Confederation of Indian Industry

Discussion Paper
on

# GREEN HYDROGEN AS AN ALTERNATIVE FUEL FOR THE INDIAN CEMENT INDUSTRY


## Is Green Hydrogen the Fuel of the Future or a Bridge Too Far?

Version - 1.0

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This paper is intended to provide a knowledge base and practical reference for cement industry stakeholders exploring the potential of green hydrogen for decarbonization. The findings and calculations presented are based on publicly available data, industry estimates, case studies, and assumptions made for illustrative purposes. While we have taken care to present technical insights, actual outcomes may vary depending on site-specific conditions, technology maturity, and future policy and market developments.

This document does not constitute a technical standard, policy directive, or investment advice. Readers are encouraged to independently verify the information and seek expert consultation before making decisions related to hydrogen integration.

CO2
H2
Net zero

# Executive Summary

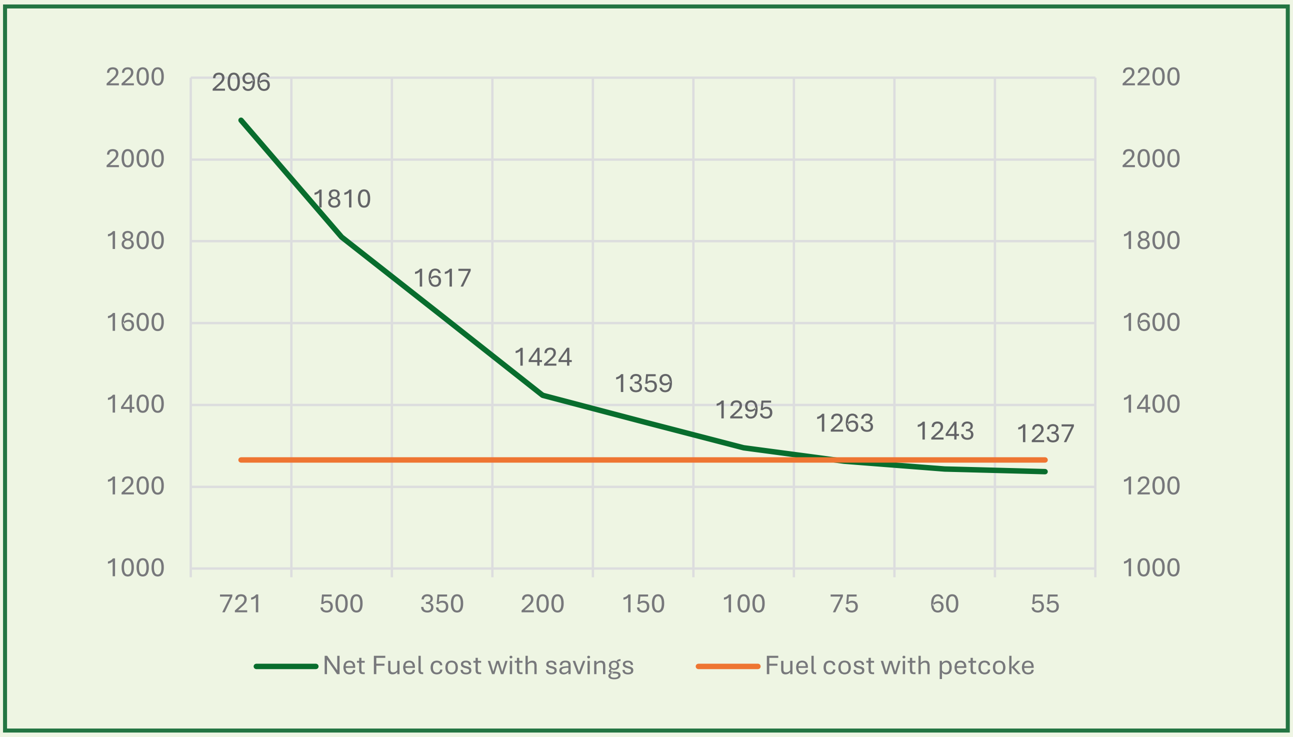
As India sets its sights on achieving Net Zero emissions by 2070, the cement industry, responsible for 7–8% of the country's total $CO_2$ emissions, must play a central role in driving deep decarbonization. The sector, historically reliant on carbon-intensive fuels like Pet-coke and coal, faces growing pressure to adopt cleaner alternatives without compromising on thermal efficiency, reliability, or cost-effectiveness.

This discussion paper explores the transformative potential of Green Hydrogen as a next-generation fuel for cement manufacturing. It begins with an overview of emissions from the Indian cement industry and highlights the urgent need to transition to low-carbon energy sources. The document introduces the fundamentals of green hydrogen, explaining its production routes, energy characteristics, and benefits over conventional fuels.

Using a model 1 million TPA cement plant, the study evaluates the resource requirement involved in Green hydrogen with the substitution ranging from 5% to 35% (focusing on Kiln firing only).

- Green hydrogen requirement is estimated to range from 909 to 6,366 tonnes per annum (TPA).
- The corresponding Electrolyser capacity ranges from 9 to 63 megawatts (MW).
- The power (renewable energy) requirement would range from 152 to 1,061 megawatt-hours per day (MWh/day).
- Water consumption for the required Green Hydrogen quantity ranges from 50 to 345 ($m^3$/day).
- Emission reduction from 5% to 35% Green Hydrogen substitution can lead to a reduction of 10,000 to 75,000 tonnes of $CO_2$ emissions per annum.
- Extension of the mines life as Green Hydrogen combustion produces no ash or fuel-derived oxides, reducing the need for lime to maintain LSF and conserving high-grade limestone. Even 5% hydrogen substitution can extend mine life by approximately 0.5-1 year.
- Enhanced thermal and electrical energy efficiency, driven by cleaner combustion.

There is an approximate 34% increase in fuel cost per tonne of clinker when carbon credits and operational savings are not considered. However, after accounting for carbon credit benefits, increased production capacity, and operational efficiency improvements, the net incremental cost is reduced to around 31% (still on the higher side) compared to the fuel cost using Pet-coke. The paper further presents cost-effective business models for hydrogen supply, including CAPEX, OPEX, and transportation aspects and conducts a cost-benefit analysis comparing hydrogen with Pet-coke. A breakeven assessment underlines the financial thresholds at which hydrogen becomes viable, accounting for carbon pricing scenarios, which says hydrogen becomes competitive if the market price drops to around ₹75-80/kg, i.e., the breakeven point to adopt Green Hydrogen from cost perspective.




***Both the cost is in Rs./Per ton clinker**

*The hydrogen cost referenced herein represents the Levelized Cost of Hydrogen (LCOH), which comprehensively accounts for both capital expenditure (CAPEX) and operational expenditure (OPEX) over the lifecycle of the hydrogen production system

The paper also maps the resource availability of green hydrogen in India versus the estimated requirements under various substitution levels (5% to 100%), highlighting scalability considerations. Finally, it identifies key policy and regulatory interventions, such as fiscal incentives, carbon markets, and infrastructure mandates, necessary to accelerate hydrogen adoption in the cement sector.

The publication concludes by highlighting that even partial substitution with Green Hydrogen offers a strategic pathway for decarbonizing the cement industry. Overcoming key barriers such as the high cost per kilogram of hydrogen, safety concerns, electrolyser efficiency, and the need for supportive policy interventions will be essential for accelerating Green Hydrogen adoption in the Indian cement sector.

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# ACKNOWLEDGEMENT

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We also sincerely acknowledge the valuable contributions of national and international cement technical experts, industry associations, and thought leaders. Their generous inputs, constructive suggestions, and thoughtful deliberations have played a vital role in shaping the content and direction of this paper. The collaborative interactions with sector experts, technology providers, and industry leaders have made this initiative a truly enriching experience for CII.

# 1 Introduction

## 1.1. Overview of Indian Cement Industry emissions w.r.t to India's total emissions

India stands as the second-largest cement producer globally with an installed capacity of ~ 700 million tonnes cement per annum. The Indian cement industry is recognized as the most energy-efficient among major global producers, driven by continuous innovation, adoption of modern technologies, and stringent energy management practices. In 2023, India produced about 375 million tonnes of cement annually, reflecting a robust compound annual growth rate (CAGR) of 6.83%, driven by sustained infrastructure development and urbanization. Cement consumption in India is around 260 kg per capita against a global average of 540 kilograms per capita, which shows significant potential for the growth of the industry.

However, cement production is also inherently carbon intensive. On average, the manufacturing of one tonne of cement results in the emission of approximately 0.62 tonnes of carbon dioxide ($CO_2$), primarily due to the calcination process and fossil fuel combustion in kilns. According to the International Energy Agency (IEA), cement manufacturing is responsible for nearly 8% of global $CO_2$ emissions.

India's $CO_2$ emissions were 3.4 billion tonnes of $CO_2$ annually in 2023, the cement industry alone contributes approximately 0.235 billion tonnes of $CO_2$, highlighting the urgent need for decarbonization strategies within this critical sector.

## 1.2 Need for alternative fuels and deep decarbonization strategies like Green Hydrogen:

India currently spends close to USD 90 billion annually on importing its primary energy requirements, which contribute to 40% of the country's total consumption. Ensuring energy security has become a national priority for India to safeguard the country against global crises and the instability caused by political conflicts like wars. In recent years, India's energy infrastructure has been exposed to significant risks due to factors such as fluctuating fuel prices, disruptions in supply chains, extreme weather conditions, and geopolitical tensions. The COVID-19 pandemic highlighted the vulnerabilities in global supply chains, while conflicts like the Russia-Ukraine war have posed serious threats to the nation's energy security. To safeguard against such disruptions, India has focused on diversifying its energy mix.

India possesses the fourth-largest coal reserves globally, totalling approximately 378.21 billion metric tons as of April 2023 . These reserves are predominantly located in eastern and south-central regions, including Jharkhand, Odisha, and Chhattisgarh. Despite this abundance, the quality of domestic coal is often suboptimal due to high ash content, leading to continued imports, especially of coking coal. To address this challenge and safeguard against future disruptions, India has focused on diversifying its energy mix and investing in sustainable alternatives, with green hydrogen emerging as a key player. Green hydrogen aligns with India's *Panchamrit* commitments by driving decarbonization across critical sectors and improving energy security. Green hydrogen, as a clean energy carrier, plays an essential role in integrating with renewable sources like solar and wind energy, significantly contributing to India's goal of achieving 500 GW of non-fossil energy capacity.

India's pivot towards green hydrogen represents a strategic imperative to enhance energy security, reduce environmental impact, and position itself as a leader in sustainable energy. While implementation challenges remain, the combined push by government and industry reflects a strong resolve to overcome barriers and build a resilient and greener future. As per the recent GCCA Net Zero Roadmap, it is envisaged that the cement industry would increase the share alternative fuels. Further, the low-carbon fuel mix would have a substantial share of green hydrogen which would perhaps become viable beyond 2047.

## 1.3 Brief description of hydrogen - green fuel for cement manufacturing

India is accelerating its transition to a low-carbon economy with a strong focus on clean energy adoption across industries. As part of this effort, the government is promoting alternative fuels like green hydrogen to decarbonize energy-intensive sectors, including cement manufacturing. The launch of the National Green Hydrogen Mission marks a significant step towards reducing reliance on fossil fuels and integrating hydrogen into India's industrial energy mix.

The Indian cement industry, a major contributor to industrial emissions, is proactively exploring hydrogen as a fuel for kilns to cut $CO_2$ emissions and align with sustainability goals. By embracing cleaner energy alternatives and adapting to evolving environmental standards, the sector is positioning itself at the forefront of India's green transition.

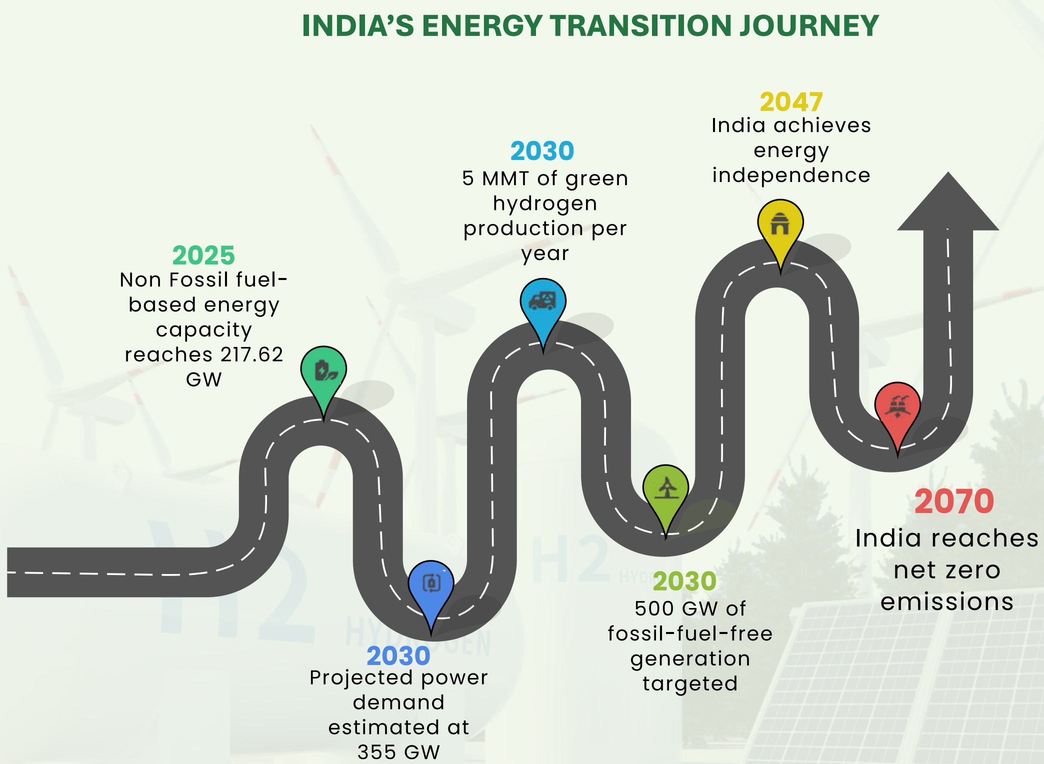



Figure 1: Goals and Targets set by the Ministry of New and Renewable Energy

# 2 GREEN HYDROGEN TERMINOLOGY AND FACTS

## 2.1 Basics of Green Hydrogen- Terminology & Characteristics

- **Green Hydrogen:** Produced via water electrolysis using renewable energy, resulting in no $CO_2$ emissions (Ministry of New & Renewable Energy has decided to define Green Hydrogen as having a well-to-gate emission (i.e., including water treatment, electrolysis, gas purification, drying and compression of hydrogen) of not more than 2 kg $CO_2$ equivalent / kg $H_2$.
- **Yellow hydrogen:** Produced via electrolysis where the electricity powering the electrolysis process, is generated from a mix of renewable and fossil fuels.
- **Pink Hydrogen:** Produced through electrolysis powered by nuclear energy.
- **Blue Hydrogen:** Generated from Methane (Steam Methane Reforming) with carbon capture and storage (CCS) to prevent $CO_2$ release. (1.5-6.2 Kg $CO_2$/Kg of Hydrogen produced)
- **Turquoise Hydrogen:** Produced through methane pyrolysis, which generates solid carbon instead of $CO_2$; currently in experimental stages.
- **Grey Hydrogen:** Created from fossil fuels, particularly natural gas, through steam methane reforming, releasing $CO_2$ into the atmosphere. (10-14 Kg $CO_2$/Kg of Hydrogen produced)
- **Brown or Black Hydrogen:** Derived from coal gasification; both types are highly polluting due to $CO_2$ and carbon monoxide emissions (22-26Kg $CO_2$/Kg of Hydrogen produced)

