Plasma pyrolysis for a sustainable hydrogen economy

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[Standfirst] Producing low-carbon hydrogen to use as a clean energy carrier is an important step towards a decarbonized economy. Plasma pyrolysis is an emerging technology that has great potential for the large-scale production of low-carbon and affordable hydrogen.

The depletion of fossil fuels and the global warming crisis have generated increasing interest in the development of new, low-carbon energy sources. Hydrogen is increasingly seen as a potentially zero-carbon and zero-pollution energy vector that can substitute fossil fuels in residential, transport, industrial and commercial sectors with hard-to-abate emissions, enabling a transition to a net-zero carbon circular economy. To meet the ambitious emission reduction targets set in the COP26 Glasgow agreement, global annual greenhouse gas emissions will need to be reduced by 45% by 2030 from 2010 levels and to net zero by 2050. A sustainable hydrogen-based economy has the potential to enable the achievement of these goals and to decarbonize global energy markets.

To date, 96% of hydrogen is produced from fossil fuels via reforming — the rearrangement of the molecular structure of a hydrocarbon — and pyrolysis — the thermal decomposition of organic molecules in the absence of air. The most common processes include steam methane reforming (48%), naphtha and heavy oil reforming (30%) and coal gasification (18%). All these processes emit a high amount of CO_2 (ref.[1]). While 80–90% of the emitted CO_2 can be sequestrated by combining the steam methane reforming process with CO_2 capture to produce low-carbon hydrogen, this process inevitably increases costs. Low-carbon (or zero-carbon) hydrogen production routes are essential to achieve an environmentally friendly hydrogen economy. Water electrolysis powered by renewable energy is the best way to produce green hydrogen but is currently costlier than steam methane reforming combined with CO_2 capture processes. Hence, in the short-to-medium term, low-carbon and affordable hydrogen production will continue to rely heavily on fossil fuels.

Plasma pyrolysis of methane is an effective route for zero-carbon hydrogen production and constitutes a promising bridge technology. A plasma is an ionized gas that consists of a variety of reactive species (such as energetic electrons, ions, excited species, photons and radicals) that provide efficient and fast heat transfer, accelerating chemical reactions that would otherwise be thermodynamically unfavourable. This method can easily crack methane (and other hydrocarbons) into H_2 and elemental carbon. If the process is powered by renewable energy, there are no CO_2 emissions. The produced hydrogen can be safely stored and transported over long distances using liquid organic hydrogen carriers, organic molecules that can store and release hydrogen through easy-to-handle chemical reactions, and can then be used as a chemical feedstock or fuel in many applications, such as power generation, hydrogen vehicles or in the production of ammonia, methanol or heat (Fig. 1). Because fossil fuels will continue to play an important role in the short run, the decomposition of methane via pyrolysis represents a promising technology for CO_2-free hydrogen production. In the long run, methane pyrolysis will contribute to the transition from fossil fuels to hydrogen as the energy carrier[2–4].

[H1] Pyrolysis of methane for zero-carbon hydrogen production

State-of-the-art methane pyrolysis processes can be grouped into three main categories: catalytic pyrolysis, thermal pyrolysis and plasma pyrolysis. Plasma pyrolysis is the closest to commercialization. A plant at the industrial scale, the Karbomont plant, was opened in Canada in 1998, with a technology readiness level (TRL) of 8 (first demonstration of commercial system). The plant closed in 2003, but the technology is still being developed, and the company Monolith Materials is in the commissioning stages of a commercial-scale plant in the United States, the Olive Creek plant, which also has TRL 8. For comparison, thermal pyrolysis is at TRL 3 (proof-of-concept demonstration) and catalytic pyrolysis, developed mainly by BASF, is at TRL 4 (prototype in laboratory environment)[2].

A techno-economic analysis taking into account different parameters, such as the electricity supply, showed that plasma pyrolysis of methane for hydrogen production using electricity from renewable sources generates significantly lower CO_2 emissions than the other methane pyrolysis routes and the steam methane reforming process[4]. Based on life-cycle assessment and a techno-economic analysis, the levelized cost of hydrogen produced using plasma pyrolysis (the sum of costs over the plant lifetime divided by the total amount of hydrogen produced) can be 2–3 € per kilogram of hydrogen, which is much cheaper than the cost of hydrogen made from water electrolysis (3.5–4.5 € per kilogram of hydrogen)[3]. In certain scenarios, the production of zero-carbon hydrogen via plasma pyrolysis of methane would cost less than 1.5 € per kilogram of hydrogen, competitive with steam methane reforming with CO_2 capture (1.1–2.3 € per kilogram of hydrogen)[3]. The source of methane can be natural gas, flared gas, refinery gas or biomethane (which is derived from anaerobic digestion of organic waste). Hydrogen produced from biomethane can be carbon-negative even when using non-renewable energy sources.

Thus, plasma methane pyrolysis not only holds promise for the production of affordable and zero-carbon hydrogen, but can also remove carbon from the carbon cycle and create additional revenue streams from the sale of the carbon obtained in the reaction.

