Systems & Control Transactions

Research Article
Foundations of Computer Aided Process Design (FOCAPD 2024)
Breckenridge, Colorado, USA. July 14-18, 2024
Peer Reviewed Conference Proceeding

PSE PRESS

Role of Hydrogen as Fuel in Decarbonizing US Clinker Manufacturing for Cement Production: Costs and CO_2 Emissions Reduction Potentials

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ABSTRACT

As a low-carbon fuel, feedstock, and energy source, hydrogen is expected to play a vital role in the decarbonization of high-temperature process heat during the pyroprocessing steps of clinker production in cement manufacturing. However, to accurately assess its potential for reducing CO_2 emissions and the associated costs in clinker production applications, a techno-economic analysis and a study of facility-level CO_2 emissions are necessary. Assuming that up to 20% hydrogen can be blended in clinker fuel mix without significant changes in equipment configuration, this study evaluates the potential reduction in CO_2 emissions (scopes 1 and 2) and cost implications when replacing current carbon-intensive fuels with hydrogen. Using the direct energy substitution method, we developed an Excel-based model of clinker production, considering different hydrogen–blend scenarios. Hydrogen from steam methane reformer (gray) and renewable-based electrolysis (green) are considered as sources of hydrogen fuel for blend scenarios of 5%–20%. Metrics such as the cost of cement production, facility-level CO_2 emissions, and cost of CO_2 avoided were computed. Results show that for hydrogen blends (gray or green) between 5% and 20%, the cost of cement increases by 0.6% to 16%, with only a 0.4% to 6% reduction in CO_2 emissions. When the cost of CO_2 avoided was computed, the extra cost required to reduce CO_2 emissions is \$229 to \$358/ metric ton CO_2. In summary, although green hydrogen shows promise as a low-carbon fuel, its adoption for decarbonizing clinker production is currently impeded by costs.

Keywords: Cement, Clinker, Hydrogen, Decarbonization, CO2.

INTRODUCTION

In the United States, cement (and lime) production in 2022 is responsible for 31 million metric tons (MMT) CO_2 emissions of the industry sector's total CO_2 emissions [1]. These GHG emissions attributed to the cement sector are directly associated with clinker manufacturing, which constitutes 70%–90% of conventional cement blends. With clinker production volume of 79 MMT in 2022 [2], if the status quo is maintained, reduction of these emissions is vital if we intend to achieve the 1.5°C target.

Because clinker manufacturing involves the breakdown of limestone to lime and the concurrent production of byproduct CO_2 in a high-temperature pyroprocessing step, the generation of process- and combustion-related CO_2 emissions is currently inevitable. Owing to the chemistry of the reaction, process-related CO_2 emissions account for up to 60% of total clinker production CO_2 emissions with the remaining associated with energy use. Given the twofold sources of CO_2 emissions in cement production, efforts are channeled toward decarbonizing one or both.

To decarbonize the cement industry, implementation of the crosscutting decarbonization pillars—namely energy efficiency; low-carbon fuels, feedstocks, and energy sources (LCFFES); industrial electrification; and carbon capture, utilization, and storage (CCUS)—are necessary conditions to attain a low-carbon cement industry. Hence, over the years, different research efforts have been focused on these carbon-reducing strategies, technologies, and practices.