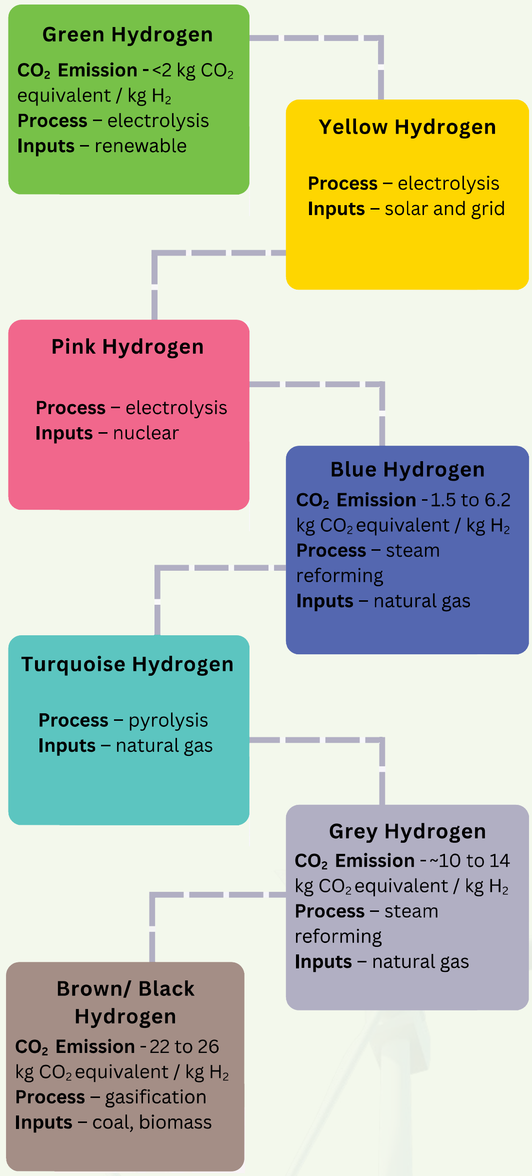


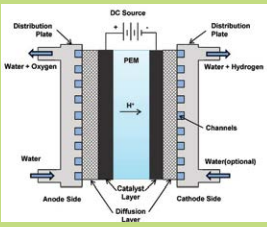

**Figure 2: Types of Hydrogen**

## 2.2 Types of Green Hydrogen Production:

Green hydrogen can be produced through electrolysis. An electrolyser consists of electrodes (an anode and a cathode), separated by an electrolyte that conducts electric current. Electrolysers use different kinds of electrodes, electrolytes, membranes (to separate the gases that are produced, oxygen and hydrogen, while allowing ions to pass through and providing electrical insulation of the electrodes) and catalysts. These determine the efficiency of the electrolysis, the range of current densities and operating temperatures that can be tolerated, and the purity of the gases that are produced.

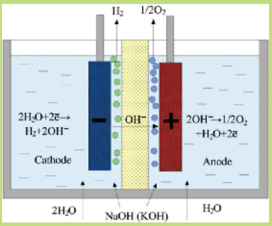
- PEM electrolysers provide high-purity hydrogen and can operate at higher pressures. They are responsive to fluctuations in power supply, making them ideal for integration with renewable energy sources.
- Alkaline electrolysers are well-established, cost-effective, and have a long operational life, making them ideal for large-scale hydrogen production. However, they generally have lower efficiency compared to PEM electrolysers and are less responsive to rapid changes in electricity supply.
- Apart from PEM and alkaline electrolysers, there are other promising technologies for water electrolysis, such as Solid Oxide Electrolysers (SOEC) and Anion Exchange Membrane Electrolysers (AEM). However, both technologies are still in the developmental stages. Solid Oxide Electrolysers (SOEC) operate at high temperatures, offering high efficiency and the potential to utilize waste heat.
- As of now, PEM Electrolysers are considered the best for Green Hydrogen production at an industrial scale because of its fast response, compact design, high purity output, and ability to operate with variable renewable energy.

**PEM ELECTROLYSER**



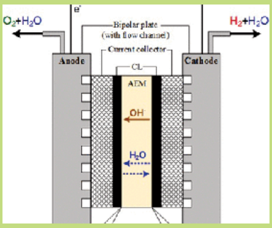

**Electrolyte:** Solid polymer electrolyte (e.g., PFSA membranes)
**Cathode:** Platinum nanoparticles on carbon black
**Anode:** Iridium oxide
**Cation:** Protons ($H^+$)
**Anion:** None (protons move through the membrane)

**ALKALINE ELECTROLYSER**



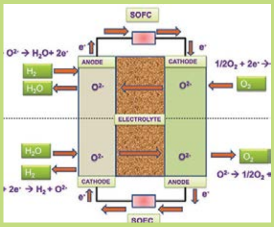

**Electrolyte:** Aqueous potassium hydroxide (NaOH or KOH) solution (5–7 mol/L)
**Cathode:** Nickel-coated perforated stainless steel
**Anode:** Nickel-coated perforated stainless steel
**Cation:** Hydroxide ions ($OH^-$)
**Anion:** Hydroxide ions ($OH^-$)

**AEM ELECTROLYSER**




**Electrolyte:** Aqueous solution of KOH or $NaHCO_3$ (1 mol/L)
**Cathode:** High surface area nickel or NiFeCo alloys
**Anode:** High surface area nickel or NiFeCo alloys
**Cation:** None (anions move through the membrane)
**Anion:** Hydroxide ions ($OH^-$)

**SOEC ELECTROLYSER**




**Electrolyte:** Yttria-stabilized zirconia (YSZ)
**Cathode:** Nickel/YSZ
**Anode:** Perovskite-type (e.g., LSCF, LSM)
**Cation:** Oxygen ions ($O^{2-}$)
**Anion:** None (oxygen ions move through the electrolyte)

**Figure 3: Types of Green Hydrogen Production**

*Source: Electrolyser Diagrams*
1. www.mdpi.com/1996-1073/13/24/6556
2. daninojzf2guidefix.z13.web.core.windows.net/alkaline-water-electrolysis-diagram.html
3. www.researchgate.net/figure/Schematic-drawing-of-the-principle-of-anion-exchange-membrane-AEM-electrolytic-cell_fig1_323023913
4. www.h2-tech.com/articles/2022/q4-2022/special-focus-future-of-hydrogen-energy/solid-oxide-electrolysis-cell-soec-potential-technology-for-low-cost-green-h-sub-2-sub/

**Table 1: Brief Description of Electrolysers**

| Technology | Description | Efficiency | Key advantages | Challenges |
|---|---|---|---|---|
| Proton Exchange Membrane (PEM) electrolysis | Uses a solid polymer electrolyte. | 60-70% | Higher efficiency, More flexible and responsive for fluctuation in RE power supply than alkaline, compact system design | High cost due to noble metal catalysts |
| Alkaline electrolysis | Uses an alkaline solution as the electrolyte. Long-established technology" | 60-65% | Mature technology, relatively low cost | Lower efficiency, slower response to load changes |
| Anion Exchange Membrane (AEM) electrolysis | Uses an anionexchange membrane, combines features of alkaline and PEM electrolysis | 50-60% | Lower cost potential, promising for decentralized systems | Still in development, limited commercial availability |
| Solid Oxide Electrolysis (SOE) | Operated at high temperatures, uses a solid ceramic electrolyte, can integrate with waste heat sources | 80-90% | High efficiency, potential for waste heat recovery | High operational temperature, expensive materials |

## 2.3 General facts of Hydrogen:

- Hydrogen is the first element of the periodic table & most abundant, making up roughly 75% of mass and 90% of atoms in the universe and around 10% of the human body by mass.
- Without hydrogen, we wouldn't have water, and life wouldn't exist.
- Roughly three-quarters of the sun's mass consists of hydrogen. Most stars consist of hydrogen; they shine by nuclear fusion reaction of hydrogen into helium.
- Since Hydrogen is so light, the gas can rise into the sky and escape Earth's gravity.
- Hydrogen does not emit any greenhouse gases at its point-of-use – only water vapor. This makes it an attractive future and low-emission fuel.
- Hydrogen can be used for variety of applications from generating electricity, powering vehicles, refining petroleum and several industrial applications like chemicals, fertiliser, metallurgy etc, but most of them produced from fossil fuels.

- Future hydrogen, especially low-emission hydrogen generation will facilitate clean energy transition (zero emissions), focussing on heavy industry, long distance transport and energy storage.
- Global hydrogen supply reached 97 million tons of $H_2$ in 2023, with China accounting almost 30%, followed by the US and Middle East with 14% each, and India at 9%. Low-emissions hydrogen production has grown marginally and remains under 1 million tons per annum $H_2$, accounting for less than 1% of global production.
- Under Net Zero Emissions 2050 Scenario (NZE Scenario), hydrogen demand reaches close to 150 million tons per annum by 2030, 45% of which is low emission hydrogen (green, pink, yellow).

# 3 OVERVIEW OF RESOURCE REQUIREMENT IN A 1 MILLION TON CEMENT PLANT

# 3. Overview of Sample Cement Plant

To assess hydrogen integration in cement manufacturing, a one-million-ton-per-annum Indian cement plant with a Precalciner Kiln and 5-stage preheater has been used as the base case, as it offers a representative and scalable reference point, allowing plants of varied capacities to extrapolate associated costs, benefits, and operational impacts. The plant currently uses Pet-coke, a high $CO_2$-emitting fuel. Hydrogen, when used in the main burner, provides high flame temperature and heat flux, enhancing sintering and enabling co-firing with alternative fuels. Therefore, hydrogen use is modelled at 35% substitution, equivalent to 100% in kiln firing only, excluding the calciner.

**Table 2: Technical specifications of one-million-ton cement plant**

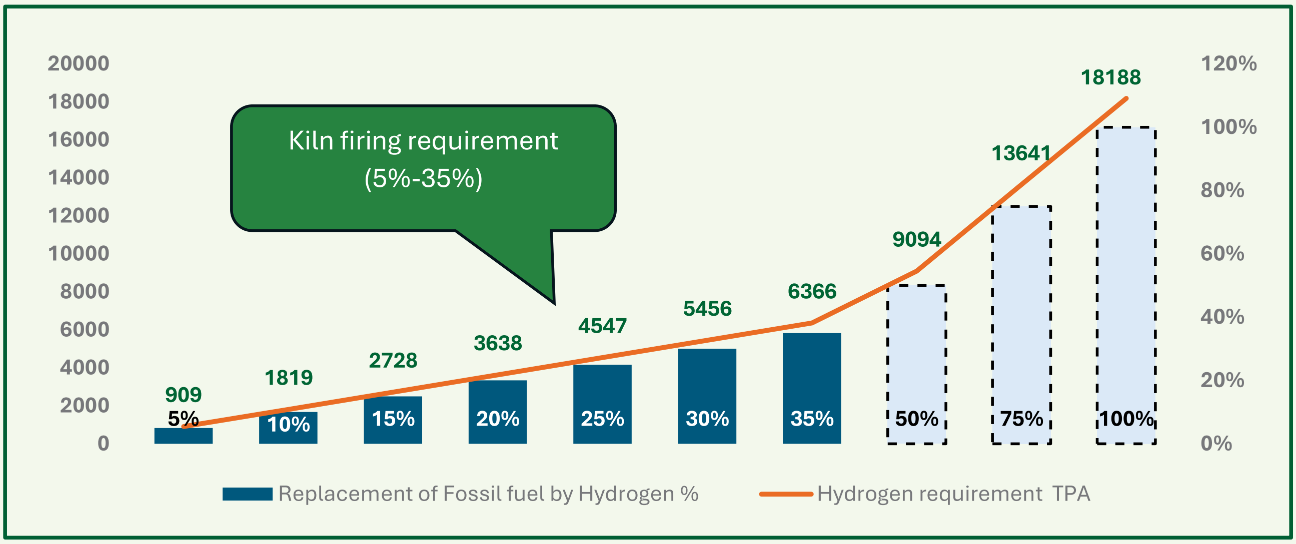
| Parameter | UoM | Value |
|---|---|---|
| Plant Capacity (Cement) | MnTPA | 1 |
| Average Clinker Factor | | 0.71 |
| Clinker Capacity | MnTPA | 0.71 |
| Kiln Type | | Precalciner Kiln (5 Stage) |
| Fuel Type | | Pet-coke |
| TSR% | % | 10% |
| Thermal SEC | kcal/kg clk | 740 |
| Preheater Exit Gas Temp. | deg C | 300-320°C |
| WHR Installed Capacity | MW | 3-3.5 MW |
| NCV of Hydrogen | Kcal/kg | 28,700 |

The following analysis evaluates the hydrogen requirements, associated resources, and input energy demand for this representative model, considering substitution levels ranging from 5% to 35%. The requirements above 35% are also represented in the graph just to have an idea of the volume of resource requirement.

## 3.1 Green Hydrogen Requirement

To replace conventional fuel like Pet-coke in this case, with Green Hydrogen, the estimated requirement for a one MnTPA cement plant varies significantly from 909 TPA to 6,366 TPA with the substitution rate ranging from 5% to 35%. The requirement above 35% are just indicated to visualize the volume requirement.

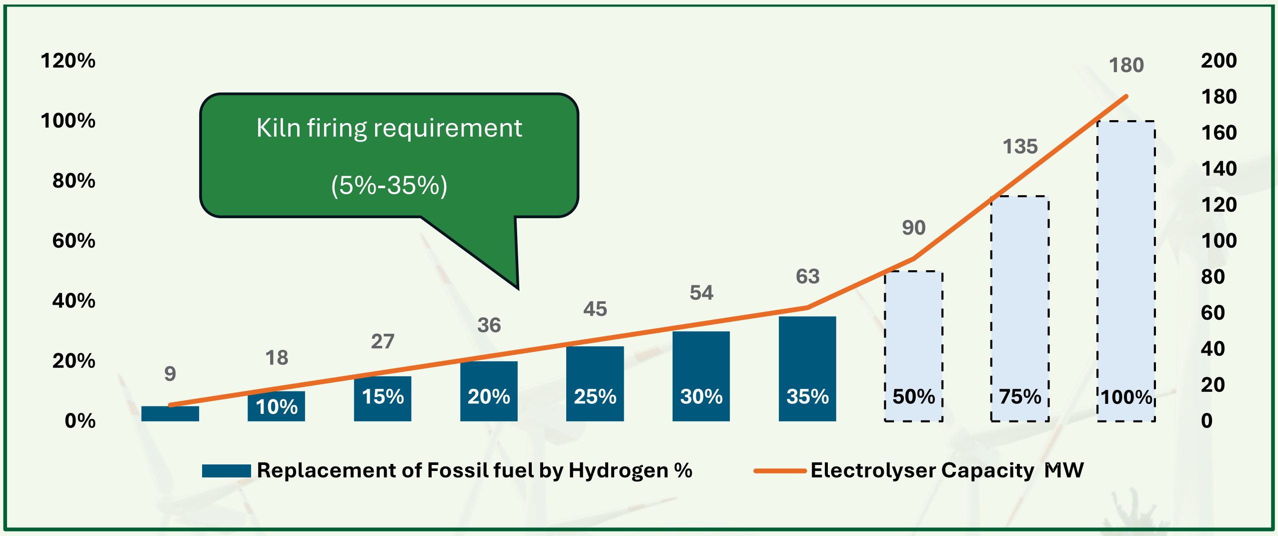
The Hydrogen requirement per ton clinker varies from 1.15 kg to 8 kg, with substitution ranging from 5% to 35%. Whereas with 100% Hydrogen, the value is 23-24 kg per ton of Clinker.




**Graph 1: Hydrogen Requirement**

## 3.2 Electrolyser Capacity

If Green Hydrogen is produced on-site using PEM electrolyser (mentioned in Chapter II), the required electrolyser capacity is determined by the hydrogen demand. Considering ~65% efficiency of a PEM (Proton Exchange Membrane) electrolyser at 50-60 kWh per kg of hydrogen, the required electrolyser size would be in the range of 9-63 MW to produce the needed hydrogen volume with the substitution varying from 5-35%.

