12CNIT-2022 - FULL PAPER

Hydrogen from municipal solid waste as a tool to compensate unavoidable GHG emissions

Vicente Soler[1], José Ignacio Linares[1], Eva Arenas[1,2], José Carlos Romero[2]

[1]Rafael Mariño Chair in New Energy Technologies, Comillas Pontificial University, Alberto Aguilera 25 – 28015 Madrid, Spain, e-mail: linares@comillas.edu

[2]Institute for Research in Technology, Comillas Pontificial University, Santa Cruz de Marcenado 26 – 28015 Madrid,

Keywords: *Renewable hydrogen; municipal solid waste; greenhouse gases (GHG); steam methane reforming; carbon capture and storage (CCUS)*

TOPIC: RENEWABLE ENERGIES, ENVIRONMENTAL IMPACT AND CIRCULARITY

1. Introduction

Hydrogen from renewable sources (green hydrogen) is called to play a key role in the energy transition. It is enough to have a look at current reports to realize that when someone talks about green hydrogen usually means hydrogen from electrolysis using renewable electricity [1]. There are many advantages in the electrolysis as a procedure to produce green hydrogen, mainly due to its ability to allow long term storage of energy so managing intermittency of wind and photovoltaic farms. Disregarding the question about if green hydrogen should be employed only to replace the current use of fossil hydrogen in industry applications [1] or as an additional energy carrier, it is clear that if the production of hydrogen free of CO_2 emissions is obtained exclusively in electrolysis a large reinforcement in the electrical grid is required. This issue can be mitigated with a smart demand management.

Additionally to electrolysis, organic wastes are a valid way to produce CO_2 neutral hydrogen [2-4]. One of these routes is the steam methane reforming (SMR), coming from the methane of the upgrading of biogas. Such methane is usually designed as biomethane, and is called to play a key role in the energy transition. Biogas is produced from organic wastes (WWTP sludges, agroindustries, crop wastes, slurry, manure, landfills and municipal solid wastes) through an anaerobic digestion process. This biogas is mainly composed by methane, CO_2 and impurities. Although in some combined heat and power installations the biogas is burned in a gas turbine or internal combustion engine [5], it is worth to valorize it through an upgrading process where CO_2 and impurities are removed, obtaining biomethane, which can be injected in the natural gas grid [6].

Steam methane reforming is a well-known technology to obtain hydrogen, being nowadays the most employed method to produce the hydrogen currently consumed mainly for industrial uses [7]. The conventional feedstock for SMR is natural gas, designating the produced hydrogen as grey one. For more than 20 years [8] CO_2 capture techniques have been applied to the SMR process in order to obtain a low carbon hydrogen, designated as blue one, and to produce CO_2 for industrial uses. So, SMR including CO_2 capture is a mature technology where the shift of natural gas by biomethane does not imply any technological challenge. Regarding the costs, maintenance will be similar, but the lower productions will affect to the scale economy at investments and to the feedstock costs.

Green hydrogen from electrolysis currently exhibits high costs, and several points can be identified that will turn this cost into affordable: electrolyzers investment reduction, electricity cost reduction, lifespan increase and electricity consumption reduction [9]. In Spain 4 GW of electrolyzers are foreseen for 2030 [3]. This effort can be compensated if additional sources for hydrogen are considered, as organic wastes. The Spanish Roadmap of biogas [4] foresees a production of 10.41 TWh/year of biogas in Spain in 2030, being 55% of it transformed in biomethane. Assuming 70% of efficiency in SMR process with CO_2 capture [7], close to 120,000 tons of hydrogen can be produced (if all the biomethane were dedicated to hydrogen production), which might replace 1.2 GW of electrolyzers, that is, more than 25% of foreseen installed capacity. So, the use of biomethane as source of hydrogen can alleviate the pressure over the electrical grid, besides supporting circular economy and allowing a sustainable treatment of wastes, producing fertilizers with the by-products of the biogas [6].

This work proposes the use of biomethane as feedstock for SMR with CO_2 capture to produce hydrogen. The hydrogen produced from biomethane is green, as the CO_2 released is biogenic. So, if this CO_2 is captured, the emissions can be considered negative, as proposed in bioenergy with carbon capture and storage (BECSS). This novel method to produce hydrogen has been designated as "golden hydrogen", considering that removing CO_2 (which is designated as blue hydrogen) is as removing the blue color from the green one, obtaining yellow. As yellow usually is reserved for electrolytic hydrogen when it is obtained taking the electricity from the grid, "golden" has been finally proposed. Besides, the word "gold" suggests an extra quality hydrogen, due to its ability to compensate unavoidable CO_2 emissions when its negative emissions are taken into account.

In this work, both the production and costs of golden hydrogen using municipal solid waste (MSW) as primary feedstock are assessed. Its application is analyzed in two cases studies, one for public transport and another for blending in CO_2 emissions hard to abate sectors.