[H1] Transforming plastic waste into hydrogen and carbon

The idea of transforming waste into valuable products is gaining increasing interest[5–7]. Turning plastic waste into hydrogen could be a cost-effective, safe and sustainable route for recovering energy and mitigating the negative impact of plastics on the environment, and would be an important addition to a circular hydrogen economy. Plasma pyrolysis can turn non-recyclable plastic waste (such as single-use face masks) into low-carbon, affordable hydrogen and value-added carbon products (such as carbon nanotubes). These value-added carbon products can be used in many applications, including as conductive or insulating agents, strengtheners for rubber in tyres, UV stabilizers, and in electrodes in electrolyser cells for green hydrogen production via water electrolysis, achieving a waste-to-energy system for a sustainable circular economy. The integration of plasma pyrolysis with effective waste sorting and processing systems will be critical to achieving an effective waste-to-energy supply chain for maximizing the recovery of value from waste by turning it into hydrogen.

[H1] Considerations, challenges and opportunities

Plasma pyrolysis is the most promising technology for the production of hydrogen and carbon from methane cracking. The Olive Creek plant built by Monolith Materials is capable of producing 5,000 tons of hydrogen per year, and the project is being developed to deploy this technology at the commercial scale (TRL 9). However, despite promising progress, many challenges remain. The hydrogen production cost is still not competitive with that of hydrogen made by state-of-the-art steam methane reforming with CO_2 capture, although the sale of the produced carbon can offset a substantial fraction of the cost. Plasma pyrolysis of non-recyclable plastic waste is very promising in terms of sustainability, but is still at the very early stages of development. Further research will be needed to reduce the cost of methane cracking and bring plastic waste pyrolysis to maturity. Further research and technology advancement from academia, as well as engagement with stakeholders, including industry and policymakers, are critical to establish plasma pyrolysis as a viable solution to achieve a sustainable hydrogen economy across all sectors (production, storage, transportation and distribution). There is still a long way to go to bring this technology to commercial maturity on a global scale, but plasma pyrolysis is currently the most promising option for the production of zero-carbon (or even carbon-negative) hydrogen from different types of feedstock with minimal environmental impact.

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Author contributions

The authors contributed equally to all aspects of the article.

Competing interests

The authors declare no competing interests.

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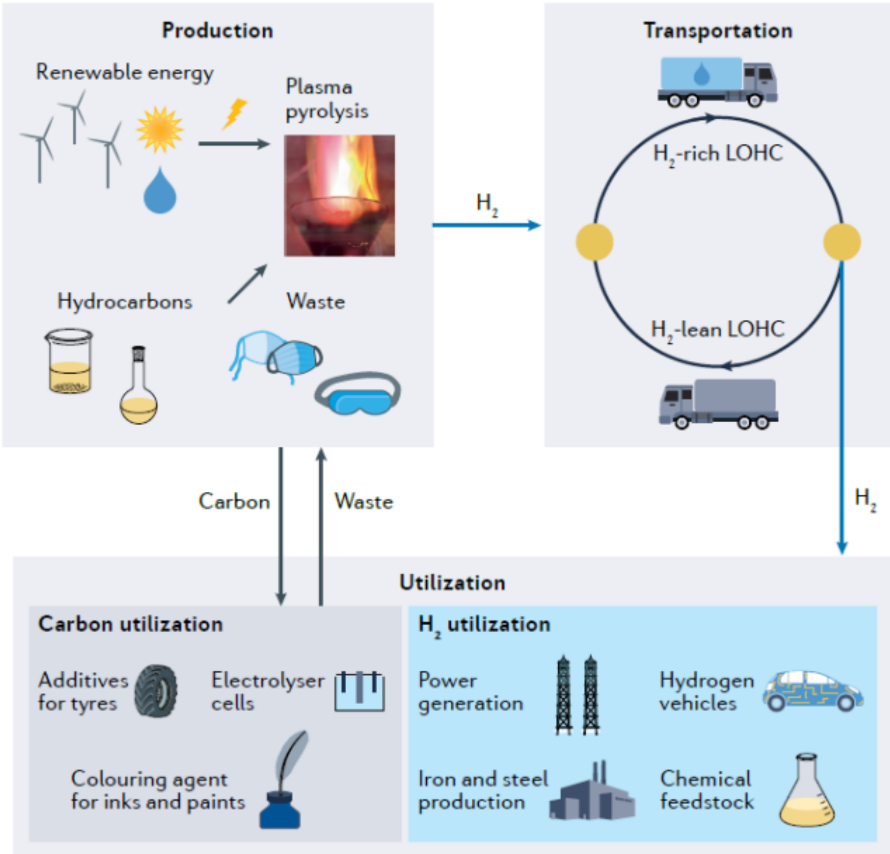

Fig. 1 | **Hydrogen production by plasma pyrolysis**. Schematic representation of hydrogen production via plasma pyrolysis and renewable electricity and of its storage and transport and utilization. LOHC, liquid organic hydrogen carrier.