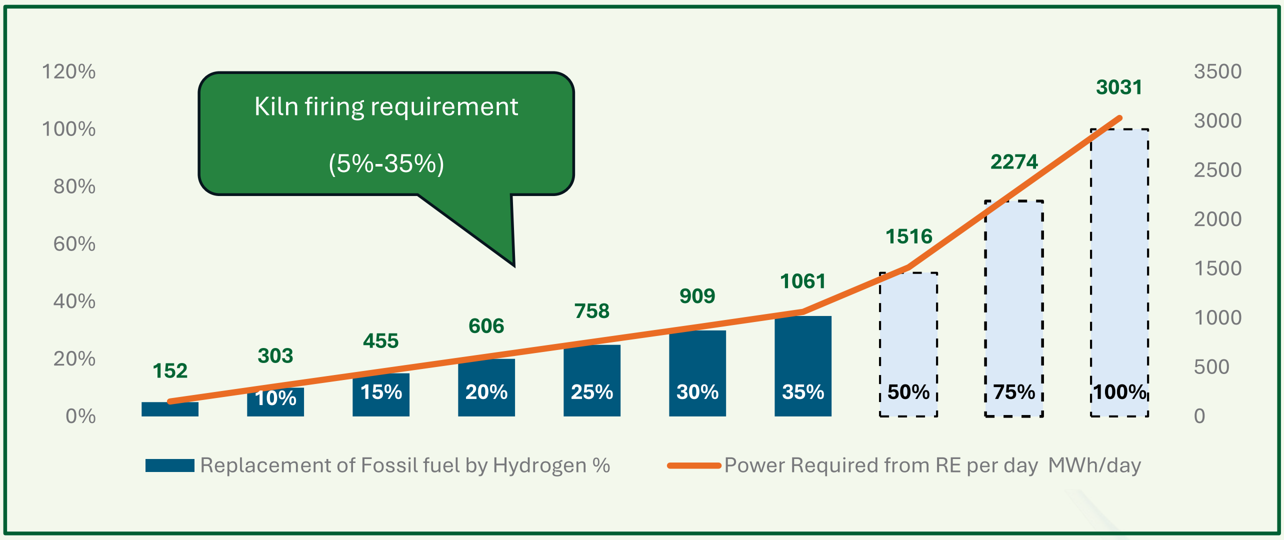



**Graph 2 : Electrolyser Capacity**

## 3.3 Power Requirement from Renewable Energy Source

The power requirement for electrolysis is a critical parameter when assessing the technical and economic feasibility of green hydrogen production. On average, producing 1 kg of hydrogen through electrolysis requires approximately 50-60 kWh of electrical energy, although this can vary slightly depending on the type and efficiency of the electrolyser.

For fossil fuel substitution with hydrogen from 5% to 35%, the total electricity consumption for hydrogen production would range between 152 MWh/day to 1,061 MWh/day. This range also accounts for variations in electrolyser efficiency (typically 70%), system configuration, and operating conditions such as temperature, pressure, and purity requirements.




**Graph 3: RE Power requirement**

Importantly, in the context of green hydrogen, the electricity used for electrolysis is sourced entirely from renewable energy sources, such as solar, or wind. This is what distinguishes green hydrogen from other forms like grey (from natural gas) or blue (with carbon capture). The use of clean, renewable electricity ensures that the hydrogen production process itself is carbon-free, thereby aligning with the broader decarbonization goals of the cement industry and contributing meaningfully to climate action targets. backup systems to ensure stable and continuous hydrogen generation.

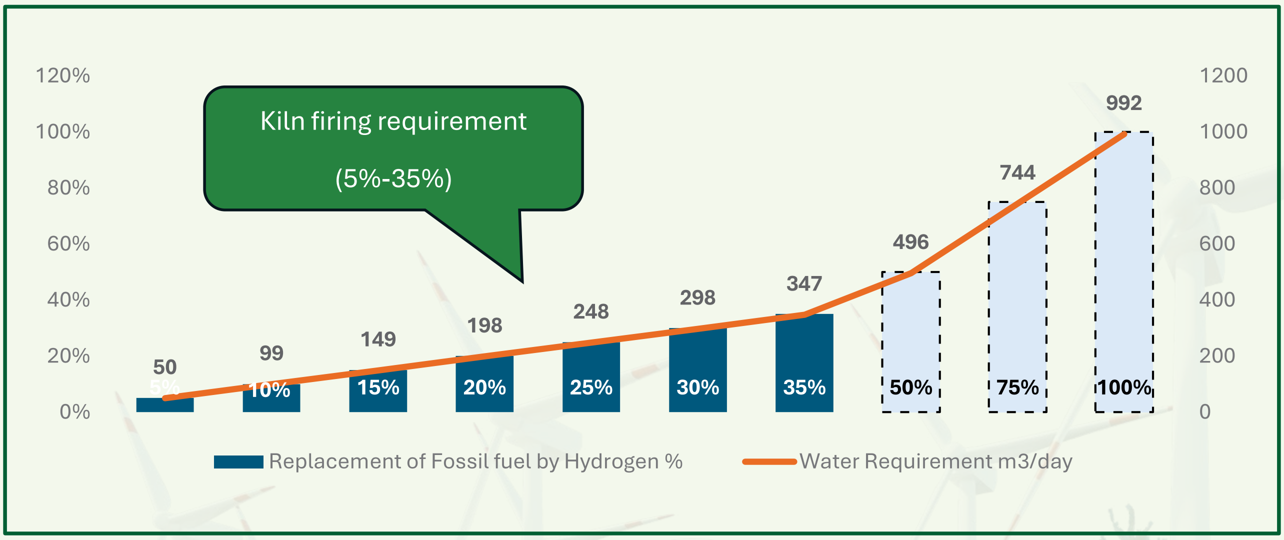
## 3.4 Water Requirement

Water is a critical input for hydrogen production through electrolysis. As cement plants explore the feasibility of integrating on-site green hydrogen generation, understanding the quantity and quality of water required becomes essential for infrastructure planning and sustainability assessment. While fresh water has traditionally been considered the primary input, many modern cement plants now operate with sophisticated water treatment and recycling systems, making treated or reclaimed water a feasible alternative.

Hydrogen production through electrolysis also requires a significant amount of water. The fundamental reaction in electrolysis of water is:

$$2H_2O \rightarrow 2H_2 + O_2$$

Which means 9 litres of water is required for producing 1 kg of Green Hydrogen. It is found that on average, proton exchange membrane (PEM) electrolysis has the lowest water consumption intensity at about 17.5 litres per kilogram of hydrogen (L/kg). Green hydrogen is the most water efficient of all clean hydrogen types. The water requirement for Hydrogen production varies primarily due to differences in purity and treatment efficiency. To produce 1 kg of green hydrogen, approximately 10–12 litres of fresh water are needed, accounting for minor purification losses. If treated water is used instead, the requirement increases to 15–18 litres due to additional treatment and filtration steps.




**Graph 4: Water Requirement**

Although both sources ultimately yield similar amounts of usable water for electrolysis (~9–10 litres/kg $H_2$), the raw water input is higher for treated water in comparison to fresh water to compensate for purification inefficiencies.

The water used in electrolysis must be of very high purity to prevent scaling, membrane fouling, and efficiency losses in the electrolyser. Key specifications include:

- Resistivity: Greater than 1 MΩ-cm at 25°C.
- Conductivity: Less than 1 µS/cm.
- Total Organic Carbon (TOC): Less than 50 ppb.
- Sodium: Less than 5 µg/L.
- Chloride: Less than 3 µg/L.
- Silica: Less than 3 µg/L.

Therefore, on-site hydrogen production for a cement plant requires careful assessment of energy, water availability, and electrolyser capacity. While hydrogen as a fuel presents an opportunity for deep decarbonization, infrastructure investment and operational challenges must be addressed for seamless integration into cement manufacturing.

# 4 IMPACT OF GREEN HYDROGEN ON CEMENT MANUFACTURING

# 4. Impact of Hydrogen on Cement Manufacturing

The integration of hydrogen as an alternative fuel in cement manufacturing signifies a fundamental shift in the way energy is utilized within the kiln system, bringing new dynamics to combustion, process efficiency, and emissions control. Unlike conventional fossil fuels, hydrogen possesses unique combustion properties such as a higher flame temperature and faster reaction kinetics which fundamentally influence the heat distribution and thermal profile inside the kiln. These altered thermodynamic conditions can lead to enhanced combustion efficiency and more uniform heat transfer.

Furthermore, the use of hydrogen contributes to a significant reduction in carbon emissions, aligning with the industry's decarbonization goals. This shift also opens opportunities to optimize the process parameters of the pyro system. With lower flue gas volumes and modified heat loads, these systems can be recalibrated to improve their energy efficiency and reduce overall power consumption. In essence, hydrogen not only serves as a clean energy source but also catalyses a broader optimization of the cement production process.

## 4.1 Carbon Emissions reduction

The cement industry is one of the largest industrial emitters of $CO_2$, primarily due to the process emission (calcination) and combustion of carbon-rich fuels like coal and Pet-coke. With India committed to reducing emissions intensity under its NDCs (Nationally Determined Contributions), introducing hydrogen, a carbon-free fuel, offers a transformative path. Substituting a portion of fossil fuel energy with green hydrogen (produced by electrolysis and renewable energy being the source of input power) can significantly reduce the Fuel emissions in (Scope-1 direct emissions) without compromising production efficiency.

**Table 3: Output (Only Scope-1 emissions)**

| Fuel Type | $CO_2$ Emission Factor ($kg\ CO_2/kcal$) | NCV (kcal/kg) | $CO_2$ Emission (kg/kg fuel) |
|---|---|---|---|
| Pet-coke | 0.418 | 7,632 | 3.19 |
| Coal | 0.396 | 5,145 | 2.04 |
| Hydrogen | 0 | 28,700 | 0.00 |

Hydrogen, when combusted, generates only water vapor. Thus, its emission factor is zero, offering significant abatement potential when substituted for carbon-based fuels.

Emission Reduction Calculation – 5% Hydrogen Substitution

**Table 4 : Input Data (Emission Calculation)**

| S. No | Description | UoM | Present Scenario | With 5% $H_2$ substitution |
|---|---|---|---|---|
| 1 | Cement Production | MnTPA | 1 | 1 |
| 2 | Clinker Production | TPD | 2,138 | 2,138 |
| 3 | Clinker factor | - | 0.71 | 0.71 |
| 4 | Electrical SEC | kWh/MT cem | 70.0 | 70.0 |
| 5 | SEC of an electrolyser (powered by Renewable source of energy) | kWh/MT cem | - | 50.0 |
| 6 | Thermal SEC | kcal/kg clk | 740 | 740 |
| 7 | Fossil Fuel % | % | 90% | 85% |
| 8 | AFR% (incl. biomass) | % | 10% | 10% |
| **9** | **Green Hydrogen** | **%** | **0%** | **5%** |
| 10 | WHR | % | 30% | 30% |
| 11 | RE | % | 10% | 10% |
| 12 | Grid | % | 10% | 10% |
| 13 | Own Generation | % | 50% | 50% |
| 14 | Fuel (Pet-coke) NCV | kcal/kg | 7,632 | 7,632 |
| 15 | Fuel (Pet-coke) Requirement | TPD | 187 | 176 |

**Table 5: Output Table (Only Scope-1 emissions)**

| Emissions | UoM | With 90% Pet-coke & 10% AFR | | With 85% Pet-coke, 10% AFR & 5% Hydrogen | |
|---|---|---|---|---|---|
| Scope-1 | | Absolute emissions (MT) | GEI (MT $CO_2$/MT cem) | Absolute emissions (MT) | GEI (MT $CO_2$/MT cem) |
| Fuel emissions | MT $CO_2$ | 1,86,039 | 0.187 | 1,75,704 | 0.177 |
| Emission reduction with 5% $H_2$ substitution | MT $CO_2$ | 10,336 | | | |

For every 5% substitution of fossil fuel energy with hydrogen in the cement kiln, the GEI i.e. greenhouse gas emission intensity reduces by approximately 6%, offering a measurable and scalable pathway towards deep decarbonisation in the cement sector.

**Cumulative Emission Reduction Potential for the Indian Cement Industry (~ 375 MnTPA actual production capacity)**

Assuming 10% of total cement production (375 MnTPA capacity) adopts 5% hydrogen substitution:

**Potential $CO_2$ reduction: (0.187-0.177) × (37.5 MnTPA) = 3,75,000 TPA $CO_2$**

Hydrogen offers a direct route to significant carbon emissions abatement in cement production. Even a modest 5% substitution delivers meaningful results, and larger substitutions can catalyse a shift towards deep decarbonisation. Beyond direct $CO_2$ reductions from fuel combustion, hydrogen substitution also reduces the need for coal mining and long-distance fossil fuel transportation, thereby curbing indirect emissions across the value chain. As hydrogen becomes more accessible and cost-competitive, its role in the cement industry will be pivotal in achieving India's 2070 net zero commitment.

## 4.2 Extended mines life due to lower ash and LSF requirement

Substituting fossil fuels like coal or Pet-coke with hydrogen in cement kilns not only leads to a significant reduction in greenhouse gas and pollutant emissions but also plays a vital role in conserving raw materials, particularly limestone by reducing the ash burden on the kiln system.

### Reduction in Ash Content from Fuel

Fossil fuels such as Indian coal, Pet-coke, or imported coal typically contain a non-combustible ash fraction. For example:

- Indian coal may contain up to 30–40% ash, while
- Pet-coke, though lower in ash (~1–2%), still adds solid residues to the clinker mix.

This ash content contributes to the total oxide mix in the kiln feed, particularly $SiO_2$, $Al_2O_3$, and $Fe_2O_3$, impacting the raw mix design. To maintain the desired Lime Saturation Factor (LSF) and burnability of the clinker, higher proportions of CaO (from limestone) are required to compensate for the fuel-derived oxides.

**However, hydrogen combustion produces only water vapor and no ash, meaning:**

- There is no contribution of fuel-derived oxides from hydrogen.
- As a result, the raw mix requires less limestone to balance the LSF.

So, when hydrogen is used as a fuel (even at a 5% thermal substitution rate), upon combustion adds no ash or oxides. As a result, the contribution of oxides from the fuel side drops by about 5-6%, thereby reducing the need for lime (CaO) from limestone to maintain the same Lime Saturation Factor (LSF) in clinker production. Consequently, the limestone requirement per ton of clinker is reduced.