For example, Worrell et al. [3] conducted an energy efficiency analysis using 30 energy-efficient technologies and measures in the US cement sector. Results of the analysis showed energy and CO_2 savings of 11% and 5%, respectively. Nevertheless, current typical energy use in the cement sector still revolves between 3.5 and 4.1 GJ/MT [4–6] and with emissions intensity as high as 900 $kgCO_2$/MT cement [7]. Advanced waste heat recovery and process intensification are still needed for the contribution of energy efficiency pillars to be significant. For LCFFES applications, the use of supplementary cementitious materials such as blast furnace slag, volcanic ash, pozzolans, fly ash, and calcined clay can reduce the clinker-to-cement ratio to about 65%–75% with the innovative limestone calcined clay allowing higher clinker substitution up to 50% [8]—thereby reducing energy use and emissions typically associated with clinker production. However, a drawback to using slag and fly ash is the transition from blast furnace and coal power plants to more sustainable alternatives [9]. Industrial electrification research has focused on the electricity-driven calciner or calciner/kiln system [4–5]—offsetting on-site scope 1 CO_2 emissions emanating from fuel combustion and enabling a CO_2-rich flue gas (pyroprocessing step), which minimizes the energy requirement for carbon capture (CC). An innovative electrified cement production in progress is the Leilac project designed to indirectly heat raw meal in a shell and tube system, efficiently separating the process CO_2 for direct capture or use [10]. Finally, CCUS is primed as the sole decarbonization pillar that can significantly reduce CO_2 intensity of the cement sector, depending on the technology implemented. However, the most feasible cement CC technologies are still at a low technology readiness level (TRL), and the high TRL technologies are very energy intensive [11], which the current cement facility is not equipped to support.

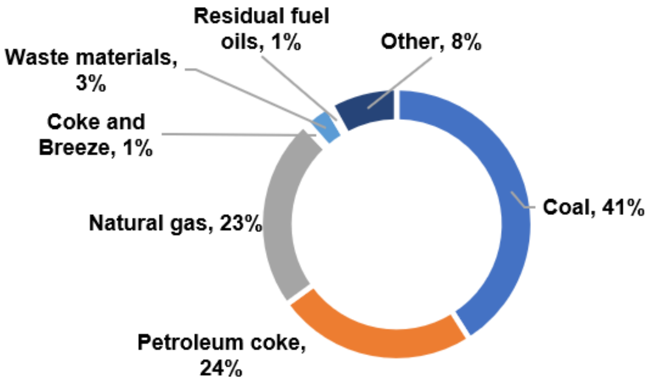

Figure 1. Average cement fuel mix [12].

Among all decarbonization pillars, fuel switching has received little or no attention. Traditionally, US cement facilities use a range of fuel mix, as depicted in Figure 1. Coal and petroleum coke with high-carbon content account for 65% of this fuel mix, dominating the energy-related emissions. In practice, cement facilities usually combust any cheap fuel in the market or even receive a tipping fee to dispose of industrial wastes in the kiln [13]. To decarbonize the cement sector, broad commitment toward clean or low-carbon fuels is needed.

Within the hydrogen economy, hydrogen as a carbon-free energy carrier is being pushed as a fuel that can decarbonize the cement industry sector. For instance, CEMEX has announced the use of hydrogen as a share in cement fuel mix for all cement facilities in Europe to attain zero CO_2 combustion emissions and improve energy efficiency [14]. Nevertheless, whereas hydrogen seems to be a viable means to decarbonize cement production, the technical challenges, costs, and potential emissions reduction that could impede the full adoption of hydrogen as a fuel need to be evaluated.

Hence, in this study, we assessed the cost and potential CO_2 emissions reduction of blending hydrogen as a fuel in cement production. This analysis explored the use of hydrogen from both conventional steam methane reformer (SMR) hydrogen (gray) and renewable-powered electrolysis hydrogen (green). In this context, scope 2 emissions of hydrogen production were considered. In addition, discussions on the near-term technical challenges currently impeding hydrogen use in the industry sector are highlighted. Performance metrics, such as facility-level CO_2 emissions, minimum cement selling price (MCSP), and cost of CO_2 avoided (CCA), were computed. Overall, insights on the current state of hydrogen adoption as a fuel in the cement sector are elucidated.

