economic constraints. By 2030, a 30% hydrogen penetration could displace 331,858 MT of coal annually while requiring manageable investments in 600 MW of hydropower capacity and $240 million for electrolyzers. Full adoption by 2035 would demand more substantial infrastructure-2,000 MW of reservoir projects ($4–5 billion) and $800 million for electrolyzers-but could achieve near-total elimination of combustion-related emissions.
Critical policy interventions include:

- Carbon pricing at $139/ton CO_2 to internalize coal's environmental costs,
- Subsidies for electrolyzer deployment and renewable integration,
- Fast-track approvals for hydrogen-dedicated hydropower projects,
- Industrial partnerships to pilot hydrogen-based clinker production.

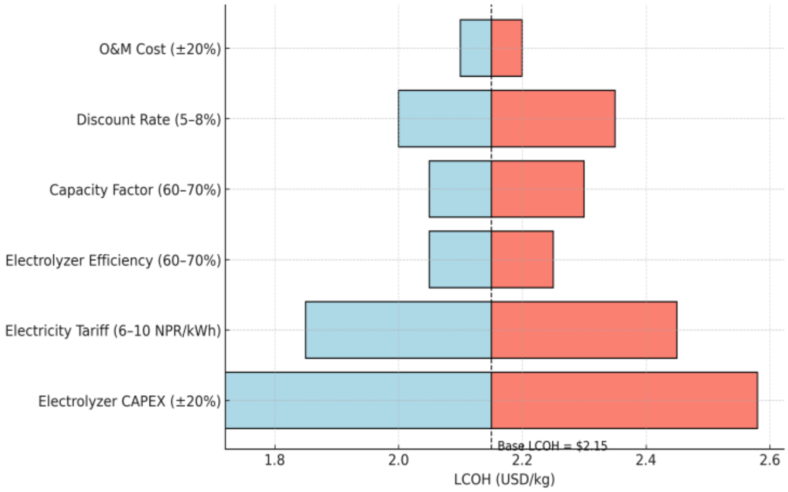

FIGURE 5. Sensitivity analysis (Tornado chart) of LCOH to key variables. Electrolyzer CAPEX and electricity tariffs have the strongest influence on hydrogen cost outcomes.

3.7. **Sensitivity and Scenario Analysis.** Sensitivity analysis shows that electrolyzer CAPEX and electricity prices have the strongest influence on hydrogen cost. A ±20% shift in CAPEX alters the Levelized Cost of Hydrogen (LCOH) between \$1.72 and \$2.58/kg under different electricity cost scenarios. A tornado chart illustrating the impact of key variables is shown in Figure 5.

TABLE 7. Scenario Modeling

Scenario	H_2 Penetration	Coal Displaced (MT)	CO_2 Reduction (MT)	Cost Premium
BAU (2024)	0%	0	0%	–
Moderate (2030)	30%	331,858	769,909	+72%
Full (2035)	100%	1,106,194	2,566,370	+87%

3.8. **Infrastructure and Policy Implications.** To enable large-scale adoption of green hydrogen in the cement sector, Nepal must invest in at least 2,000 MW of dedicated hydropower, preferably via reservoir-based or pumped storage projects to manage seasonal variability. Estimated capital requirements are between \$4–5 billion, depending on location and integration cost. Policy recommendations include:

- Introduction of a carbon price floor (approximately \$139/ton CO_2),
- Concessional financing mechanisms for electrolyzer infrastructure,
- Time-bound regulatory approvals for hydrogen-linked projects,
- Strategic co-location of cement kilns and hydropower plants to reduce transmission losses and support clustered green industrial zones.

4. Conclusion and Recommendations

This study presents a comprehensive analysis of the potential for green hydrogen to decarbonize Nepal's cement industry, highlighting both the transformative opportunities and significant challenges of such a transition. While replacing coal with green hydrogen is technically feasible, the path to implementation requires strategic planning, robust policy support, and substantial infrastructure investments.

Nepal's cement sector currently emits approximately 2.34 million metric tons of CO_2 annually from clinker production. Green hydrogen could eliminate nearly all combustion-related emissions, reducing them by 98%, but achieving this would require 227,743 metric tons of hydrogen annually and 2,002 MW of dedicated hydropower, with a deficit of 18 MW. However, 2,000 MW of reservoir projects would still be essential to ensure year-round hydrogen reliability.

Nepal's 72 clinker plants, with an average capacity of 69,444 MT, present both challenges and opportunities for phased hydrogen adoption, particularly near hydropower sites using modular electrolyzers. Economically, hydrogen production costs are projected to decline to $2.15–$3.14/kg by 2035 due to improvements in electrolyzer efficiency and low industrial electricity tariffs. Even then, hydrogen would remain 87% more expensive than coal on an energy-equivalent basis, despite a $50/ton carbon tax. Bridging this gap would require a carbon price of $139/ton CO_2 and subsidies to offset the $206/MT coal-equivalent premium. Time-of-use pricing could help optimize hydrogen production during power surpluses and improve economics.

A phased approach is recommended. By 2030, 30% hydrogen penetration could displace 331,858 MT of coal annually, reduce emissions by 769,909 MT CO_2, and require 600 MW of hydropower and $240 million in electrolyzers. This would build operational experience toward full-scale implementation by 2035. Full adoption would require $4–5 billion in hydropower reservoirs and $800 million for electrolyzers, but could nearly eliminate all combustion-related CO_2 emissions.

Policy interventions are vital. Three key recommendations include: providing financial incentives to first-mover plants near hydropower hubs to enable pilot demonstrations; offering technical assistance for retrofitting coal kilns, including workforce training; and coordinating hydrogen infrastructure development aligned with current and future plant locations, especially in regions like the Terai, where 58% of clinker plants are concentrated. These approaches are essential to addressing the limitations of Nepal's distributed production system while capitalizing on geographic advantages.

This study is based on national-level modeling assumptions and does not capture plant-level differences or real-time hydropower dynamics. Spatial variations, grid integration challenges, and plant-specific retrofitting costs were beyond its scope. Cost projections assume linear technological progress. Future research should involve pilot-scale demonstrations, dynamic seasonal system modeling, and integration of green hydrogen with CCS and alternative cement chemistries to mitigate residual process emissions[17, 33, 34, 35]. Hybrid strategies combining hydrogen, CCS, and alternative clinker materials offer a promising route to full decarbonization.

In conclusion, the shift to green hydrogen in Nepal's cement industry is technically achievable and environmentally impactful but demands coordinated effort across policy, infrastructure, and industry. By aligning with global climate goals and utilizing its hydropower potential, Nepal can position itself as a leader in low-carbon cement among developing countries. The insights from this study also serve as a reference for other hydropower-rich developing nations aiming to decarbonize hard-to-abate sectors. The pathway is challenging, but with phased execution and focused support, it is within reach.

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