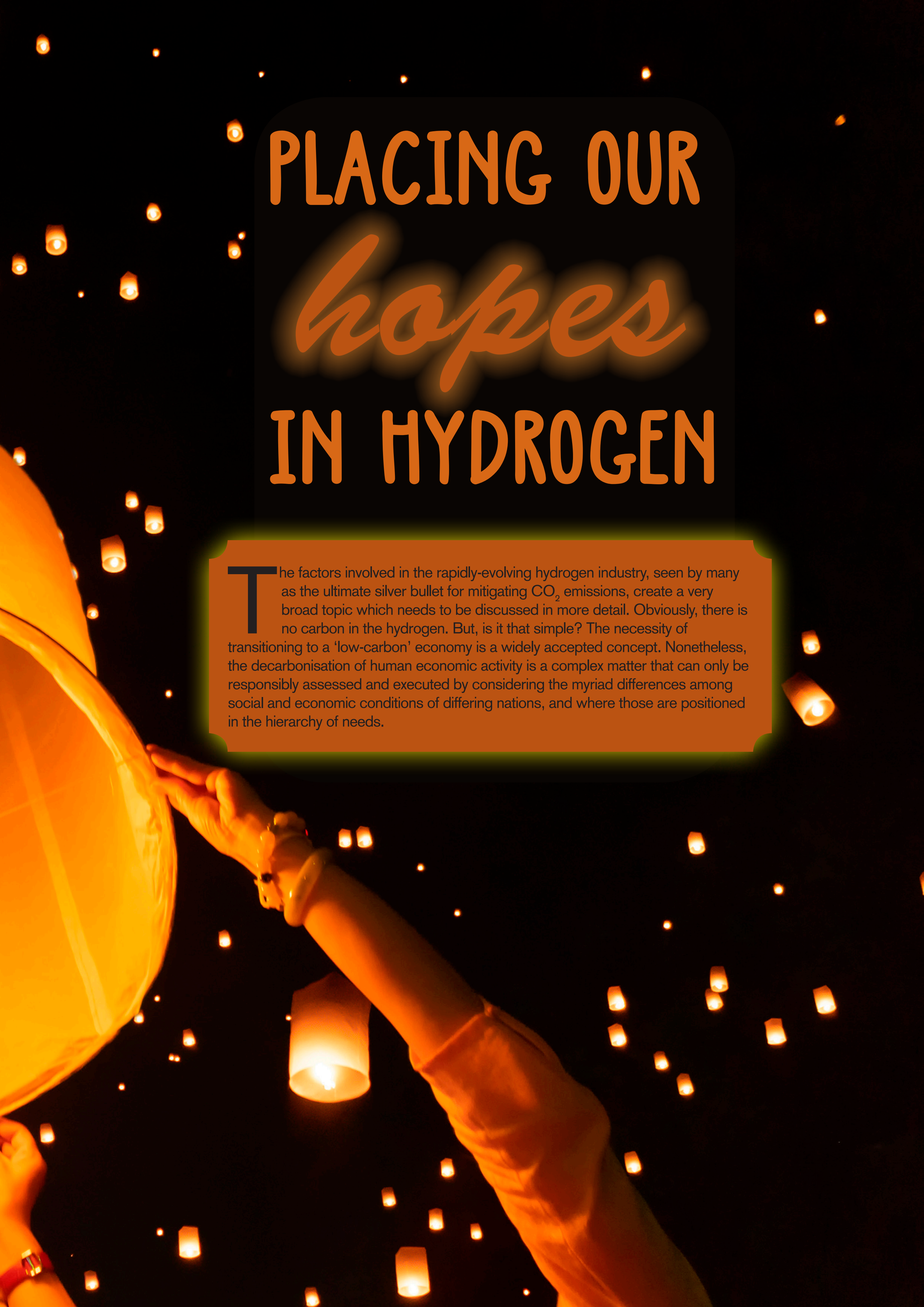
Joel Maia, FCT Combustion, explores whether hydrogen is the right method for reducing CO_2 emissions in clinker production.



PLACING OUR *hopes* IN HYDROGEN

The factors involved in the rapidly-evolving hydrogen industry, seen by many as the ultimate silver bullet for mitigating CO_2 emissions, create a very broad topic which needs to be discussed in more detail. Obviously, there is no carbon in the hydrogen. But, is it that simple? The necessity of transitioning to a 'low-carbon' economy is a widely accepted concept. Nonetheless, the decarbonisation of human economic activity is a complex matter that can only be responsibly assessed and executed by considering the myriad differences among social and economic conditions of differing nations, and where those are positioned in the hierarchy of needs.