METHODOLOGY

Process modeling and assumptions

This work employs a brown-field cement facility with a five-stage cyclone preheater with precalciner system for dry portland cement manufacturing. Clinker production is sized to be about 1.2 MMT (clinker to cement ratio = 81%) corresponding to an average US cement facility. In this proposed facility, hydrogen is assumed to substitute 5%–20% of the primary energy demand. At the time of this analysis, it is assumed that a hydrogen blend of up to 20% would not necessitate any significant modification of the equipment [24] used in the cement facility. The authors developed an Excel-based model for the energy demand of hydrogen-fired cement production using a direct energy substation method. Hydrogen supply to the cement facility is assumed to be met via SMR hydrogen (gray) and electrolysis hydrogen (green)—with associated scope 2 emissions included. For comparison, the conventional cement (based on traditional fuel mix) was also modeled. Intrinsically, it is assumed that the cement

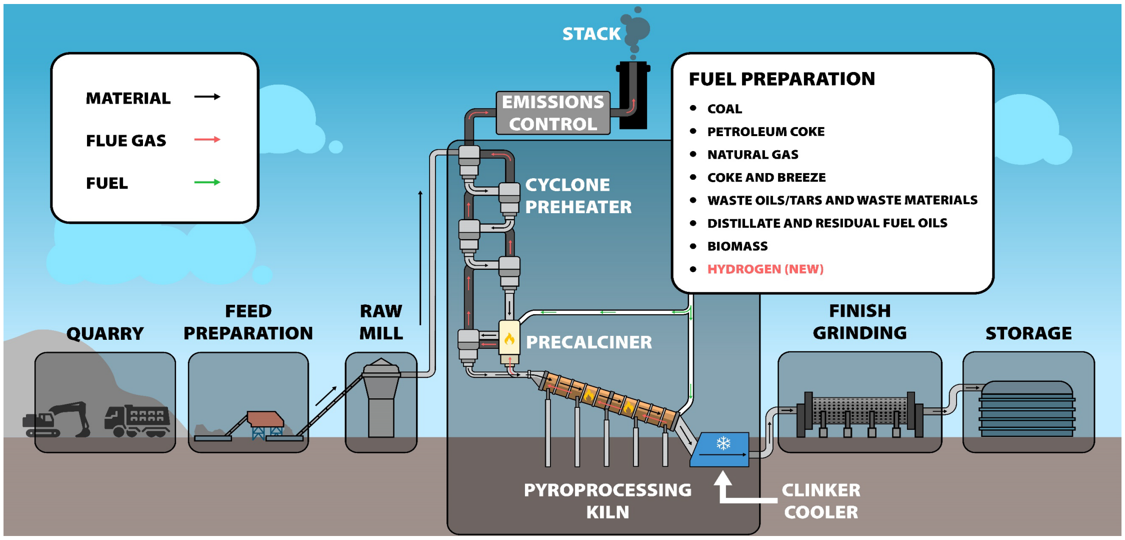

Figure 2: Proposed cement facility with hydrogen blend in fuel mix.

produced in each scenario meets the portland cement standard. Key parameters and assumptions used in the model are shown in Table 1.

Figure 2 shows the proposed cement production facility. As a decarbonization strategy, different hydrogen blend ratios are designed to substitute carbon-intensive fuels such as coal and petroleum coke while keeping natural gas and biomass fuels constant. Overall, the performance of the cement facility with different hydrogen sources at different blend ratios was assessed in terms of MCSP, facility-level CO_2 emissions (scopes 1 and 2), and CCA.

Table 1: Parameters used in the model.

Parameter	Value	Ref
Energy demand (GJ/t)		
Feed preparation	0.13	[6]
Fuel preparation	0.13	[6]
Pyroprocessing (with cooling)	3.61	[6]
Finish grinding	0.21	[6]
Primary thermal energy	3.51	[6]
Electricity (site)	0.19	[6]
Raw meal to clinker ratio	1.6	[15]

Process description

Portland cement manufacturing involves the general steps of mining or extraction of feedstock, feedstock preparation via crushing and grinding operations, fuels preparation, the pyroprocessing operation (preheater/precalciner), kiln with cooling system, and final grinding with additives, as shown in Figure 2.

Raw materials for cement production such as limestone, clay, shale, marl, and iron ore are mined or extracted at quarries typically located near the cement facility. Additional raw material such as gypsum needed in the finishing grind operation is also sourced. Cement facilities currently use waste materials such as fly ash and blast furnace slag, etc. as raw materials [16].