**Table 6: Reduction in total oxides from fuel**

| Sp. Heat Consumption | kcal/kg clk | 740 | | | | | |
|---|---|---|---|---|---|---|---|
| **Fuel Type** | **UoM** | **Fuel Mix %** | **Ash%** | **kg ash/ MT clk** | **$SiO_2$ in Ash** | **$Al_2O_3$ in Ash** | **Total oxides from fuel** |
| **Present scenario** | | | | | | | |
| Pet-coke | % | 60% | 1.9 | 1.11 | 25% | 10% | 0.39 |
| Indian Coal | % | 10% | 42.8 | 7.25 | 55% | 30% | 6.16 |
| Imported Coal | % | 20% | 21.7 | 5.23 | 40% | 20% | 3.14 |
| MSW/RDF/ Plastic | % | 9% | 30.6 | 8.96 | 40% | 20% | 5.37 |
| Biomass | % | 1% | 16.7 | 0.42 | 50% | 10% | 0.25 |
| | | | | | | | **15.32** |
| **with 5% $H_2$ substitution** | | | | | | | |
| Pet-coke | % | 57% | 1.9 | 1.04 | 25% | 10% | 0.37 |
| Indian Coal | % | 9% | 42.8 | 6.85 | 55% | 30% | 5.82 |
| Imported Coal | % | 19% | 21.7 | 4.94 | 40% | 20% | 2.97 |
| MSW/RDF/ Plastic | % | 9% | 30.6 | 8.96 | 40% | 20% | 5.37 |
| Biomass | % | 1% | 16.7 | 0.42 | 50% | 10% | 0.25 |
| Hydrogen | % | 5% | 0.0 | 0.00 | 0% | 0% | 0.00 |
| | | | | | | | **14.78** |

**Reduction in oxides from fuel is: (15.32-14.78)/15.32% = 3.5 %**

**In case of 100% Pet-coke usage, the reduction in oxides from fuel is less i.e. 0.5%, as the ash content in Pet-coke is very less compared to Coal.**

**For a specific case, considering the following:**

- Clinker production: 3,000 TPD
- Standard limestone consumption: 1.52 tons per ton of clinker
- Ash oxide absorption reduction: 3.5%
- CaO content in limestone: 45%

**Current Limestone Requirement: 3,000 TPD ×1.52 = 4,560 TPD**

Impact of 3.5% reduction in oxide absorption with 5% $H_2$ substitution: 3.5% reduction in absorbed oxides implies ~3.5% lesser CaO needed to maintain same LSF, hence:

Reduction in CaO requirement= **3.5% * 4560 TPD * 45% = 72 TPD**

Hence, Limestone saved per day = **72 TPD/45% = 160 TPD**

Considering 330 days of Kiln operation, Limestone saved per year = **160 TPD * 330 days = 52,891 TPA**

**Let's say the Mines have a Limestone reserve of 100 MnT,**

Table 7: Extension of mines life

| Description | UoM | Present Scenario | With 5% $H_2$ substitution |
|---|---|---|---|
| LS to Clinker Factor | | 1.52 | 1.47 |
| Kiln operation days in a year | days | 330 | 330 |
| Clinker Production | TPD | 3,000 | 3,000 |
| Say the LS Reserve is of | MnT | 100 | 100 |
| LS Consumption before Hydrogen substitution | MnTPA | 1.50 | 1.45 |
| Mines Life | yrs | 66.45 | 68.87 |
| Increase in mines life with 5% substitution | yrs | 2.42 | |
| Increase in mines life with 1% substitution | yrs | 0.48 | |
| | months | ~6 | |

**So, for every 1% $H_2$ substitution, there will be an extension of the mines life by ~ 6 months**

- The substitution of fossil fuels like coal and Pet-coke with hydrogen in cement kilns significantly reduces the ash and sulphur load introduced from the fuel side. This leads to a lower absorption of fuel-derived oxides in the clinker, especially sulphur trioxide ($SO_3$) and other acidic oxides, which would otherwise consume lime (CaO) during clinker formation. With green hydrogen contributing no ash or sulphur, the lime requirement to maintain the same Lime Saturation Factor (LSF) decreases by approximately 1% with every percentage of $H_2$ substitution.
- This reduction translates into a direct decrease in high grade limestone consumption per ton of clinker. Over time, this seemingly small percentage has a compounding effect, conserving large volumes of high-grade limestone and extending the operational life of captive mines. In India, where limestone availability is under increasing pressure, this conservation is both economically and environmentally strategic. Thus, hydrogen substitution not only decarbonizes the fuel mix but also enhances the long-term sustainability of raw material resources critical to cement manufacturing.

## 4.3 Impact on Specific Volume of Flue Gas

One of the most direct impacts of hydrogen combustion is the reduction in the specific volume of flue gas generated per kg of fuel/clinker. Unlike carbon-based fuels, which produce $CO_2$ as the main by-product, hydrogen combustion yields only water vapor. Consequently, for every unit of energy supplied, the mass and volume of flue gases decreases—typically by 1-2% depending on the substitution percentage.

**Table 8: Theoretical Air requirement of Fossil fuels, Alternative fuel & Hydrogen**

| Element / Description | Unit | Pet coke Indian | Indian Coal - B grade | Indian Coal - C grade | Imported Coal | Solid Waste | Biomass | Green Hydrogen |
|---|---|---|---|---|---|---|---|---|
| Carbon | % | 83.15 | 54.80 | 47.20 | 67.12 | 31.00 | 33.95 | |
| Hydrogen | % | 3.43 | 3.80 | 3.30 | 3.95 | 2.01 | 5.01 | 100 |
| Oxygen | % | 2.67 | 5.46 | 6.37 | 6.80 | 16.35 | 32.52 | |
| Sulphur | % | 8.85 | 0.70 | 0.30 | 0.48 | 0.08 | 0.09 | |
| Moisture | % | 0.00 | 0.00 | 0.00 | 0.00 | 20.00 | 10.80 | |
| Ash | % | 1.90 | 35.24 | 42.83 | 21.65 | 30.56 | 16.73 | |
| NCV | kcal/ kg | 7,632 | 5,145 | 4,371 | 6,123 | 2,272 | 2,952 | 28,700 |
| Theoretical Air requirement | kg/kg fuel | 10.91 | 7.79 | 6.73 | 9.18 | 4.51 | 4.89 | 34.48 |
| | $Nm^3$/1000 kcal | 1.11 | 1.17 | 1.19 | 1.16 | 1.54 | 1.28 | 0.93 |
| | $Nm^3$/kg fuel | 8.44 | 6.02 | 5.21 | 7.10 | 3.49 | 3.78 | 26.67 |

Here's a comparative analysis of three typical fuel mix scenarios in Indian cement plants with and without 5% hydrogen substitution.

**Table 9: Three Scenarios of different fuel mix**

| Description | Case-1 | | Case-2 | | Case-3 | |
|---|---|---|---|---|---|---|
| | Mixed Coal with 10% AFR | | Pet-coke with 10% AFR | | Pet-coke with no AFR | |
| | Present | With 5% $H_2$ substitution | Present | With 5% $H_2$ substitution | Present | With 5% $H_2$ substitution |
| Hydrogen | 0% | 5% | 0% | 5% | 0% | 5% |
| Pet-coke | 60% | 57% | 90% | 85% | 100% | 95% |
| Indian Coal | 10% | 9% | 0% | 0% | 0% | 0% |
| Imported Coal | 20% | 19% | 0% | 0% | 0% | 0% |
| Solid Waste | 9% | 9% | 9% | 9% | 0% | 0% |
| Biomass | 1% | 1% | 1% | 1% | 0% | 0% |
| PH Heater Gas Volume ($Nm^3$/ kg clk) | 1.59 | 1.58 | 1.62 | 1.60 | 1.58 | 1.56 |
| Reduction in Sp. Gas volume (%) | 0.9 | | 1.1 | | 1.1 | |

At low substitution levels (e.g., ~5-10%), the reduction in $CO_2$ outweighs the increase in $H_2O$:Net flue gas volume decreases slightly (typically 0.9–1.1% reduction) At higher substitution levels (>20–30%), the rising water vapor may: potentially increasing total flue gas volume and moisture load.

The influence of hydrogen combustion on flue gas composition, particularly the increased generation of water vapor, necessitates further investigation. Elevated $H_2O$ concentrations may induce localized quenching or cold zones within the kiln, potentially affecting clinker formation and thermal efficiency. Comprehensive assessment through pilot-scale trials is recommended to quantify and mitigate these effects.

### 4.3.1. Impact on Production:

In Indian cement plants, the major process fans like preheater fan and main bag house fan are typically sized based on a design-specific gas volume ($Nm^3$/kg clinker). With conventional high-carbon fossil fuels like Pet-coke, the specific flue gas volume often ranges from 1.55-1.65 $Nm^3$/kg clinker, which pushes the preheater and fan system to their volumetric limits.

Substituting even 5% of fossil fuel thermal input with Hydrogen, which produces only water vapor without $CO_2$, results in a measurable reduction in the specific gas flow by 0.9–1.1%. This directly alleviates the volumetric stress on preheater cyclones, riser ducts, and ID fans, reducing static pressure drop and enabling higher feed rates.

This improved gas handling margin allows for a clinker production increase of 25-35 TPD in a typical 3,000 TPD kiln line without modifications to mechanical components.

However, at higher substitution levels (>20–30%), the proportion of water vapor in the flue gas increases significantly, which may offset the gains from $CO_2$ reduction and lead to an overall increase in flue gas volume and moisture content. This could impact kiln heat balance, fan load and dew point behavior. Therefore, the implications of higher hydrogen substitution on production capacity, system stability, and thermal efficiency must be thoroughly assessed through detailed modeling and pilot-scale validation before large-scale implementation."

**Increase in Production (TPD)**

| Description | Case-1 | | Case-2 | | Case-3 | |
|---|---|---|---|---|---|---|
| | Mixed Coal with 10% AFR | | Pet-coke with 10% AFR | | Pet-coke with no AFR | |
| | Present | With 5% $H_2$ substitution | Present | With 5% $H_2$ substitution | Present | With 5% $H_2$ substitution |
| PH Heater Gas Volume | 1.59 | 1.58 | 1.62 | 1.60 | 1.58 | 1.56 |
| Clinker TPD | 3,000 | 3,028 | 3,000 | 3,034 | 3,000 | 3,035 |
| Increase in TPD | 28 | | 34 | | 35 | |

### 4.3.2. Reduction in Electrical SEC (kWh/MT clinker):

Reduction in the flue gas volume due to hydrogen substitution directly impacts the power consumption of process fans, particularly the preheater ID fan and main bag house fan. These fans typically handle large volumes of hot gases and are major consumers of electrical energy in cement plants.

**Reduction in Electrical SEC (kWh/MT clk)**

| Description | Case-1 | | Case-2 | | Case-3 | |
|---|---|---|---|---|---|---|
| | Mixed Coal with 10% AFR | | Pet-coke with 10% AFR | | Pet-coke with no AFR | |
| | Present | With 5% $H_2$ substitution | Present | With 5% $H_2$ substitution | Present | With 5% $H_2$ substitution |
| PH Gas Volume ($Nm^3$/kg clk) | 1.59 | 1.58 | 1.62 | 1.60 | 1.58 | 1.56 |
| Considering average PH Fan efficiency | 0.9% | | 1.1% | | 1.1% | |
| PH Fan SEC (kWh/MT clk) | 6.50 | 6.44 | 6.50 | 6.43 | 6.50 | 6.43 |
| Reduction in PH Fan SEC (kWh/MT clk) | 0.06 | | 0.07 | | 0.07 | |
| Main Bag House Fan SEC (kWh/MT clk) | 2.00 | 1.98 | 2.00 | 1.98 | 2.00 | 1.98 |
| Reduction in B/H Fan SEC (kWh/MT clk) | 0.02 | | 0.02 | | 0.02 | |

**Additionally, the coal mill power reduces due to a lower requirement for grinding Pet-coke or coal.**

**Table 10: Reduction in Coal Mill Electrical SEC**

| Description | UoM | Values |
|---|---|---|
| Clinker Production per day | TPD | 3,000 |
| Thermal SEC | kcal/kg clk | 740 |
| Average TSR% | % | 10% |
| Fossil Fuel | % | 90% |
| Hydrogen | % | 0% |
| Fuel (Pet-coke) NCV | kcal/kg | 7,632 |
| Fuel (Pet-coke) Requirement | TPD | 262 |
| Fossil Fuel (Pet-coke with 5% Hydrogen substitution) | % | 85% |

| | | |
|---|---|---|
| Fuel (Pet-coke) Requirement | TPD | 247 |
| Reduction in Fuel Requirement | TPD | 15 |
| Coal Mill SEC (Considering 45 kWh/MT mat as average) | kWh/MT mat | 45 |
| Power saved for reduced Pet-coke quantity | kWh/day | 655 |
| Electrical SEC saved | kWh/MT clk | 0.22 |

**For every 1 tonne reduction in Pet-coke grinding per day, the overall power consumption reduces by approximately 0.22 kWh per tonne of clinker.**

### 4.3.3. Improved Thermal efficiency:

When hydrogen is used as a partial replacement fuel in the cement kiln, it offers distinct thermal advantages due to its unique combustion characteristics. Hydrogen burns at a significantly higher flame temperature compared to conventional fossil fuels like coal or Pet-coke. This high flame temperature contributes to an increased heat flux within the kiln, which enhances the transfer of thermal energy to the raw meal. As a result, the sintering reactions particularly the formation of clinker phases such as alite can be accelerated. This could potentially lead to improvements in kiln throughput and overall production capacity. However, the impact on clinker quality, kiln refractory life, and heat distribution must be thoroughly assessed through further trials and process modelling before full-scale adoption. These effects translate into reduction in thermal SEC .

In water electrolysis technologies, there is potential for generating oxygen as a by-product. This oxygen can be partially used to replace combustion air, significantly reducing the specific flue gas volume by lowering nitrogen content in the preheater exhaust. This presents a promising opportunity for debottlenecking and increasing the throughput of cement kilns, but further detailed assessment is required before concluding on this.

**PH Fan SEC Reduction**

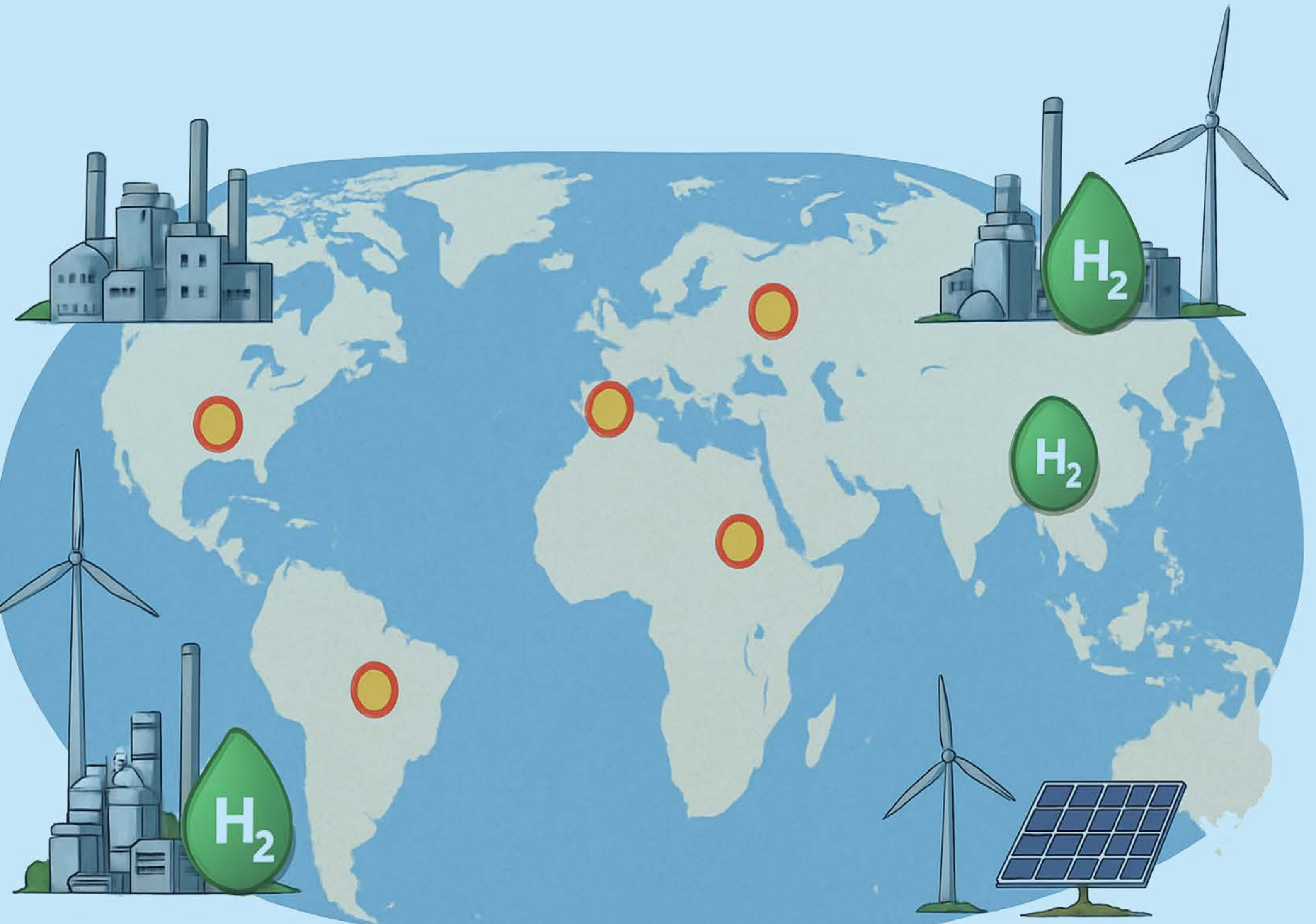
| Description | UoM | Present | With 5% $H_2$ Substitution |
|---|---|---|---|
| PH Gas Volume | $Nm^3$/kg clk | 1.62 | 1.60 |
| Average PH Exit temp of 5 Stage PH | deg C | 310 | 307 |
| Exhaust Heat Loss | kcal/kg clk | 174 | 171 |
| Savings in Thermal SEC | kcal/kg clk | 3 | |