In that context, the utilisation of hydrogen on a large industrial scale has been identified as one of the paths to reducing carbon dioxide emissions, but it is still 'only one piece of the puzzle', as highlighted by the International Energy Agency (IEA) in its Global Hydrogen Review 2021 Report (Figure 1).

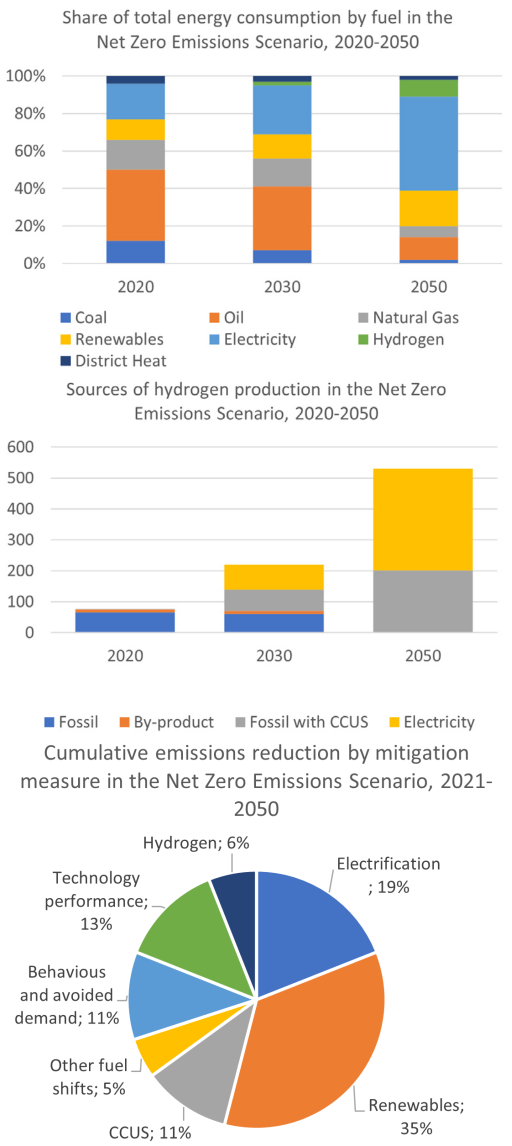


Figure 1. Hydrogen is an important part of the net zero emissions scenario ZNE, but it is only one piece of the puzzle (IEA).

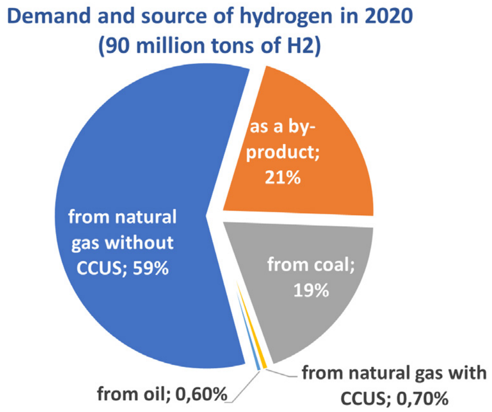


Figure 2. Demand and source of hydrogen in 2020 (IEA).

This article will try to shed some light on the potential role of hydrogen utilisation in the cement industry by breaking down the approach into three main categories: environmental footprint, economics, and specific challenges in clinker production.

Hydrogen's environmental footprint

The first myth to be addressed is that hydrogen is a clean fuel. Although the straight combustion of hydrogen does not generate any carbon dioxide, most of the hydrogen produced in the world is responsible for a fair amount of greenhouse gas emissions. The IEA estimates that hydrogen production accounts for the formation of 830 million tpy of CO_2 (with the current hydrogen production matrix (Figure 2), 1 kg of hydrogen produced generates around 10 kg CO_2).

However, there is an important differentiation to be made depending on production processes. Colours are often used to indicate how 'clean' the hydrogen production is: ranging from grey (brown or black are also used), to blue, and green, from the least to the most environmental-friendly process.