To ensure the homogeneity of the mixture and that the appropriate chemical and physical properties are achieved, these raw materials are crushed into smaller particles using hammer or jaw crushers [6]. The crushed particles are further processed by grinding to form raw meal, which is sent to the preheater [6]. This raw material processing takes place in the feed preparation unit which is powered primarily by electricity.

Owing to the diverse nature of fuel mixes (solids, liquids, and gases) used in cement production, fuel preparation is a standard process. Conventional fuels like coal, petroleum coke, and waste tire are crushed, creating fine particles that improve combustion. These fuels are then combusted in the calciner and kiln to drive the calcination and sintering reactions.

Raw meal from the grinder is sent to the pyroprocessing step, where the moisture content is reduced in the cyclone preheater system before the meal is sent to the precalciner. In the precalciner, the initial calcination reaction takes place at about 900°C, driving off CO_2 from the raw meal and improving the overall thermal efficiency of the process. Clinker formation occurs in the rotary kiln, which operates at 1,450°C to produce hot solid clinker products.

The final cement production step involves air cooling and subsequent grinding of the clinker into a fine powder, which is mixed with gypsum and other additives to form cement.

Facility-level CO_2 emissions assessment

In this analysis, the facility-level CO_2 emissions are based on scopes 1 and 2 emissions emanating from onsite (process and combustion) and upstream (electricity and hydrogen) emissions. Other on-site CO_2 emissions such as mobile equipment use are not considered. The facility-level CO₂ emissions are computed as:

$$CO_{2_t} = CO_{2_p} + CO_{2_f} + CO_{2_e} \qquad (1)$$

$$CO_{2_f} = \sum_i CO_{2_i} \qquad (2)$$

where CO_{2_t} is the total facility-level CO₂ emissions, CO_{2_p} is the process-related CO₂ emissions, CO_{2_f} is the fuel combustion CO₂ emissions, CO_{2_i} accounts for the combustion-related CO₂ emissions of i^{th} fuel, and CO_{2_e} is the electricity CO₂ intensity.

For the fuel-related emissions, the waste biomass used as fuel is assumed to be sustainable; hence, biomass combustion CO₂ equals zero. Whereas the fuel emissions intensity is obtained from EPA's emission factors for GHG inventories [17], we used the following emissions factors: for electricity, 0.4 kg/kWh; for conventional SMR hydrogen, 10 kgCO₂e/kg H₂; and for electrolysis green hydrogen, 0.97 kgCO₂e/kg H₂ [18].

Cost assessment

Cost performance of the proposed cement manufacturing is conducted to assess the economic viability of this decarbonization strategy when compared with the conventional cement pathway. The direct equipment cost (DEC) of the cement facility is estimated based on [4] using the sixth-tenth rule to adjust for plant capacity.

The equipment cost is presented in $US2020 using the Chemical Engineering Plant Cost Index [19]. Based on the computed DEC, the total capital investment is calculated using correlations from [20,21]. The operating costs (variable and fixed) were estimated as a function of plant-size consumables (feedstock, fuel, electricity), labor, maintenance, operating overhead, and property insurance costs [4,21]. The MCSP is computed by conducting a discounted cash flow rate of return over the assumed lifetime of the plant using the economic parameters presented in Table 2.

Parameter	Value	Parameter	Value
Plant life (years)	30	Tax rate (%)	40
Plant avail. (%)	75	Rate of return (%)	12
Plant loan (years)	10	Depreciation	MACRS
Loan interest (%)	9.5	Working capital	15%
Debit/equity (%)	50	Operating hours	8,000
Fuel costs ($/GJ)			
Coal	2.01	Distillate fuel oils	9.70
Petroleum coke	2.69	Biomass	3.34
Natural gas	2.93	SMR H₂	7.09
Waste oils/tars	0.01	Electrolysis H₂	31.91
Coke and breeze	2.02		

Table 2: Economic parameters and assumptions.