**Table 11: Impacts of Green Hydrogen in Cement Manufacturing**

| S. No. | Description | Positive Lever | Negative Lever | Thumb rule / correlation needed |
|---|---|---|---|---|
| 1 | Carbon emission | Fuel emission, coal handling, coal transportation | Water footprint, power source for hydrogen | Carbon emission reduction by 0.01 to 0.08 MT $CO_2$ per MT cement |
| 2 | Production | Increase in production capacity as the specific PH gas volume will be low, Higher $C_3S$ due to better flame | Impact of refractory to be studied | |
| 3 | Mines Life | Extended mines life due to lower ash and LSF requirement | Training and infrastructure to analyse, handle gas analysis, sampling | For every 1% $H_2$ substitution, there will be an extension of mines life by 0.5 to 1 year. |
| **Energy Consumption** | | | | |
| 4 | Electrical | SEC Reduction in PH fan | SEC for hydrogen production, Additional MD for hydrogen | For every 5% $H_2$ substitution, there will be reduction in E. SEC by 0.05-0.07 kWh/MT clk |
| 5 | | SEC Reduction in RABH fan | Land for RE | For every 5% $H_2$ substitution, there will be reduction in E. SEC by 0.02 kWh/MT clk |
| 6 | | Coal mill SEC - Reduction | Process fans MOC/ Parameter impact | For every 5% $H_2$ substitution, there will be reduction in E. SEC by 0.2 kWh/MT clk |
| 7 | Thermal | Reduction in gas volume | Impact on WHR generation | For every 5% $H_2$ substitution, there will be reduction in T.SEC by 2 kcal/kg clk & WHRS generation will be affected by 1-1.4% |
| 8 | | Improvement in heat transfer in PH | Change in cooler design | |
| 9 | | Coal mills heat requirement | Burner change | |

| | | | | |
|---|---|---|---|---|
| **Environment** | | | | |
| 10 | Water | Rainwater can be used as source, mines | Increase in specific water consumption | |
| 11 | Emission | Reduction in fugitive emission due to lesser / No coal handling | There will not be any fuel NOX. However higher adiabatic flame temperature can lead to thermal NOX. Possibility of CO may also exist due to slower heat transfer to raw meal and longer temperature profile in kiln. | |
| 12 | Bag filter / duct / APC | lower bag filter size, better efficiency due to water vapor | Higher dew point temperature, corrosion | |
| **Finance, Social, Safety** | | | | |
| 13 | Finance | Reduction in coal handling, coal mill operating cost including inventory | Hydrogen generation and handling - Capex | Capex- ₹ 45-55 Cr./ per MW of electrolyser capacity OPEX- ₹ 350-400 per kg $H_2$ |
| 14 | Social | Manpower engaged in Coal transportation, handling, coal handling circuit | Skilled manpower needed for producing, handling hydrogen - including safety | |
| 15 | Safety | | Higher risks with hydrogen production, storage, handling, feeding and safety. Hydrogen is highly explosive in nature | |
| 16 | Infrastructure | Lesser space for storage and handling | Additional infrastructure, equipment for hydrogen | |
| 17 | Insurance/ Risk | | Insurance and other liabilities with respect to gas handling instead of solid fuel | |

# 5 GLOBAL TRIALS OF HYDROGEN



# 5. Global Trials of Green Hydrogen

### Experiences/ Trials on Hydrogen usage in cement plants across the Globe

As the global cement industry accelerates its journey towards decarbonization, hydrogen has emerged as a promising clean energy vector capable of replacing fossil fuels in high-temperature processes. Among various alternative fuels, green hydrogen produced using renewable electricity offers a long-term solution due to its zero-carbon emissions profile. Over the last few years, a few demonstration projects and trials have been conducted across cement plants globally to assess the technical feasibility of hydrogen as a fuel source.

This chapter highlights key trials conducted by cement manufacturers and provides insights into the outcomes, challenges, and potential of hydrogen use as an alternative fuel in cement kilns.

### 5.1 Ribblesdale plant of Hanson UK (a HeidelbergCement subsidiary)

A cement kiln at the Ribblesdale plant of Hanson UK (a Heidelberg Cement subsidiary) has been successfully operated using a 100% net zero fuel mix in a world-first hydrogen-based trial for commercial-scale cement production.

- **First-of-its-kind Trial:** Successfully operated a cement kiln using a 100% climate-neutral fuel mix, including hydrogen, biomass (meat & bone meal), and glycerine.
- **Fuel Mix Composition:** Approximately 39% hydrogen, 12% meat and bone meal (MBM), and 49% glycerine.
- **Emission Reduction Potential:** If applied across the entire kiln system, it could eliminate up to 180,000 tonnes of $CO_2$ emissions annually at Ribblesdale.
- **Part of a £3.2 Million Project:** The trial builds on a 2019 BEIS-funded feasibility study that showed complete fossil fuel replacement is possible using hydrogen, biomass, and plasma.
- **Technology Demonstration Scope:** Used grey hydrogen for the trial, with potential to switch to green hydrogen in future applications.

### 5.2 Cemex Ventures

Cemex Ventures, the corporate venture arm of Cemex, has initiated its first industrial-scale deployment of hydrogen at the Rugby cement plant in the UK, in partnership with British hydrogen innovator HiiROC. Cemex Ventures, announced hydrogen deployment at industrial scale with HiiROC, the British hydrogen company that produces affordable, clean hydrogen, at its Rugby cement plant in the United Kingdom.

HiiROC produces carbon-neutral hydrogen using its proprietary Thermal Plasma Electrolysis (TPE) process, which requires just one-fifth of the electrical energy used in water electrolysis and captures carbon as a solid byproduct, avoiding $CO_2$ emissions. HiiROC's modular solution can be deployed as single units to full-scale industrial plants.

- **Hydrogen Deployment Initiated:** Cemex has launched its first industrial-scale hydrogen project at its Rugby plant, in collaboration with HiiROC.

**Technology Used – Thermal Plasma Electrolysis (TPE):**

- HiiROC's proprietary TPE process produces carbon-neutral hydrogen, using 80% less electricity than water electrolysis.
- The process captures carbon in solid form, eliminating $CO_2$ emissions.

**Strategic Importance:**

- Hydrogen will be used to fuel the clinker production process, replacing fossil fuels.
- Marks a significant step toward Cemex's net-zero target by 2050.
- Modular & Scalable: HiiROC's technology is modular—scalable from small units to full industrial plants.

**Long-Term Partnership:**

- Partnership began in 2021 with Cemex's initial investment in HiiROC.
- In 2023, Cemex increased its stake to boost hydrogen capabilities at the Rugby site

### 5.3 Titan Cement

TITAN Cement Group, a Greek based company launched a H2CEM, to use green hydrogen as climate-neutral fuel to further lower the carbon footprint of cement production. The project will contribute to TITAN Group's target to improve the carbon footprint of its operations, supporting the European goal for 55% greenhouse gas emissions reduction by 2030 and carbon neutrality by 2050.

- **Emission Reduction:** Targeted $CO_2$ reduction of 160,000 tons per year, equivalent to at least 8% per ton of cement produced.
- **Pilot Rotary Kiln:** Development and operation of a pilot-scale kiln specifically designed to run primarily on hydrogen fuel for clinker production.
- **Research & Development:** The project aims to address the technical challenges of hydrogen combustion, contributing critical knowledge for future hydrogen-based cement plant designs.
- **Strategic Importance:** H2CEM is a milestone project on Europe's decarbonization roadmap for the cement industry, pushing forward climate-neutral cement manufacturing technologies.

**As concluded by one of the European cement plants:**

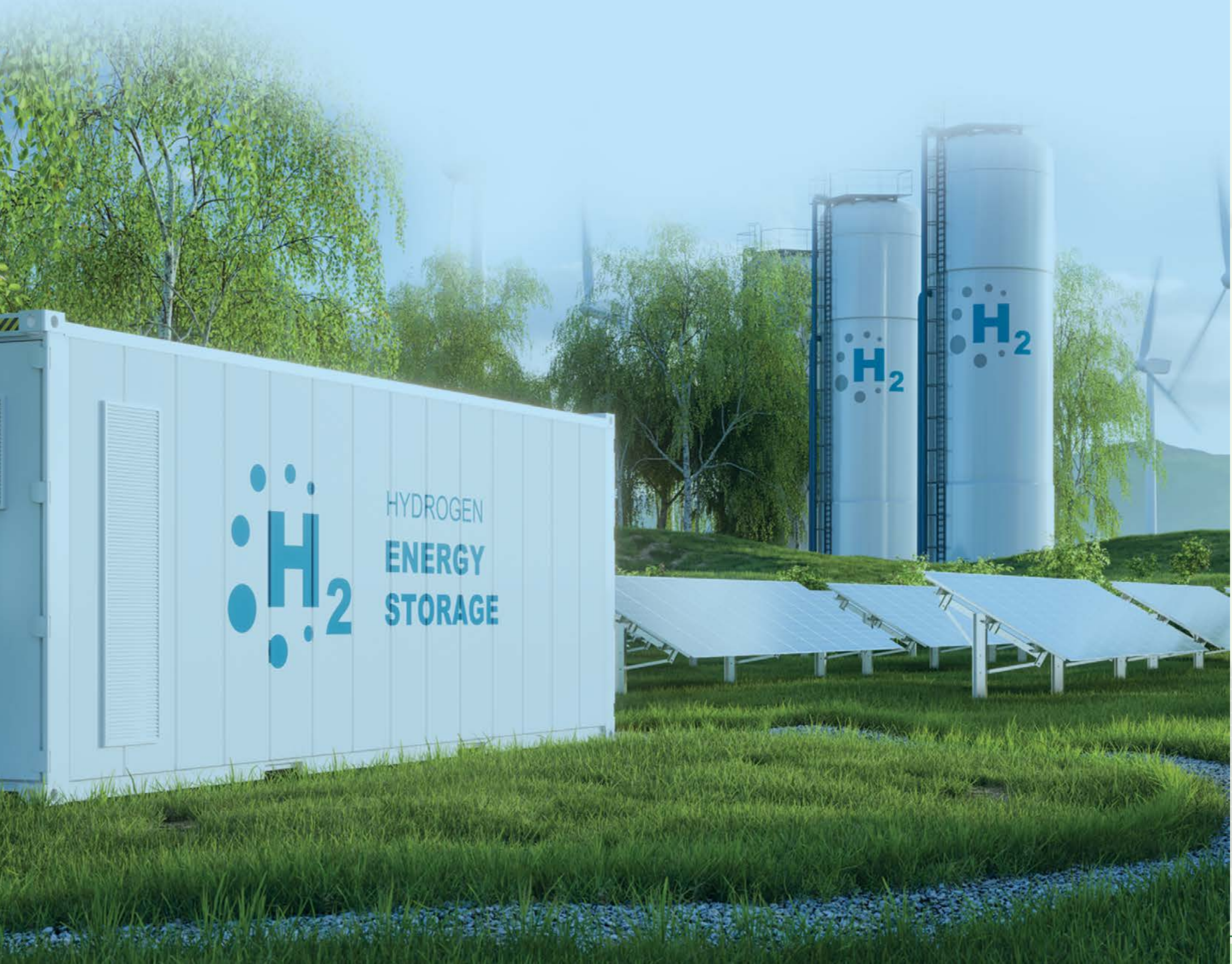
- Hydrogen is a viable fuel option for future cement plants, and according to EU strategies, its availability is not expected to be a constraint.
- Hydrogen combustion in clinker production may initially face technical limitations within the kiln, potentially restricting use to a 5–10% Thermal Substitution Rate (TSR). However, these challenges—as well as infrastructure constraints—can be gradually addressed over time.
- Operational costs for hydrogen remain significantly higher than those of conventional, relatively low-cost fuels. The availability of abundant, affordable renewable electricity is critical for the competitiveness of green hydrogen. Additionally, carbon pricing under the EU ETS will be a key driver in improving the economic viability of hydrogen.
- Combining captured $CO_2$ with hydrogen to produce e-fuels is still in the early stages of development. Its future depends heavily on market demand from other sectors over the next 5–10 years. Robust policy support will be essential to accelerate the development and adoption of such sustainable fuels.
- Funding is vital for hydrogen investments, whether through capital grants or operational subsidies (e.g., €/ton incentives for producing or purchasing green hydrogen). Strong policy frameworks are also needed to support the use of hydrogen as a feedstock, especially in emerging applications like e-fuel production.

**Other cement groups into Green Hydrogen trials and usage are**

- Limak Cement
- Tarmac Lime plant (CRH – UK Subsidiary)

Many industrial scale trials in cement plants across the Globe have proven that the Green Hydrogen as a fuel is technically viable, even at higher volumes. The trials substantiated that the Hydrogen can be used as a fuel. There are no major changes observed in the stack emissions, clinker quality and energy demand of the Pyro processing section. This indicates Green Hydrogen as a potential future fuel for the Cement industry technically.

# 6 COST EFFECTIVE BUSINESS MODEL FOR ADOPTION OF GREEN HYDROGEN IN CEMENT INDUSTRY



# 6. Hydrogen Production and Supply – A Cost-Effective Business Model for the Cement Industry

Referencing the previous chapter on the impact of hydrogen substitution in cement manufacturing, it becomes clear that Hydrogen is emerging as a powerful alternative fuel for hard-to-abate sectors such as cement manufacturing. However, its adoption is fundamentally tied to economic viability. To enable widescale hydrogen substitution in cement kilns, it is essential to develop cost-effective business models that balance capital expenditure (CAPEX), operational expenditure (OPEX), and overall supply chain costs.

Let's evaluates hydrogen production through PEM Electrolysis, associated costs (CAPEX and OPEX), and outlines a model that could work effectively in the Indian cement industry context.