- Grey (brown and black) hydrogen is produced from fossil hydrocarbon-based fuels, typically natural gas (grey hydrogen) or coal (brown or black hydrogen). The fossil fuel components are broken down into hydrogen and carbon dioxide, among other minor components. This method, known as the 'steam reforming process' (SRP, or SMR for steam methane reforming, when the hydrocarbon used is methane), releases the same or larger amounts of CO_2 per unit of energy when compared to the direct use of the originating fuel (natural gas or coal for example). The reason for this is that this process requires an additional energy source to break the fossil fuel into hydrogen and CO_2 and this additional energy source usually comes from fossil fuels.
- Blue hydrogen: the production process is similar to grey hydrogen, with the difference being that the majority (80 – 90%) of the CO_2 produced by the blue hydrogen process is captured and stored through a carbon capture, usage, and storage (CCUS) unit.
- Green hydrogen: the hydrogen is produced using water electrolysis powered by renewable energy such as solar or wind. As a consequence, oxygen is released

to the atmosphere (or used for other processes) as a byproduct. From this list, it is clear that green hydrogen is the only truly carbon neutral source of hydrogen (not considering the CO_2 generated to produce the solar or wind equipment).

There are other 'colours' of hydrogen, depending on the processes, or the power source used to generate it. Up to now, these continue to represent a pretty minor percentage of the hydrogen production environment and therefore will not be discussed.

It means, in a broader context, that the combustion of grey hydrogen has a larger CO_2 footprint per unit of energy released than natural gas and fuel oil (Figure 3) and a similar CO_2 footprint to coal combustion. Therefore, the use of grey hydrogen as direct substitute for natural gas or fuel oil is actually environmentally detrimental, while even direct coal substitution is barely environmentally beneficial.

As a matter of fact, over 99% of the hydrogen produced in the world is still in the 'grey' category – blue/green hydrogen accounts for less than 1% of total production.

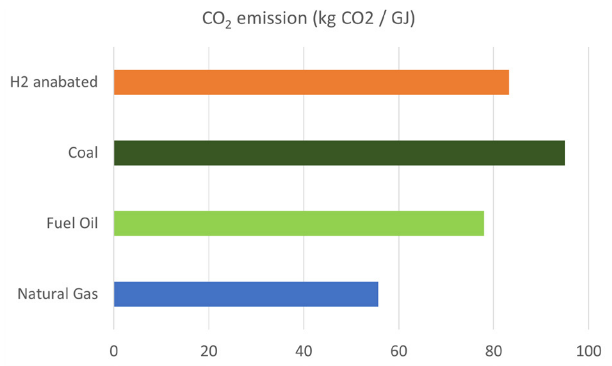


Figure 3. CO_2 emission (kg CO_2/GJ LHV heat released).

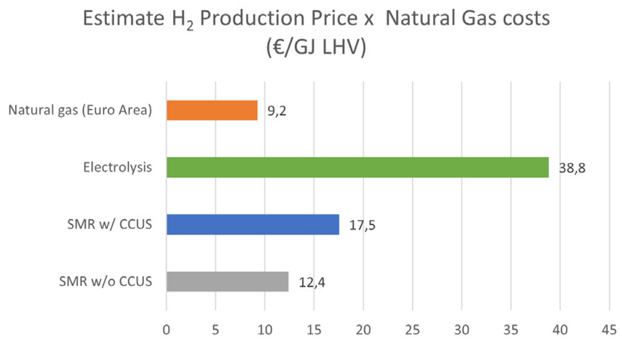


Figure 4. Estimated hydrogen production cost and natural gas price.[1]

Economics

Production cost

Production of blue/green hydrogen is not cheap (Figure 4). There is still an important price gap between natural gas and hydrogen.

The electrical consumption and CAPEX of electrolytical units varies depending on the technology (proton exchange membrane, alkaline, anion exchange membrane or solid oxide), configuration of the unit and provider, however production of hydrogen using electrical power is still energy intensive (Figure 5).

From Figure 5, it is possible to conclude that the production process of green hydrogen is still pretty inefficient. For each kW of 'chemical energy' in hydrogen, it requires between 1.50 and 2.35 kW of electrical energy, meaning an efficiency of between 42 and 66%.

If compounded with the conversion efficiency of renewable energy sources (15 – 20% and 20 – 50% for solar panels and windmills, respectively), the result is a meagre 6 – 33% overall efficiency. This is something that is worth considering, although the renewable sources mentioned are virtually endless.

Scalability

Green hydrogen production facilities are quite small. Although this is a fast-evolving field, it is believed that the largest green hydrogen plant in the world in 2020 had a hydrogen production of equivalent to 20 MW, and it was in reality an assembly of smaller units. More recent information indicates the development of newer plants, with larger capacity in 2022.

Likewise, the total production of green hydrogen in 2021 was around 300 MW.

If all of this energy was used for clinker production, it would be possible to operate just two kilns at a production rate of 4000 tpd and 775 kcal/kg over the course of a year, considering 100% hydrogen as fuel.