Cost of CO₂ avoided

We computed the CCA to ascertain the additional cost incurred to offset a unit amount of CO₂ in cement manufacturing. The CCA formulation is given in Eq. (2) based on [22,23]:

$$CCA = \frac{MCSP_s - MCSP_c}{CO_{2,c} - CO_{2,s}} \qquad (2)$$

where $MCSP_c$ and $MCSP_s$ are the minimum cement selling price of the conventional and scenario hydrogen fuel fired cement in $/MT cement, respectively; and $CO_{2,c}$ and $CO_{2,s}$ are the CO₂ emissions of both the conventional cement and scenario hydrogen fuel blended cement in kgCO₂eq/MT cement, respectively.

RESULTS

Systems performance: Gray hydrogen blend

Table 3 shows the MCSP, facility-level CO₂ emissions, and CCA for different blends of gray hydrogen ratios when compared with the conventional clinker. The MCSP for conventional cement is $106.9/MT, whereas a blend of hydrogen between 5% and 20% changes the

Table 3: Costs and performance analysis of SMR hydrogen blend ratios with conventional fuels

Metric	Unit	Conventional	5% H₂	10% H₂	15% H₂	20% H₂
Cost						
Fuel	M$/year	7.02	7.71	8.39	9.09	9.76
Electricity	M$/year	4.03	4.03	4.03	4.03	4.03
Capital	M$	369.3	369.3	369.3	369.3	369.3
Fixed O&M	M$/year	36.42	36.42	36.42	36.42	36.42
Variable O&M	M$/year	7.22	7.22	7.22	7.22	7.22
MCSP	$/MT	106.9	107. 6	108.2	108.9	109.7
Emissions						
Combustion CO₂	kgCO₂/MT	230	227	225	221	218
Process CO₂	kgCO₂/MT	518	518	518	518	518
Total CO₂	kgCO₂/MT	749	746	743	739	736
Cost of CO₂ avoided	$/MT CO₂	–	228.9	246.9	228.9	228.9

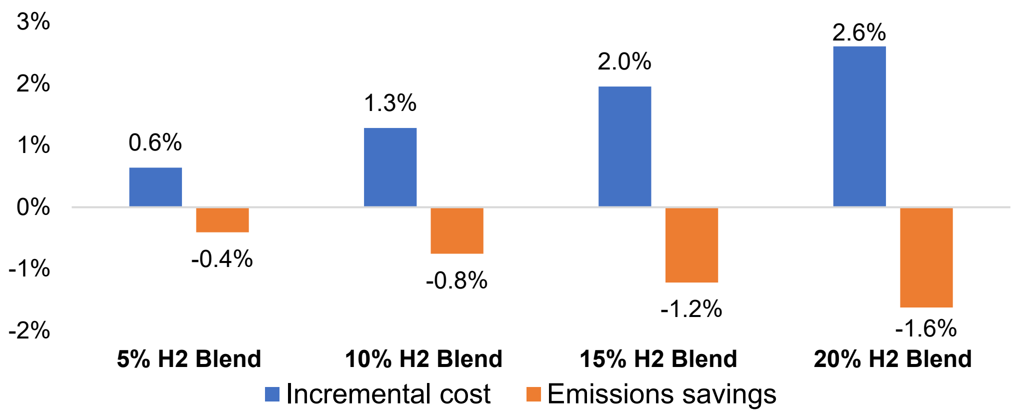

Figure 3: Percentage change in cost and emissions of cement for SMR hydrogen blends.