For a 1 MnTPA cement plant replacing 5% of its Pet-coke fuel with hydrogen (approx. 3.5 TPD hydrogen required), the following cost breakdown applies:

**Table 12: Electrolyser System (PEM-based): Input Details/ Requirement**

| Description | UoM | Sample Plant |
|---|---|---|
| Cement Plant | MnTPA | 1 |
| Average Clinker factor | | 0.71 |
| Kiln operating days | days | 330 |
| Clinker Production per day | TPD | 2,138 |
| Average SEC | kcal/kg clk | 740 |
| Average TSR% | % | 10% |
| Average NCV of Green Hydrogen | kcal/kg | 28,700 |
| Replacement of Fossil fuel by Hydrogen | % | 5% |
| Heat Value | kcal/kg clk | 33 |
| Hydrogen requirement | kg/day | 2,480 |
| Sp. Energy Consumption (considering 67% Electrolyser efficiency) | kWh/kg | 55 |
| Electrolyser Capacity | MW | 9-10 |
| Water Requirement | TPD | 45 |
| | Litre/day | 44,643 |
| Total electricity requirement for day (RE Source) | MWh/day | 136 |

To evaluate the feasibility of hydrogen adoption at the plant level, it is essential to understand the capital investments involved. The following table outlines the estimated CAPEX for setting up a **8-10 MW PEM electrolyser system, suitable for generating ~2.5 TPD of hydrogen required for 5% fuel substitution in a 1 MnTPA cement plant.**

**Table 13: CAPEX Cost**

| Component | Description | Unit Cost | Total Cost for 8-10 MW (₹ Cr ) |
|---|---|---|---|
| **Electrolyser + Stack** | PEM Electrolyser Technology | 25-35 Cr./- | 225-315 Cr./- |
| **Balance of Plant (BoP)** | Cost of Balance equipment (power electronics, water circulation and hydrogen processing subsystems) | 17-23 Cr./- | 150-210 Cr./- |
| **Installation & Civil Works** | EPC, foundation, safety systems | 5-8 Cr./- | 45-75 Cr./- |
| **Feeding system, piping, burner etc** | | 2-4 Cr./- | 20-40 Cr./- |
| **Miscellaneous** | | 0.5-1 Cr./- | 3-5 Cr./- |
| **Contingency (5-10%)** | | | 20-40 Cr./- |
| **Total Estimated CAPEX** | | **₹ 45-55 Cr./-** | **₹ 500-660 Cr./-*** |

* Which is equivalent to setup a 1-2 MnTPA Cement plant in India as on 2024

**Table 14: OPEX Cost**

| Description | UoM | Sample plant | Remarks |
|---|---|---|---|
| **Electricity Cost** | ₹ In Cr. /yr | 16 | Assuming this is from RE source with ₹ 3.5/ kwh |
| **Water Cost** | ₹ In Cr. /yr | 6 | ~₹4/litre including treatment |
| **Maintenance** | ₹ In Cr. /yr | 9 | 2-3% of the Capex value |
| **Manpower, miscellaneous** | ₹ In Cr. /yr | 1 | |
| **Total Opex** | ₹ In Cr. /yr | 32 | |
| **Total Hydrogen produced per year** | kg/yr | 8,18,461 | |
| **Sp. OPEX cost of Hydrogen** | ₹ /kg | 385 | |

Next, we will analyse the per kilogram cost of hydrogen when it is supplied to the plant from a distant production facility to assess its economic viability.

**Table 15: The cost, if Hydrogen is supplied from a distant production facility (~200-300 km away from the cement plant):**

| Description | UoM | Values | Remarks |
|---|---|---|---|
| **Purchase cost (Green Hydrogen)** | ₹ In Cr. /yr | 25-35 | ₹ 300-400/kg $H_2$ (India-based production cost range) |
| **Transportation cost** | ₹ In Cr. /yr | 2-7 | ₹ 380/kg $H_2$ Gas trailer |
| **Storage & handling infrastructure** | ₹ In Cr. /yr | 3-5 | |
| **Unloading cost & turnaround time** | ₹ In Cr. /yr | 3-5 | |
| **Burner for firing, piping etc** | ₹ In Cr. /yr | 10-15 | |
| **Total CAPEX Cost** | ₹ In Cr. /yr | 10-20 | |
| **Total OPEX Cost** | ₹ In Cr. /yr | 30-50 | |
| **Summary table (Total CAPEX + OPEX cost)** | ₹ In Cr. /yr | 40-70 | |
| **Sp. cost of Hydrogen** | **₹ /Kg** | **450-600** | |

## Cluster-Based Hydrogen Production Hubs:

To overcome the challenges of high CAPEX and logistics costs, a Cluster-Based Hydrogen Hub Model is emerging as a cost-effective and decentralized solution.

**Model Description:**

- Multiple cement plants in a high-renewable-energy region (e.g., Rajasthan, Gujarat, Maharashtra, Tamil Nadu) collaboratively invest in a centralized hydrogen production facility powered by solar/wind farms.

**Shared infrastructure includes:**

- Central PEM electrolysers
- Utility-scale solar/wind farms
- Storage and compression systems
- Hydrogen pipeline or trailer delivery within the cluster

**Advantages:**

- Lower individual CAPEX burden due to shared investment
- Optimized OPEX from economies of scale
- Proximity to RE generation minimizes electricity cost and intermittency
- Localized hydrogen logistics reduce transportation cost and risks
- Enables phased capacity addition as hydrogen demand grows

**Challenges:**

- Requires long-term collaboration among cement manufacturers
- Need for policy support for cluster infrastructure
- Potential underutilization if uptake is delayed

**Hydrogen Valleys:** Enabling Regional Ecosystems for Cement Sector Adoption Under the National Green Hydrogen Mission (NGHM), India is developing Hydrogen Valleys—integrated regional ecosystems that combine production, storage, distribution, and consumption of green hydrogen within a defined geography. These hubs are designed to create early demand, reduce supply chain complexities, and enable cross-sectoral collaboration.

One of the first such initiatives is the Hydrogen Valley Innovation Cluster (HVIC) in Kerala, where BPCL is leading efforts to establish hydrogen refuelling stations in Kochi and Trivandrum. This cluster supports R&D, pilot projects, and commercial deployment, serving as a model for sector-specific decarbonization strategies, including cement. In parallel, additional Hydrogen Valleys are being developed in Visakhapatnam and by Adani Energy Solutions in Gujarat. These hubs aim to create industrial-scale demand by integrating large consumers like refineries, steel, and cement plants. For the cement industry, locating within or near these valleys offers significant advantages—such as access to reliable green hydrogen supply, reduced logistics costs, and inclusion in government-supported pilot projects.

By aligning with Hydrogen Valley models, cement companies can de-risk early adoption, test hydrogen co-firing technologies, and scale up usage in a cost-effective, collaborative ecosystem—paving the way for long-term decarbonization.

**Table 16: Business Model Options for Hydrogen Supply:**

| Model Type | Description | Pros | Cons |
|---|---|---|---|
| **On-site PEM Electrolyser** | Plant owns & operates hydrogen production unit | Control, reliability, | High CAPEX |
| **Cluster based model with prices based on supply.** | Cement plant in Clusters with abundant renewable resources can collaborate to install Hydrogen facility | Shared burden of High capex cost involved | Price fluctuations may occur if the local renewable energy supply is inconsistent. |
| **Green $H_2$ Purchase & supply from distant facility** | Purchase from nearby green hydrogen hub & supply through trailer | No infra needed | Dependency on external logistics, supply frequency and availability |

In the early phase of green hydrogen adoption in cement kilns, rate-contract supply models from hydrogen hubs may offer flexibility, while cluster-based hydrogen production hubs represent the most promising long-term model for India, balancing cost, infrastructure burden, and supply reliability. Regions rich in renewable energy such as Rajasthan, Gujarat, Maharashtra, and Tamil Nadu can be the early movers in adoption of Green Hydrogen.

However, each cement plant must evaluate feasibility individually, factoring in:

- Distance from hydrogen hub or RE source
- Hydrogen storage and firing integration needs
- Policy incentives and demand aggregation opportunities
- With the right ecosystem and collaborative models, hydrogen adoption can unlock a low-carbon future for Indian cement.

# 7 COST BENEFIT AND BREAK-EVEN ANALYSIS

## 7.1 Cost Benefit analysis- Savings vs. Cost

In evaluating the financial implications of substituting hydrogen for conventional fossil fuel in cement kilns, it's essential to look beyond the fuel price differential alone. While hydrogen carries a significant premium—driven by production or transport expenses—its zero carbon footprint, absence of ash, and operational advantages can translate into measurable gains in energy efficiency, throughput, and maintenance savings.

**Table 17: Comparison with Fossil Fuel Cost:**

| Fuel | Cost per ton | NCV (kcal/kg) | ₹/ Mnkcal |
|---|---|---|---|
| **Pet-coke** | ₹ 14,501 | 7,632 | ₹ 1,900 |
| **Hydrogen (Produced at plant site through PEM Electrolyser)** | ₹ 3,85,480 | 28,700 | ₹ 13,431 |
| **Hydrogen (Supplied from 200-300 km from plant)** | ₹ 4,96,603 | 28,700 | ₹ 17,303 |

Hydrogen is 7 to 9 times more expensive per Mnkcal compared to Pet-coke, but has zero $CO_2$ emissions, zero ash, and facilitates other cost-saving advantages (e.g., reduced flue gas volume leading to increased production capacity, improved Electrical & thermal efficiency and extended mines life)

Let's assess whether the operational and environmental benefits can outweigh the incremental fuel expenditure, quantify the net impact on a 1 MnTPA cement plant by examining:

- **Fuel Cost Differential:** Comparing annual expenditures for a 5% hydrogen substitution.
- **Production Gains:** Additional clinker output driven by reduced flue gas volumes.
- **Efficiency Improvements:** Electrical and thermal savings resulting from cleaner combustion.
- **Other Savings:** Extended mines life and potential carbon credits as per Carbon Credit Trading Scheme (CCTS) of the Indian Carbon Market.

By bringing these elements together, we derive a clear net annual benefit (or shortfall), identify key sensitivity levers (e.g., hydrogen price threshold), and highlight strategic implications for green cement production.

**Table 18: Additional Cost Due to Hydrogen:**

| Description | UoM | Baseline | After 5% $H_2$ substitution |
|---|---|---|---|
| **Cement Production** | MnTPA | 1 | 1 |
| **Clinker Production** | TPD | 2,138 | 2,138 |
| **Overall, Clinker factor** | | 0.71 | 0.71 |
| **Kiln Operation days** | days | 330 | 330 |
| **Thermal SEC** | kcal/kg clk | 740 | 740 |
| **Fossil Fuel %** | % | 90% | 85% |
| **AFR% (incl. biomass)** | % | 10% | 10% |
| **Hydrogen** | % | 0% | 5% |
| **Pet-coke cost** | ₹/MT | 14,501 | |
| **Hydrogen (Produced at plant site through PEM Electrolyser)** | ₹/MT | 3,85,480 | |
| **Pet-coke consumed per year** | TPA | 61,558 | 58,138 |
| **Hydrogen Consumed per year** | TPA | 0 | 909 |
| **Cost of Fuel** | ₹ In Cr./yr | 89.3 | 119.4 |
| **Sp. Fuel cost** | ₹/MT clk | 1,265 | 1,692 |
| **Increase in Fuel cost** | ₹ /MT clk | (-)427 | |

**Table 19:Operational Savings**

| Description | UoM | Baseline |
|---|---|---|
| **Cement Production** | MnTPA | 1 |
| **Increase in Production** | TPD | 24 |
| **Savings in Electrical SEC** | kWh/MT cement | 0.31 |
| **Savings in Thermal SEC** | kcal/kg clk | 3 |
| **Clinker realisation rate** | ₹ /MT | 600 |
| **Power Rate** | ₹ /kWh | 7.5 |
| **Fuel Rate** | ₹ /ton | 14,501 |
| **Gain through increase in production** | ₹ In Cr./yr | 0.41 |
| **Savings in Electrical SEC** | ₹ In Cr./yr | 0.23 |
| **Savings in Thermal SEC** | ₹ In Cr./yr | 0.44 |
| **Total Savings** | ₹ In Cr./-yr | 1.08 |
| **Total Savings per MT clinker** | ₹/MT clk | 15.30 |

**Table 20: Comparative Analysis of Specific Cost on per ton clinker – Additional Fuel cost vs. Savings with Hydrogen Substitution**

| Description | Cost (₹ Cr/year) | Sp. Cost (₹ /MT clk ) |
|---|---|---|
| Increased Fuel Cost (Hydrogen substitution) | -30.1 | -427 |
| Savings thru Increased Production capacity | 0.41 | 5.8 |
| Electrical Savings | 0.23 | 3.27 |
| Thermal Savings | 0.44 | 6.26 |
| Net Incremental cost (w/o Carbon credits) | -29.0 | -411 |
| Carbon Credits (once CCTS is fully functional)- considering ₹1,000/MT $CO_2$ | 1.04 | 14.7 |
| Net Incremental cost (with Carbon credits i.e. benefits of $CO_2$ abatement is added) | -28.0 | -397 |

At the current hydrogen cost (~₹350-400/kg), replacing fossil fuel with Hydrogen in a cement plant increases the Specific fuel cost by approximately ₹ 430 per ton of clinker. However, this premium can be offset through modest operational improvements and market shifts:

- Hydrogen cost to be below ₹60/kg
- Carbon credits/tax become more stringent
- Indigenising electrolyser manufacturing can reduce the CAPEX cost involved in Green Hydrogen production at Cement plant site.
- Increasing efficiency of electrolyser, RE power generation can supplement the reduction of the production cost of Green Hydrogen

Consequently, strategic investments in process optimization, coupled with evolving carbon regulations and local hydrogen manufacturing, will transform today's fuel cost challenge into tomorrow's competitive advantage—paving the way for truly green cement production.

## 7.2. Breakeven Analysis: Pet-coke vs. Green Hydrogen – Fuel Cost Perspective

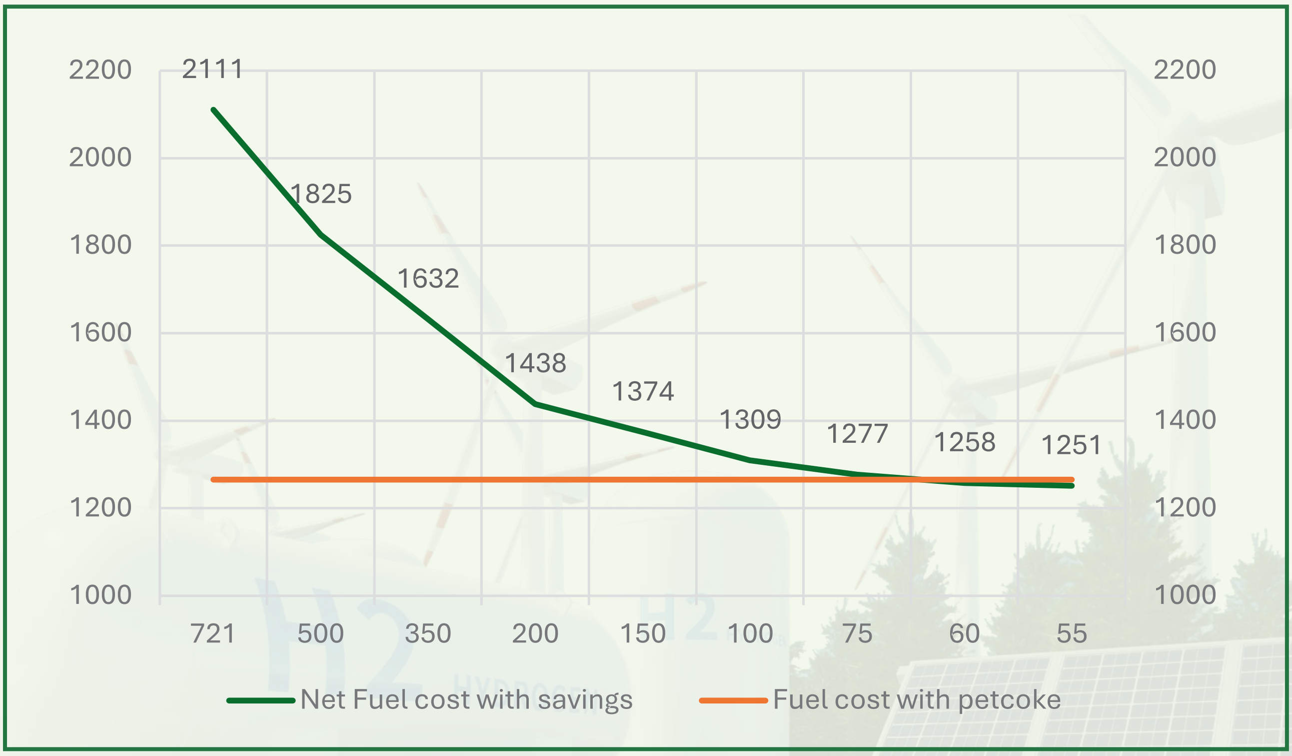
The comparison between the fuel cost of Pet-coke and green hydrogen in the cement industry hinges on their respective energy content and unit prices. Pet-coke, widely used as a primary fuel, has a Net calorific value of ~7,632 kcal/kg (reference to table#2) and is currently priced around ₹14,501 per ton, resulting in a fuel cost of ₹1,900 per million kcal (reference to table#8)

Whereas Green hydrogen, with an energy value of 28,700 kcal/kg, is priced at ₹385/kg. This translates to a fuel cost of ~₹13,431 per million kcal, which is nearly 7 times costlier than Pet-coke. When hydrogen is used to substitute 5% of thermal energy in a 1 MnTPA cement plant, the net additional fuel cost can rise significantly, adding ~₹400 per ton of clinker, based solely on energy substitution.