Infrastructure

There is no large-scale infrastructure or distribution network supplying hydrogen to industrial facilities. The existing natural gas pipelines, compressors, accessories are not fully adapted to transport 100% hydrogen for several reasons, including among others:

- Hydrogen carries about 67% less energy per cubic meter (distribution equipment and pipelines depend mostly on volumetric flow rather than mass flow) when compared to natural gas.

- Hydrogen at high pressures may penetrate the steel structure and cause embrittlement of the metal.

Therefore, the implementation of distribution networks will require substantial CAPEX.

At this point, it is clear that the only environmentally viable type of hydrogen is green hydrogen. Extensive research is being conducted and large incentives are being granted, in order to reduce the price gap between the green hydrogen production and other types of fuels, to improve the efficiency of its production process as well as making it

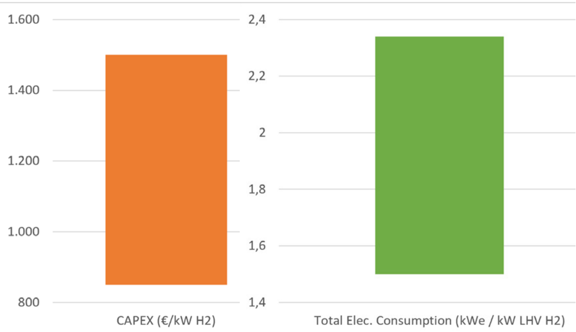


Figure 5. CAPEX and electric consumption of electrolytic systems.

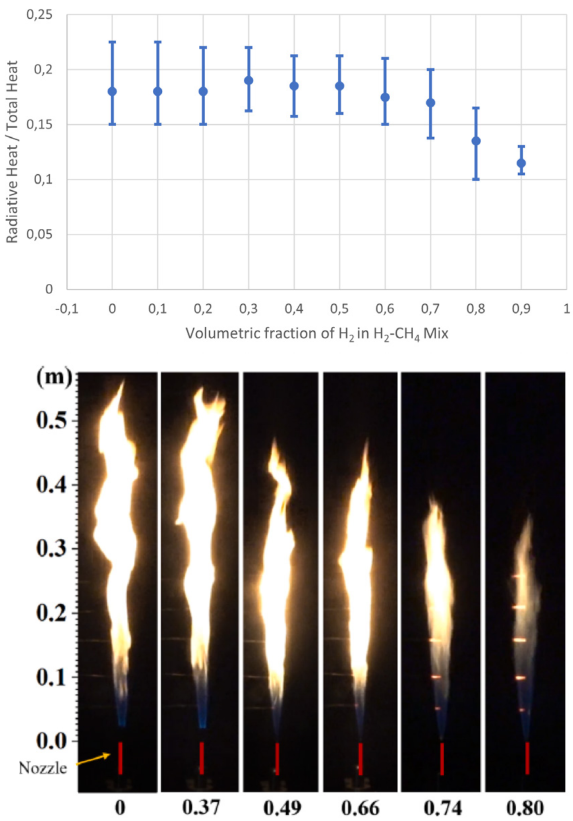


Figure 6. Decrease in emissivity over 60% of H_2 in H_2/propane mix (top). Decrease of turbulent flame length with the increase of H_2 in H_2/propane mix (bottom).[2]

available to 'heavy consumers'. Although there is still a long way to go, there is a general optimism that these gaps will be reduced or eliminated in the future.

Cement production

Assuming that all the other aspects are addressed, i.e. green hydrogen is readily available at the kiln platform at a reasonable cost, next the cement process itself must then be tackled. Firing hydrogen in clinker kilns requires special attention to few points:

Heat transfer

Pure hydrogen flames are non-luminous and poorly radiative because, unlike solid fuel flames, they do not generate soot or contain particles.

FCT foresees co-firing as a feasible solution to improve radiative properties of the flame. Although none of them have been tried in large scale combustion units, FCT is confident there is sufficient evidence to back those alternatives.

Recent studies suggest that a mixture of up to 25% hydrogen/75% natural gas (volume basis) has no significant impact in the overall emissivity of the flame, when compared to 100% natural gas.

Other experiments with propane/hydrogen mixtures have shown that heat transfer by radiation sharply drops, but only when the blend is over 60% hydrogen (Figure 6).

The injection of pulverised fuel is another alternative to address the emissivity and heat transfer issue. It significantly increases the emissivity and therefore the heat transfer properties of a gaseous fuel flame (Figure 7).