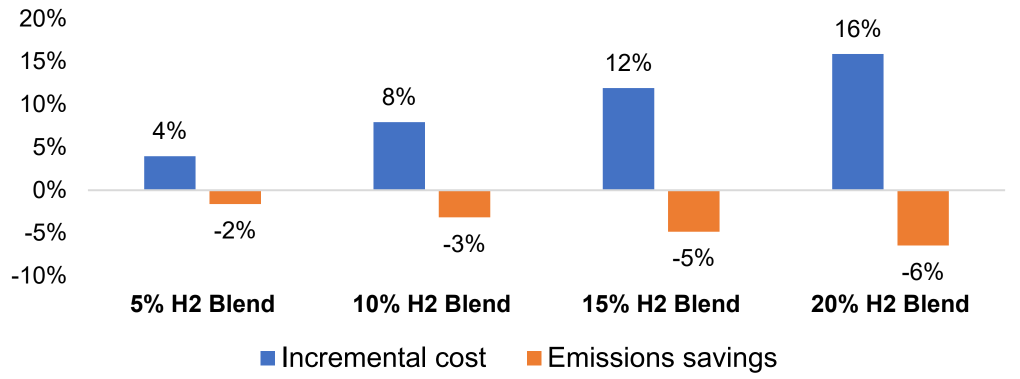

Figure 4: Percentage change in cost and emissions of cement for green hydrogen blends.

MCSP to \$107.6–\$109.6/MT. This represents an increase of up to \$2.8/MT cement. As can be observed (Table 1), the change in cement cost affects only the fuel cost owing to hydrogen use. Other cost components such as electricity (power), capital, fixed operating & maintenance (O&M), and variable O&M were assumed to remain the same. This assumption is feasible because hydrogen blends up to 20% are currently stipulated as the maximum limit before major infrastructure change is required [24].

In terms of emissions reduction, whereas the process emissions remain unchanged when hydrogen is blended in the fuel mix (Table 1), energy-related CO_2 emissions change depending on the amount of hydrogen blended. Hence, the total scopes 1 and 2 CO_2 emissions for the 5%–20% H_2 blends ranged between 736.4 and 745.5 kgCO_2/MT cement. If only the energy-related CO_2 emissions are considered, a 5% maximum CO_2 emissions reduction is achieved. This extent of emissions reduction is due to the scope 2 emissions associated with hydrogen production. Hypothetically, only when the scope 2 emissions of SMR hydrogen are zero can a significant reduction (as high as 23%) in energy-related CO_2 emission be achieved.

The CCA—a function of the additional cost incurred to avoid CO_2 emission—ranged between \$228.9 and \$246.9/MT CO_2. An interesting observation in the computed CCA is the increase in CCA from \$228.9/MT (for 5% H_2) to \$246.9/MT (for 10% H_2), followed by a decrease back to \$228.9/MT (for 15% and 20% H_2 blends, respectively). This phenomenon is linked to the extent of emissions offset when compared with the extra cost incurred to achieve such an extent of reduction.

Figure 3 depicts the comparative emissions savings of an H_2 blend with the corresponding change in MCSP necessary to achieve the CO_2 reduction. Blending 5% H_2 in the clinker fuel mix had only a 0.4% reduction in total facility-level CO_2 emissions while increasing the cost by 0.6%. When 10% H_2 is blended, only 0.8% reduction in CO_2 emissions is achieved—increasing the cost of cement by 1.3%. At 20% H_2 blend, emissions reduction is still below 2%, whereas the clinker cost increases by 2.6%. One might wonder why the emissions reduction is not significant for a zero-carbon fuel like hydrogen. We considered indirect CO_2 emissions (scope 2) associated with hydrogen production, which, on a mass basis, are higher than the fossil fuels for which they substitute.

Systems performance: Green hydrogen blend

When green hydrogen is considered as the source

Table 4: Costs and performance analysis of green hydrogen blend ratios with conventional fuels