### Scenario 1: Without Carbon Credits

Without any carbon credit mechanism or incentives, the use of green hydrogen leads to a net financial loss. The increased energy cost outweighs the operational efficiency benefits like increase in production, improved Electrical & Thermal Specific energy consumption. As a result, widespread adoption of hydrogen is financially unattractive unless hydrogen prices fall below ₹60-₹65/kg, i.e. the breakeven point to adopt Green Hydrogen.

**Graph 5: Break-even cost of Hydrogen without Carbon Credits**

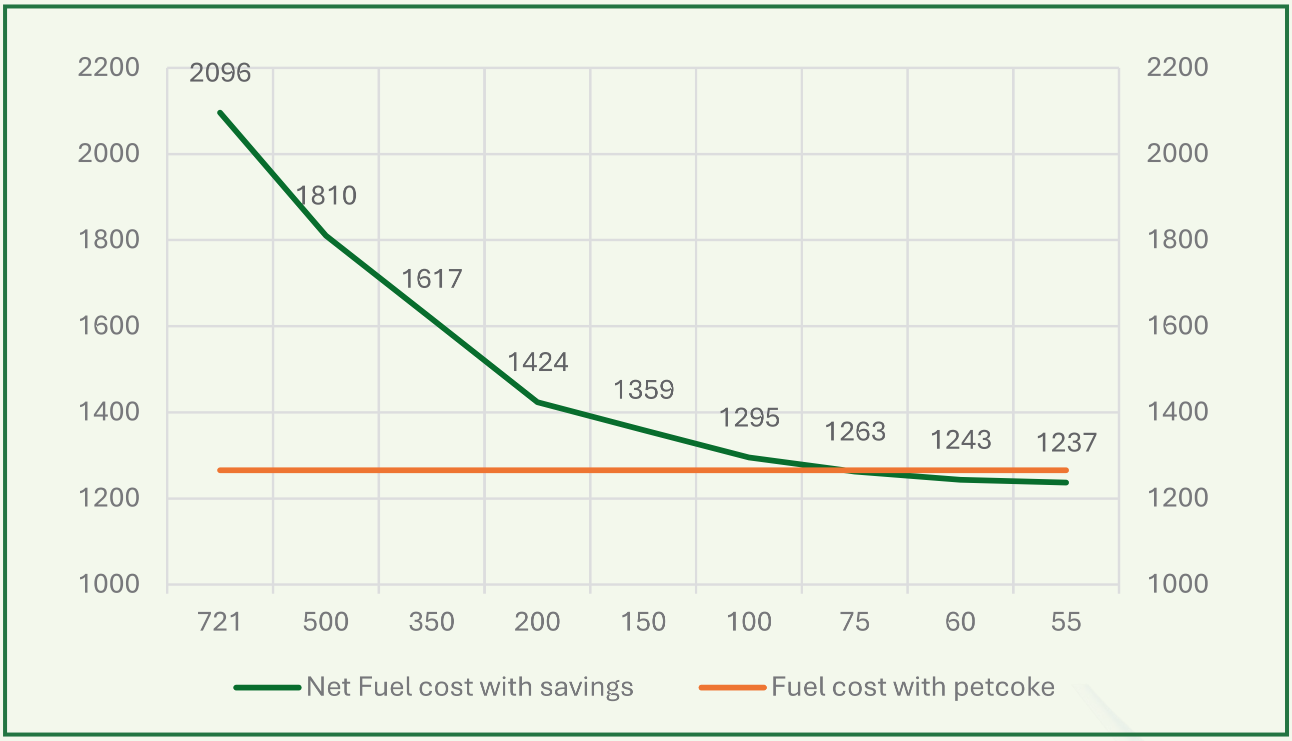



***Both the cost is in Rs./Per ton clinker**

### Scenario 2: With Carbon Credits

Including benefits from carbon credits changes the equation slightly. Assuming a carbon credit price of ₹1,000/ton $CO_2$, although this still doesn't fully bridge the cost gap, it narrows the breakeven point. In this case, hydrogen becomes competitive if the market price drops to around ₹75-80/kg i.e. the breakeven point to adopt Green Hydrogen.

**Graph 6: Break-even cost of Hydrogen with Carbon Credits**




***Both the cost is in Rs./Per ton clinker**

While green hydrogen holds transformative potential for decarbonizing the cement sector, its economic feasibility remains constrained at current price levels. A viable pathway to adoption lies in reducing hydrogen production costs supporting significant market penetration, Indigenizing electrolyser manufacturing to reduce equipment costs, strengthening carbon pricing mechanisms, and creating supportive policy frameworks that can bridge the cost gap and accelerate the transition.

# 8 INTEGRATION OF GREEN HYDROGEN IN CEMENT INDUSTRY

# 8. Integration of Green Hydrogen as a fuel in Cement Industry- Opportunity, Challenges and Potential solutions:

Green hydrogen—produced via water electrolysis powered by renewable electricity—offers the cement industry a carbon free fuel alternative capable of deeply decarbonizing kiln combustion. In India, where cement is both strategically important and energy intensive, green hydrogen adoption can help meet the country's 2070 net zero target.

Let's explore the key opportunities, challenges, and actionable solutions for integrating green hydrogen into Indian cement plants.

## 8.1 Key Opportunities:

**$CO_2$ Emissions Reduction**

8.1.1 Hydrogen combustion emits only water vapor, eliminating direct $CO_2$ from fuel.

8.1.2 Potential to increase TSR% (Thermal substitution rate) in the fuel mix, as with each 5% Hydrogen substitution, the $CO_2$ emission intensity reduces by ~1.45%.

8.1.3 Supports India's commitment to reach net zero emissions by 2070 under its Nationally Determined Contributions (NDC).

**Lower $NO_x$ Formation**

8.1.4 Hydrogen contains no nitrogen, reducing both fuel $NO_x$ and prompt $NO_x$ compared to fossil fuel like coal or Pet-coke. Although its higher flame temperature can increase thermal $NO_x$ formation, this can be managed through process optimization.

**Enhanced Process Efficiency**

8.1.5 Hydrogen's zero carbon composition cuts flue gas volume, lowering electrical SEC for both pre heater and main baghouse fans, and reducing overall thermal losses.

8.1.6 The decreased flue gas volume also boosts clinker production capacity.

**Resource Conservation and Extended Mines Life**

8.1.7 Hydrogen combustion produce no ash or fuel derived oxides ($SiO_2$, $Al_2O_3$, $Fe_2O_3$), reducing the need for lime (CaO) to maintain the Lime Saturation Factor (LSF), directly conserving high grade reserves and extending the operational life of captive limestone mines.

**Renewable Energy Synergy**

- States like Gujarat, Rajasthan, Maharashtra, Karnataka and Tamil Nadu boast abundant solar and wind resources.
- Co -locating electrolysers with cement plants leverages captive renewables and grid stability.

**Economic & Employment Growth**

- Green hydrogen projects drive new business models: equipment manufacturing, EPC, O&M services.
- Job creation across renewable energy, electrolyser manufacturing, and plant operations.

## 8.2 Major Challenges:

**Table 21: Major Challenges**

| Category | Challenge | Remarks |
|---|---|---|
| High CAPEX | On-site PEM electrolyser systems cost ₹45–55 Cr/MW—including Power systems, feeding system, piping, Burner, engineering & design, service & installation, civil works | For a 1 MnTPA Cement plant with 5% Hydrogen substitution with a thermal SEC of 740 kcal/kg clk, requires 9-11 MW Capacity electrolyser. ~ ₹ 500-700 Cr./- (Equivalent to setting up a complete greenfield 1-2 MnTPA Integrated Cement plant |
| Resource Intensity | Water, RE power & infrastructure | A 1 MTPA plant requires ~3 TPD $H_2$, ~150 MWh/day power, ~45-50 KL of water per day, storage, feeding and firing system |
| Infrastructure Gaps | Lack of established infrastructure for Green Hydrogen production, storage, handing and utilization in cement plants | |
| Safety & Handling | Safety considerations in transport, storage, handling and utilization – requires robust infrastructure, leak detection & safety protocols | |
| Plant Retrofitting | New burners, high pressure piping, and on site storage add incremental capex and opex. | |
| Electrolyser Efficiency | Commercial PEM systems operate at ~65–70% LHV efficiency; improvements are needed. | The electrolyser power consumption is 50-55 kwh/kg Hydrogen, ~ very high |
| Capacity Building | Capacity building of Cement professionals on Green Hydrogen and its management | |

## 8.3 What Could Go Wrong?

Even with planned interventions, several unexpected risks could derail the hydrogen transition:

**Supply Chain Disruption**

- Fluctuations in global electrolyser prices (due to geopolitical factors or supply bottlenecks) could cause project cost overruns.

**Uncertain Policy Landscape**

- If subsidies, carbon pricing, or tax incentives are rolled back or delayed, business cases may become financially unviable.
- Delays in environmental clearances, land use approvals for RE or hydrogen infrastructure can slow projects.

**Operational Risks**

- Hydrogen leaks, undetected due to its colourless and odourless nature, may cause safety incidents.

**Water & Power Supply Constraints**

- Continuous Renewable energy supply instability or water shortages, especially in arid zones may affect electrolyser uptime, reducing hydrogen availability.

## 8.4 Potential Solutions & Enablers:

- The government should introduce incentive schemes to alleviate the financial burden of green hydrogen production.
- The GoI (Government of India) and the National Green Hydrogen Mission must develop and promulgate standards and guidelines for green hydrogen production and its integration within cement plants.
- Support the development of hydrogen infrastructure and stimulate demand for green hydrogen through targeted policy measures.
- Promote more public–private partnership (PPP) models and increase R&D funding, including the creation of dedicated innovation hubs to fast track advanced green hydrogen technologies.
- Form a cement industry consortium—comprising government bodies, technology providers, and consultants—to pilot and scale up green hydrogen adoption across India’s cement sector.
- Implement carbon pricing or taxation mechanisms to provide a robust financial incentive for cement manufacturers, complemented by programs like CCTS and PAT to encourage green hydrogen utilization.

- Enhance electrolyser efficiency and expand renewable energy capacity to further reduce the production cost of green hydrogen.
- Encourage the indigenization of electrolyser manufacturing to lower CAPEX for on site green hydrogen production, enabling more plants to generate hydrogen in situ.
- Aim to drive green hydrogen prices below ₹60/kg to achieve long term financial viability for the cement and other energy intensive industries.

Green hydrogen integration in Indian cement plants presents a compelling opportunity to drastically cut $CO_2$ emissions, improve process efficiency, and conserve resources.

Although challenges, from high initial investments to safety and infrastructure gaps are significant, a coordinated approach combining government initiatives like National Green Hydrogen Mission, Carbon Credit Trading Scheme, cluster based infrastructure, technology innovation, and workforce development can accelerate adoption over the next five years.

# 9 RESOURCE REQUIREMENT VS AVAILABILITY

# 9. Resource Requirement vs. Availability Scenario for using Green Hydrogen- General aspect (Hydrogen Substitution varying from 5% to 35%)

Effectively decarbonizing India's cement industry through hydrogen substitution demands a precise assessment of the hydrogen volume required, the infrastructure needed, and how this aligns with national availability.

**Table 22: Assumptions**

| Description | UoM | Indian Cement Plant Capacity |
|---|---|---|
| Cement Plant | MnTPA | 375 |
| Average Clinker factor | | 0.71 |
| Clinker Production | MnTPA | 265 |
| Kiln operating days | days | 330 |
| Clinker Production per day | TPD | 8,01,591 |
| India's average SEC | kcal/kg clk | 740 |
| Average TSR% | % | 10% |
| Average NCV of Green Hydrogen | kcal/kg | 28,700 |
| Water Consumption for electrolysis (considering 65% efficiency of electrolysis, purification losses etc) | Ltr/kg $H_2$ | 18 |
| Renewable Power Requirement | kWh/ kg $H_2$ | 55 |

**Table 23: Hydrogen Requirement by Substitution Level**

| $H_2$ Substitution (%) | Energy from $H_2$ (kcal/kg clinker) | $H_2$ Required (kg/ton clinker) | $H_2$ Required for 375 MnT (Indian Cement Plant) (MnTPA ) |
|---|---|---|---|
| **5%** | 37 | 1.29 | 0.34 |
| **10%** | 74 | 2.58 | 0.69 |
| **15%** | 111 | 3.87 | 1.03 |
| **20%** | 148 | 5.16 | 1.37 |
| **25%** | 185 | 6.45 | 1.72 |
| **30%** | 222 | 7.74 | 2.06 |
| **35%** | 259 | 9.02 | 2.40 |

**Table 24: Water Requirement by Hydrogen substitution level**

| $H_2$ Substitution (%) | $H_2$ Required for 375 MnT (Indian Cement Plant) (MnTPA) | Annual Water Required (million KL/Year) |
|---|---|---|
| **5%** | 0.34 | 6 |
| **10%** | 0.69 | 12 |
| **15%** | 1.03 | 19 |
| **20%** | 1.37 | 25 |
| **25%** | 1.72 | 31 |
| **30%** | 2.06 | 37 |
| **35%** | 2.40 | 43 |

**Table 25: Renewable Power Requirement by Hydrogen substitution level**

| $H_2$ Substitution (%) | $H_2$ Required for 375 MnT (Indian Cement Plant) (MnTPA) | Power Required (TWh/year) |
|---|---|---|
| **5%** | 0.34 | 19 |
| **10%** | 0.69 | 38 |
| **15%** | 1.03 | 57 |
| **20%** | 1.37 | 76 |
| **25%** | 1.72 | 94 |
| **30%** | 2.06 | 113 |
| **35%** | 2.40 | 132 |

**Table 26: Comparison with India's Green Hydrogen Targets & Resources**

| Resource | Requirement (5-35% substitution) | India's Target |
|---|---|---|
| **Hydrogen Production** | 0.3 to 2.4 MnTPA | 5 MnTPA by 2030 |
| **Renewable Power** | 19 to 132 TWh/year | 500 GW by 2030<br>(eq. to 900-1,000 TWh/year) |
| **Water for Electrolysis** | 6-43 million KL/year | |