Obviously, the addition of materials without any calorific value increases the fuel consumption as part of the energy will be used to heat such particles, however, it is believed that the benefits of the higher emissivity and improved heat transfer properties of the flame overcome the increased fuel usage in a typical clinker kiln. An easier way, that is already available today, to avoid the reduced emissivity of hydrogen combustion would be to use it in calciners, where the flame's radiation is not the main energy transfer mechanism.

NOx

Hydrogen generates a higher flame temperature, and therefore increased NOx emissions. Some research points out that up to 10% blending of hydrogen in natural gas (in volume) is manageable in terms of NOx emissions, with no significant impact detected; however, a 25% hydrogen mixture causes a significant increase in NOx formation (Figure 9).

Laboratory-scale research leads to the same conclusion: the higher the hydrogen concentration, the higher the NOx formation. The industry must bear in mind that the aggregate effect of lower radiative heat transfer and higher flame peak temperatures potentialise the kinetics of NOx generation reactions.

Table 1. Average radiative fraction from different pre-mixture conditions.

Fuel-Air Mix	Methane-Air	Methane-Air-25g/m³ Coal	Methane-Air-25g/m³ Sand	Methane-Air-25g/m³ $NaHCO_3$
Radiative heat/Total heat	2.7 – 6.0%	10.5 – 17.5%	11.5 – 27.0%	12.7 – 27.0%

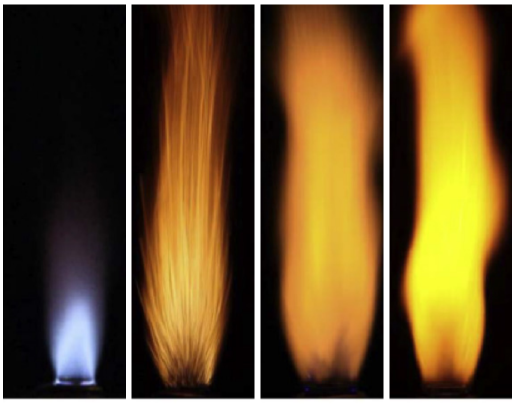


Figure 7. Instantaneous flame images showing the effect of particle addition at 25 g/m³ on methane-air stoichiometric flame.[3]

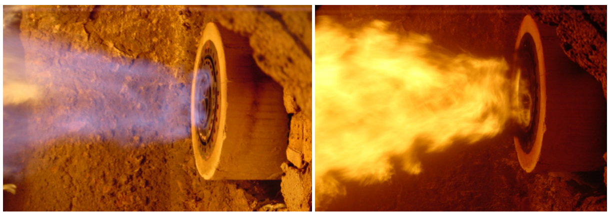


Figure 8. White cement kiln with retracted burner firing 100% natural gas (left), and firing 70% natural gas/30% pulverised fuel (right).

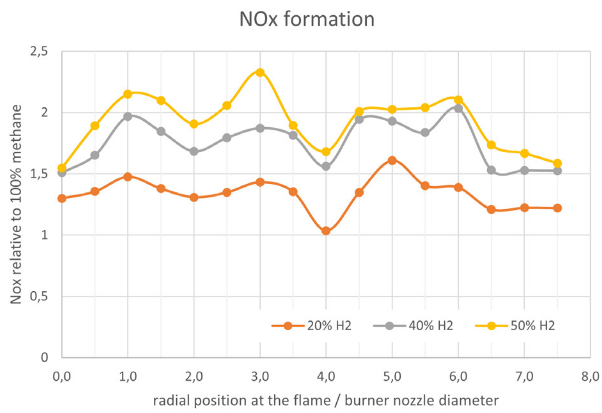


Figure 9. Measured relative radial NO concentration profiles for different % H_2 volume fractions in the hybrid fuel.[5]

Conclusion

Despite cement production being an energy intensive process, combustion accounts for around 35% of the total CO_2 emissions of the cement production chain (from quarry to final consumer).[4] Any potential reduction in CO_2 emissions in this area will only impact around one third of the total CO_2 generated. The vast majority of CO_2 emissions come from the calcination of the limestone, a field in which advances are also being made for reducing the CO_2 emissions, but this is a topic for another article.

For the time being, hydrogen as a fuel is still a widely unavailable, expensive to be produced on a large and sustainable scale, with challenges that inhibit it being used efficiently in rotary kilns for clinker production, even though fewer challenges are present for its use in the calciner. However, these challenges are being intensively investigated by both industry and academia, leading some to believe that breakthroughs are about to happen in the short- to medium-term. ■

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