2. Materials and method

2.1. Production

Steam methane reforming is based on equation (1), the reformation itself, and equation (2), the so-called gas shift reaction. So, theoretically 4 moles of hydrogen are formed per 1 mole of methane. However, a self-consumption of methane occurs in order to maintain the thermal conditions in the reformer, which leads to a SMR efficiency (η_{SMR}): energy associated to the hydrogen produced regarding the energy associated to the methane consumed, both in lower heating value (LHV) basis. Taking into account this efficiency, the ratio of hydrogen outlet to the methane inlet (*HMR*) is given by equation (3). The same ratio is obtained for hydrogen to CO_2, which can be transformed into the mass ratio of CO_2 to hydrogen (*CHMR*) in equation 4. Regarding the capture of CO_2, there are three possible locations where CO_2 could be captured within the hydrogen plant: from the shifted syngas, from the pressure swing adsorption (PSA) tail gas or from the flue gas of the SMR. The last option produces the highest capture rate [7], so this option will be considered in this work.

$$CH_4 + H_2O \rightarrow CO + 3\,H_2 \quad (1)$$

$$CO + H_2O \rightarrow CO_2 + H_2 \quad (2)$$

$$HMR = \eta_{SMR} \cdot \left(\frac{LHV_{CH_4}}{LHV_{H_2}}\right) \quad (3)$$

$$CHMR[kg\ CO_2/kg\ H_2] = \frac{1}{HMR[Nm^3\ H_2/Nm^3\ CO_2]} \cdot \left(\frac{44}{2}\right) \quad (4)$$

Table 1 gives the results obtained for usual values of efficiencies [7], taking into account a LHV of 3 kWh/Nm^3 for hydrogen and 9.92 kWh/Nm^3 for methane.

Table 1. Conversion ratios for SMR with and without CO_2 capture.

	SMR efficiency [%]	H_2 production (HMR) [Nm^3 H_2/Nm^3 CH_4]	CO_2 emitted (CHMR) [kg CO_2/kg H_2]	CO_2 capture efficiency [%]	CO_2 captured [kg CO_2/kg H_2]
No CO_2 capture	75.9	2.51	8.77	---	0
CO_2 captured in flue gas	69.1	2.285	0.96	90.0	8.67

From the point of view of the feedstock, the organic fraction of the municipal solid waste is considered. In Spain an average value of 100 Nm^3 of biogas is obtained from anaerobic digestion of 1 ton of organic fraction of MSW [6, 10], being the average production of MSW of 485.9 kg/pax-year [11], with an organic fraction of 59.1% [10]. Assuming a content in volume of methane of 65% in biogas, and taking into account the conversion ratios explained before, 3.81 kg of hydrogen could be produced from the MSW of one person in one year by means of SMR with carbon capture in the flue gas. Although such number might be low, taking into account the Spanish population (47.35 million inhabitants), the production potential rises to 180,404 tons/year, which represents 30% of current hydrogen consumption (industrial uses mainly). If such production was produced by electrolyzers operating 5,800 h/year, they would sum up 1.8 GW, which represents 45% of the foreseen capacity for 2030 by the Spanish Roadmap for Renewable Hydrogen [3].

As CO_2 capture is the key element of golden hydrogen, it is necessary to take into account the storage of such CO_2 removed from the flue gas. Up to ten storages for CO_2 captured have been identified in Spain, with a capacity ranging from 500 to 15,000 Mton [12]. As an order of magnitude, one typical coal power plant (500 MWe) operating 4,000 hour/year produces around 1.7 Mton/year [13]. As the whole hydrogen production in Spain from MSW would be 0.18 Mton/year, the CO_2 captured would be about 1.56 Mton/year. That is, the overall CO_2 captured from the maximum hydrogen production potential from MSW is similar to the CO_2 emissions captured from only one typical coal power plant, and, in the worst case (500 Mton of storage capacity), the storage resource will be enough for 320 years.

2.2. Costs

Levelized cost of hydrogen (LOCH) is considered, based on the formulation of Bejan [14], and calculated according to equation 5, where *INV* stands for the investment, *HP* the hydrogen production, *CRF* the capital recovery factor (equation 6), $CELF_x$ the constant escalation levelization factor (equation 7) for cost *x* and *C* the annual cost; superscript *bg* refers to biogas, *ug* to upgrading, *om* to operation and maintenance and CO_2 to carbon tax; subscript *0* stands for costs in year zero. In equations 6 to 8, *r* represents the nominal escalation rate (taken zero for all items except for carbon tax), *wacc* the weighted average capital cost and *Ny* is the life span of the project. Where the nominal escalation rate is considered zero, the term in brackets in equation 7 results in the inverse of capital recovery factor, so the constant escalation levelization factors turns one.