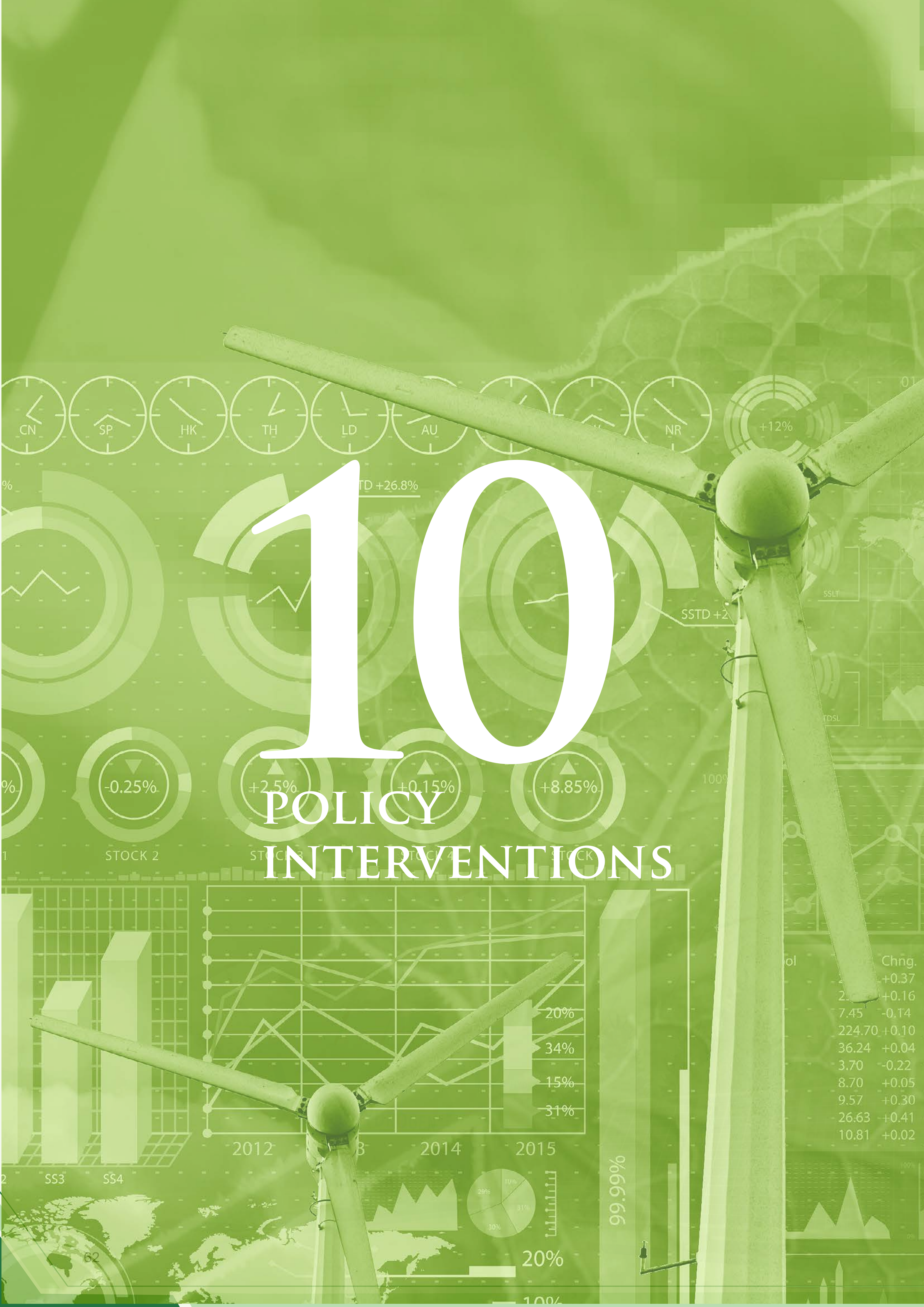
- At 35% substitution, the cement sector alone would require 2.4 MnTPA $H_2$, nearly 50% of India's 5 MTPA 2030 target under National Green Hydrogen Mission.
- Renewable power demand (132 TWh/year) represents ≈13% of annual renewable generation Target capacity.
- Water demand (43 million KL/year) is modest relative to India's annual water usage but highlights the need for treated process water or rainwater harvesting.

While low-level hydrogen blending (5–10%) is technically feasible and aligns with India's green hydrogen production targets, deeper decarbonization through high substitution levels (>50%) presents significant challenges.

The resource gap, spanning electrolyser capacity, renewable power availability, and water infrastructure becomes increasingly stark at higher substitution levels.

Moreover, at the current green hydrogen price of around ₹400/kg, its use in cement manufacturing remains economically unviable.

To enable adoption at scale, the price must fall to the range of ₹45–70/kg. A phased, cluster-based implementation strategy, backed by strong policy support and cross-sector collaboration, will be critical to overcoming these barriers and realizing the full decarbonization potential of hydrogen in the Indian cement industry.




# 10 POLICY INTERVENTIONS

# 10. Policy or Regulatory Intervention for Scaling Up the Adoption of Hydrogen and Existing Efforts of Government of India

While the National Green Hydrogen Mission (NGHM) has set the stage for a green hydrogen economy in India, a robust policy and regulatory framework focused on industrial use-cases, especially in cement, is crucial to bridge the gap between potential and practice.

These interventions address key challenges such as high production costs, infrastructure bottlenecks, lack of demand certainty, and sustainability concerns. This topic outlines the policy landscape and emerging regulatory needs critical to scaling up hydrogen adoption in India.

## 10.1 National Green Hydrogen Mission

The National Green Hydrogen Mission (NGHM) was launched in January 2023 and acts as a visionary blueprint, executing this framework through targeted initiatives to establish a self-sustaining and scalable green hydrogen economy, ensuring long-term energy security and sustainability for the nation. Aiming to develop a production capacity of at least 5 million metric tonnes (MMT) of green hydrogen annually by 2030 (refer to fig. 1), with the potential to scale up to 10 MMT per year as global export markets expand. To build a robust green hydrogen ecosystem, seamless integration of key elements such as policy incentives, private sector participation, and strengthened supply chains is essential.

The NGHM, backed by streamlined policies and incentives, is a strategic initiative to foster India's green hydrogen sector and ensure the country's transition to a sustainable, energy-secure future country's transition to a sustainable, energy-secure future.

The NGHM, with a budget of ₹19,744 crores , aims to accelerate India's green hydrogen transition. The allocated funds are strategically deployed to stimulate demand, incentivize supply, advance research and development for cost reductions, enhance capacity building, and support skill development, ensuring a robust and sustainable green hydrogen ecosystem. The Strategic Interventions for Green Hydrogen Transition (SIGHT) Programme which provides direct financial support to drive domestic manufacturing and hydrogen production accounts almost 89% of the budget. 7.4% being allocated to Pilot projects initiative focused on sectoral applications to drive early adoption and technology validation.

### 10.2 Complementary and Enabling Policies Supporting NGHM

To ensure the holistic development of the hydrogen ecosystem, a set of interconnected policies support NGHM's objectives:

- **Green Hydrogen Certification & Compliance:** The Bureau of Energy Efficiency (BEE) has been designated as the nodal agency for certifying green hydrogen and its derivatives. This framework will ensure traceability, reliability, and compliance with domestic and international environmental standards, facilitating global trade and carbon accounting.
- **Renewable Energy Round-the-Clock (RE-RTC) Framework:** Hydrogen production demands 24x7 renewable power. The RE-RTC policy ensures uninterrupted supply through hybrid combinations of solar, wind, and storage, thus improving electrolyser utilization and lowering hydrogen production costs.

### 10.3 State-Level and Sectoral Support Mechanisms

Beyond national policies, states like Gujarat, Rajasthan, Maharashtra, Odisha, Andhra Pradesh, Uttar Pradesh and Tamil Nadu have introduced industrial green hydrogen policies offering land, infrastructure, and demand aggregation incentives. Cement clusters in these states stand to benefit through:

- Access to green hydrogen corridors or industrial hubs with shared infrastructure to reduce the individual cost.

### 10.4 Safety, Certification, and Environmental Management

Hydrogen's high flammability and small molecular size demand stringent safety protocols. Key interventions include:

- Development of hydrogen safety codes and standards aligned with international benchmarks (ISO, IEC)
- Establishing mandatory risk assessments for production, storage and utilisation of Hydrogen

- Dedicated training programs for emergency response teams and plant personnel

Additionally, policies must address resource sustainability, especially water use. Electrolysis consumes around 17-18 Liters (theoretically 9 kg but due to purification loss and lower electrolyser efficiency) of water per kg of hydrogen, necessitating:

- Water-efficient electrolysis technologies
- Mandatory water management plans for hydrogen projects

The Carbon Credit Trading Scheme offers a concrete opportunity for the cement sector to monetize emissions reductions from hydrogen adoption. When coupled with the right demand mandates, co-processing guidelines, and infrastructure support, green hydrogen can emerge as a cornerstone of India's cement decarbonization strategy.

A focused policy push, including cement's formal inclusion in the NGHM's demand-side incentives and CCTS's priority sectors will accelerate India's progress toward net-zero manufacturing while positioning Indian cement producers as global leaders in clean construction materials.

# 11

# CONCLUSION

# 11. The Role of Green Hydrogen in India's Cement Industry: A Concluding Perspective

This paper has comprehensively explored the technical, economic, and environmental dimensions of integrating green hydrogen as a fuel in the Indian cement industry. From potential emissions reductions to process impacts and cost implications on clinker production, the analysis demonstrates both the opportunities, and the challenges involved in adopting hydrogen as a viable decarbonization pathway.

India currently stands at a pivotal moment in its energy transition, with a growing emphasis on decarbonizing hard-to-abate sectors like cement. Despite possessing the world's fourth-largest coal reserves, the country spends nearly USD 90 billion annually on energy imports, largely due to the suboptimal quality of domestic coal and reliance on imported coking coal. This heavy dependence exposes India to price volatility and supply insecurity arising from global disruptions.

In this context, green hydrogen emerges as a strategic enabler—not only for enhancing energy security but also for reducing the carbon footprint of one of the most emissions-intensive industries. It directly supports India's commitment to achieve net zero emissions by 2070 under its Nationally Determined Contributions (NDCs).

Even a modest 5% substitution of fossil fuel with green hydrogen in a 1 million ton per annum cement plant can reduce $CO_2$ emissions by approximately 20,000 tons annually. Higher substitution rates can drive deeper decarbonization and set the foundation for a low-carbon transformation of the industry.

**Beyond carbon reduction, hydrogen combustion brings several co-benefits:**

- No NOx or SOx emissions from fuel nitrogen or sulphur compounds.
- No ash contribution, resulting in a 5–6% reduction in fuel-derived oxides in the clinker, which reduces the lime (CaO) demand and thus conserves limestone, extending mines life.
- Reduced fossil fuel processing, such as grinding, leading to lower auxiliary power consumption per ton of cement.

Given its high calorific value and flame characteristics, hydrogen is most suitable for use in the main kiln burner rather than the calciner. For the initial phase i.e. over the next 10 to 15 years, it is advisable to limit hydrogen use to kiln burner only (i.e., 30-35% substitution of the total Thermal energy). This phased approach allows for process stabilization while industry learns from pilot integrations and scales up safely.

**However, the transition is not without challenges. Key barriers include:**

- Process optimization to adapt to new combustion profiles and flue gas compositions.
- Higher dew point in flue gases due to increased water vapor, potentially affecting the flue gas volume subsequently the succeeding equipment like Bag House, Waste Heat Recovery Systems (WHRS), etc.
- Water requirements for electrolysis, which is especially critical given that around 30% of Indian cement plants operate captive power plants (CPPs) and already face acute water stress, creating risks for local community and agricultural water access.
- High capital and operating costs, particularly for electrolysers, hydrogen storage, and fuel handling & feeding (burners, piping etc) systems.
- Safety concerns, as hydrogen is highly flammable and demands robust infrastructure for safe production, storage, and utilization. Most existing cement plants will need retrofitting with advanced safety mechanisms.
- Dependable renewable energy supply is essential to ensure consistent electrolyser operation, as fluctuations in solar or wind availability can limit hydrogen production and impact fuel planning.

**Way Forward: Making Hydrogen Techno-Economically Feasible in Cement**

1. **Lower Hydrogen Production Costs**
   - Scale up domestic electrolyser manufacturing
   - Enable low-cost RE through PPAs and hydrogen hubs
   - Support R&D in advanced electrolysis technologies to improve electrolyser efficiency (present PEM electrolysers have 65-70% efficiency only)
2. **Consistent Renewable Energy Supply -** Developing hybrid RE systems (solar + wind) with storage
3. **Infrastructure upgradation for integration of Hydrogen-** Retrofit kilns with hydrogen-compatible burners, safety systems.
4. **Policy intervention and financial support/incentives from GoI-**
   - Offer CAPEX subsidies or incentives or financial support for pilot projects
   - Enable carbon pricing or credit schemes, Incentivize hydrogen use
5. **Strengthen Safety and Workforce Readiness -** Develop hydrogen codes and standards for use in cement manufacturing
6. **Public-Private Partnerships and Regional Demonstration Projects**
   - Facilitate Public-Private Partnerships (PPPs) to implement pilot-scale hydrogen co-firing trials in cement kilns
   - Government to fund region-specific demonstration projects in areas with renewable energy surplus or existing hydrogen infrastructure, enabling collaborative innovation and early de-risking of hydrogen integration

The India cement sector is well known for faster implementation of new & innovative technologies. If the challenges associated with Green Hydrogen can be reduced, especially financial bottlenecks there is a substantial potential of developing clean fuel hubs across all cement clusters. With the support of all stakeholders Indian cement industry can accelerate their actions towards Net zero cement manufacturing by utilising Green Hydrogen as future fuel.

While green hydrogen is not an immediate substitute for fossil fuels in cement manufacturing, it is not a bridge too far. With phased integration, technology validation, and supportive policy frameworks, Green Hydrogen can become a key enabler of India's net-zero cement industry in the coming decades.

## Abbrevations:

| | |
|---|---|
| AEM | Anion Exchange Membrane |
| AFR | Alternative Fuel and Raw Materials |
| $Al_2O_3$ | Aluminium oxide |
| BEE | Bureau of Energy Efficiency |
| BoP | Balance of Plant |
| $CaCO_3$ | Calcium Carbonate (Limestone) |
| CAGR | Compound Annual Growth Rate |
| CaO | Calcium Oxide (Lime) |
| CAPEX | Capital expenditure |
| CCTS | Carbon Credit Trading Scheme |
| $CO_2$ | Carbon dioxide |
| CPP | Captive Power Plant |
| Cr | Crore |
| $Fe_2O_3$ | Ferric oxide |
| GEI | Greenhouse Gases Emission Intensity |
| GoI | Government of India |
| GW | Gigawatt |
| $H_2$ | Hydrogen |
| HVIC | Hydrogen Valley Innovation Clusters |
| IEA | International Energy Agency |
| IEC | International Electrotechnical Com-mission |
| ISO | International Organization for Stand-ardization |
| kcal | kilo calorie |
| kg | kilogram |
| KL | Kilo Litre |
| kWh | Kilowatt-hour |
| LS | Limestone |
| LSF | Lime Saturation Factor |
| MMT | Million Metric Tonne |
| MnTPA | Million Tonne per annum |
| MSW | Municipal Solid Waste |
| MT | Metric Tonne |
| MW | Mega Watt |
| NCV | Net Calorific Value |
| NDCs | Nationally Determined Contributions |
| NGHM | National Green Hydrogen Mission |
| $NO_x$ | Nitric oxide & Nitrogen dioxide |
| NZE | Net Zero Emissions |
| OPEX | Operating Expenses |
| PAT | Perform Achieve and Trade |
| PEM | Proton Exchange Membrane |
| PH | Pre - heater |
| PPP | Public-Private Partnership |
| R & D | Research and Development |
| RABH | Reverse air baghouse |
| RDF | Refuse Derived Fuel |
| RE | Renewable Energy |
| RE-RTC | Renewable Energy Round-the-Clock |
| SEC | Specific Energy Consumption |
| SIGHT | Strategic Interventions for Green Hydrogen Transition |
| $SiO_2$ | Silicon dioxide |
| SOEC | Solid Oxide Electrolysis Cell |
| $SO_x$ | Sulfur oxides |
| TPD | Tonne per day |
| TSR | Thermal Substitution Rate |
| TWh | Terawatt-hour |
| USD | United States Doller |
| WHRS | Waste Heat Recovery System |

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**We warmly invite you to share your feedback and inputs on this discussion paper with us at encon@cii.in**

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