Metric	**Unit**	**Conventional**	**5% H_2**	**10% H_2**	**15% H_2**	**20% H_2**
Cost						
Fuel	M$/year	7.02	13.8	19.0	24.2	29.4
Electricity	M$/year	4.03	4.03	4.03	4.03	4.03
Capital	M$	369.3	369.3	369.3	369.3	369.3
Fixed O&M	M$/year	36.42	36.42	36.42	36.42	36.42
Variable O&M	M$/year	7.22	7.22	7.22	7.22	7.22
MCSP	$/MT	106.9	111.1	115.4	119.6	123.9
Emissions						
Combustion CO_2	$kgCO_2$/MT	230	218	206	194	182
Process CO_2	$kgCO_2$/MT	518	518	518	518	518
Total CO_2	$kgCO_2$/MT	749	736	725	712	700
Cost of CO_2 avoided	$/MT CO_2	–	351.7	358.3	351.7	351.7

of hydrogen in the fuel mix, cost and emissions performance differs, as shown in Table 4. In terms of cost, H_2 blends between 5% and 20% yield an MCSP of $111.1–$123.9/MT with corresponding CO_2 emissions of 700–736 $kgCO_2$/MT cement. Comparing the emission reduction achieved using green hydrogen to that of gray hydrogen, additional 5% and 16% improvements in facility-level and energy-related CO_2 emissions are achieved, respectively. For a 5% reduction in facility-level emissions, up to a 13% increase in MCSP is observed for green hydrogen-fired cement compared with the gray hydrogen counterpart. Clearly, this premium for decarbonized cement might be difficult for cement manufacturers to compete in the market, given the extent of reduction.

It is not surprising that the CCA for the use of green hydrogen ranges between $351.7 and $358.3/MT CO_2. Again, this computed CCA is more expensive than the cost of carbon capture reported for the cement industry ($50–$60/MT) [25]. This implies that it is economically and even environmentally competitive to adopt and use CC in cement rather than use hydrogen as a fuel for decarbonization purposes.

Finally, Figure 4 directly compares the emissions reductions achieved and the associated costs for different H_2 blend ratios relative to conventional cement. For a 2% reduction in CO_2 emissions, a 4% increase in MCSP was observed for a 5% H_2 blend. A maximum of 6% reduction in facility-level CO_2 can be achieved when 20% H_2 is blended in a clinker fuel mix—at the expense of a 16% increase in MCSP. Given the minimal reduction in emissions at a high cost, at present it does not make economic sense to use hydrogen as a decarbonization lever in the cement industry.

Sensitivity analysis

Because green hydrogen blend in cement fuel mix offers more CO_2 emissions reduction when compared with gray hydrogen, the effect of green hydrogen's cost on MSCP is assessed via sensitivity analysis. Figure 5 shows the effect of green hydrogen's cost on MCSP for different hydrogen blend ratios.

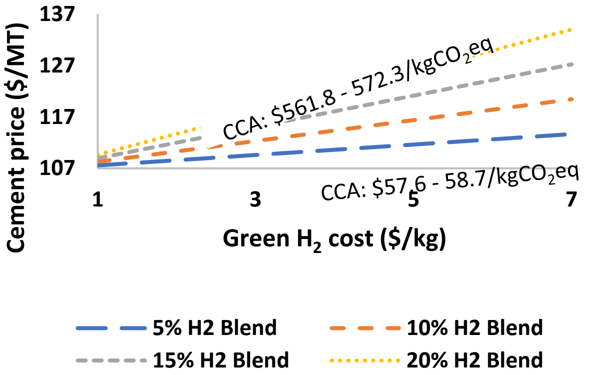

Figure 5: Sensitivity analysis of the effect of green hydrogen cost on cement price.

At a green hydrogen price of $1/kg owing to the federal Infrastructure Reduction Act 45 V tax credit that incentivizes green hydrogen products, the MCSP is between $107.6 and $109.7/MT for 5%–20% hydrogen blend ratios. Even at $1/kg for green hydrogen, the selling price of cement is still $0.70/MT higher than that of conventional cement. The CCA of the cement at this hydrogen price is between $57.6 and $58.7/MT CO_2 avoided, which is competitive with that achieved via CCS. To a greater extent, because CCS implementation at a specific cement facility can be impeded by a lack of CO_2 transportation and sequestration sites, use of green hydrogen proves to be more suitable. Nevertheless, on an emissions intensity basis, a CCS-enabled cement facility at 85% capture (112.3 $kgCO_2$/MT) outperforms the green hydrogen-fired (700 $kgCO_2$/MT) cement facility.

At a $7/kg green hydrogen price, the cost of cement increases between $113.7 and $134/MT with a corresponding CCA of $562–$572/$kgCO_2eq$ avoided. Overall, the high cost of hydrogen when compared with the extent of emissions reduction limits its use as a decarbonization strategy in cement production.

DISCUSSIONS

Decarbonizing cement production is vital to attaining US economy-wide GHG reduction goals. With an interest in decarbonizing industrial process heat, cement manufacturers are beginning to propose the adoption of hydrogen as fuel. Argos and CEMEX are pushing toward a hydrogen share in their cement fuel mix for facilities in Honduras [28] and Europe [14], respectively. However, this analysis shows that pursuing this route as a decarbonization strategy is highly limited by cost when compared with the amount of reduction attained. At best, when green hydrogen (with zero emissions) constitutes 100% of fuel used in cement production (not shown in this analysis), only a 29% reduction in scope 1 emissions is achieved. Nevertheless, when scope 2 emissions of hydrogen and electricity are considered, the reduction amount drops to 26%. Therefore, it is evident that hydrogen should be channeled to other industrial applications.

Despite the emissions- and cost-related challenges, supply chain and other technical barriers still impede the widespread adoption of hydrogen as fuel (blend mix or 100% H_2). At 100% use of hydrogen in the cement sector, the demand for hydrogen per annum will be about 2 MMT (based on 2022 clinker production of 78 MMT). Because the current annual US hydrogen production is about 10 MMT, a supply-demand issue might arise. In addition, significant reconfiguration of existing cement facilities with high CAPEX will be required [26].

Technical challenges associated with hydrogen include storage owing to low volumetric energy density, increasing tendency of fire or explosion because of its wide flammability range in air, burning challenges linked to its burning velocity that will require complex control systems, high NO_x formation because it has a high adiabatic flame temperature (burner modification required, with associated costs), and low thermal radiative heat transfer owing to the absence of soot exhibited by hydrogen flames [27] that affect clinker quality. Other technical challenges include hydrogen leakage and equipment/pipeline embrittlement, etc. Hydrogen leaks appear to be very detrimental because hydrogen tends to react with hydroxyl radicals, reducing the amount of OH needed to break down methane in the atmosphere [29].

Overall, more research and development are needed in the efforts to adopt hydrogen as fuel in the cement industry and other sectors in which hydrogen has the potential to contribute to decarbonization goals. In addition, government funding and policies will play a key role in reducing the cost of hydrogen (green) for industries to begin this much-needed shift.

CONCLUSION

Clean hydrogen is a low-carbon fuel, feedstock, and energy source that can play a key role in the decarbonization goals of the US economy. Nevertheless, the use of hydrogen as a fuel has inherent supply chain technical challenges that must be overcome before it can safely and easily be adopted as a fuel mix. Even though these challenges are addressed, the cost implications could prove to be prohibitive for industry—particularly, the cement industry, with low margins—to adopt hydrogen as fuel. At 20% green H_2 blend, a CO_2 emissions reduction of 6% can be achieved at a significant 16% increase in cement cost. Therefore, it might not be economically viable for the cement industry to adopt hydrogen as a fuel in clinker manufacturing.

As observed, the CCA did not change for the hydrogen blend ratios except for 10%. The obvious explanation for this impact is that blending hydrogen as fuel (within this ratio) in clinker production does not really affect carbon emissions reduction, given the significant contribution to the overall emissions by the pyroprocessing step. Because there is an additional 8% increase in CCA for the 10% hydrogen blend, any cement facility considering blending hydrogen in the fuel mix is better off with any of the other blend scenarios because the cost increment is commensurate with the emissions offset.

ACKNOWLEDGEMENTS

This research is funded by DOE Industrial Efficiency and Decarbonization Office Strategic Analysis.

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