Note that carbon tax has been included in equation (5) as a negative cost, assuming that the CO_2 credits due to negative emissions are sold in a renovated Emissions Trading System (this is not possible in the current regulation). It has been also considered another scenario where such selling is not possible, which would lead to compensate unavoidable emissions of other installation but without any revenue for the hydrogen production. In this latter case C_0^{CO2} in equation (5) would be set to zero, designating the LCOH as "gross cost".

$$LCOH = \frac{INV \cdot CRF + C_0^{bg} \cdot CELF_{bg} + C_0^{ug} \cdot CELF_{ug} + C_0^{om} \cdot CELF_{om} - C_0^{CO2} \cdot CELF_{CO2}}{HP} \quad (5)$$

$$CRF = \frac{wacc \cdot (1+wacc)^{Ny}}{(1+wacc)^{Ny}-1} \quad (6)$$

$$CELF_x = \left[\frac{k_x \cdot \left(1-k_x^{Ny}\right)}{1-k_x}\right] \cdot CRF \quad (7)$$

$$k_x = \frac{1+r_x}{1+wacc} \quad (8)$$

Lifespan is taken as 25 years, wacc as 8% and nominal escalation rate for carbon tax as 8% (term in brackets in equation 7 turns in *Ny* when *k* is one). Nominal escalation rate for fuel and maintenance are set to zero. Biogas cost is taken as 35 €/MWh (LHV based) [6], and carbon tax as 80 €/ton, according with CO_2 market level in early 2022. Upgrading cost depends on the volume flow rate of biogas treated (Q_{bg}), according with equation (9) [6].

$$C_0^{ug}[€/year] = \begin{cases} 41.289 \cdot HP[kg/year] \cdot \left(Q_{bg}\left[\frac{Nm^3}{h}\right]\right)^{-0.704} & \text{if } Q_{bc} < 200\ Nm^3/h \\ 10.023 \cdot HP[kg/year] \cdot \left(Q_{bg}\left[\frac{Nm^3}{h}\right]\right)^{-0.365} & otherwise \end{cases} \quad (9)$$

A scale law has been assumed for investment. Scale factors have been adjusted from data in [8], carrying out an update to present time based on [7]. Equation 10 shows the resulting expression. Maintenance costs have been taken from [8], being similar than in [7], equation 11.

$$INV[€] = 417.68 \cdot \left(HP\left[\frac{kg}{year}\right]\right)^{0.713} + 19.079 \cdot \left(HP\left[\frac{kg}{year}\right]\right)^{0.87} \quad (10)$$

$$C_0^{om}[€/year] = 0.186 \cdot HP\left[\frac{kg}{year}\right] \quad (11)$$

3. Results and discussion

3.1. Levelized cost of hydrogen production

Applying the proposed cost model to blue hydrogen cost, a value of 1.8 €/kg is obtained for a natural gas cost of 25 €/MWh and a production of 250,000 ton/year, so the model is assumed to give correct results [9]. Once this verification has been passed, the model is applied to different population sizes. Figure 1 shows the dependence of cost and production with the population who supplies the MSW. As expected from equations (7) and (8), scale economy is unveiled, reaching a reasonable cost (lower than 2 €/kg when CO_2 credits are considered) for population higher than 300,000 inhabitants, which entails productions higher than 1,160 tons per year, equivalent to an electrolyzer larger than of 11.6 MW operating 5,800 hours per year with a consumption of 58 kWh/kg.

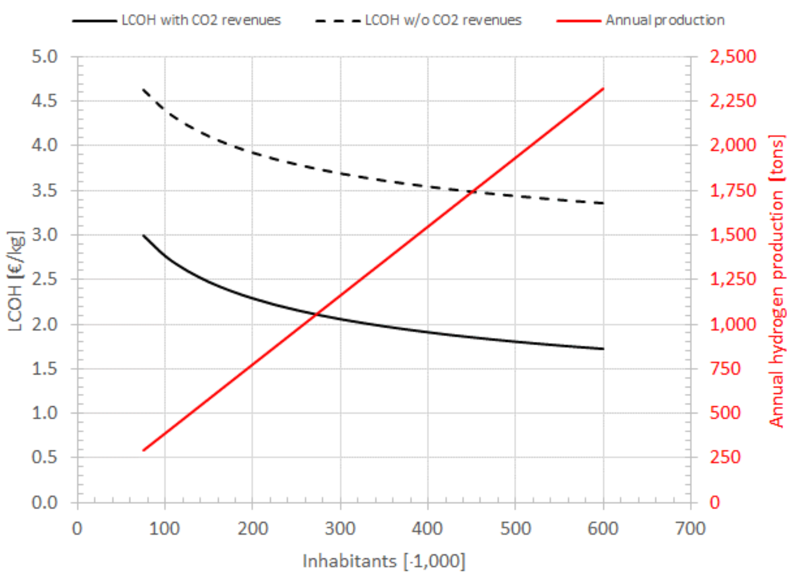

Figure 1. Levelized cost of golden hydrogen as a function of the number of inhabitants whose MSW are collected. Two scenarios have been considered: revenues from carbon tax (black solid line, Equation 5) and no revenues from CO_2 negative emissions (black dashed line, gross LCOH).

Figure 2 shows the breakdown of the levelized cost for 500,000 inhabitants. The gross cost, before the revenue for carbon tax, is 3.45 €/kg, which is reduced to 1.81 €/kg when the income corresponding to 80 €/ton CO_2 (1.64 €/kg H_2) is considered. The major share of the gross LCOH corresponds to the fuel (49.3% to feedstock and 19.5% to upgrading), followed by investment (25.8 %) and maintenance (5.4 %).

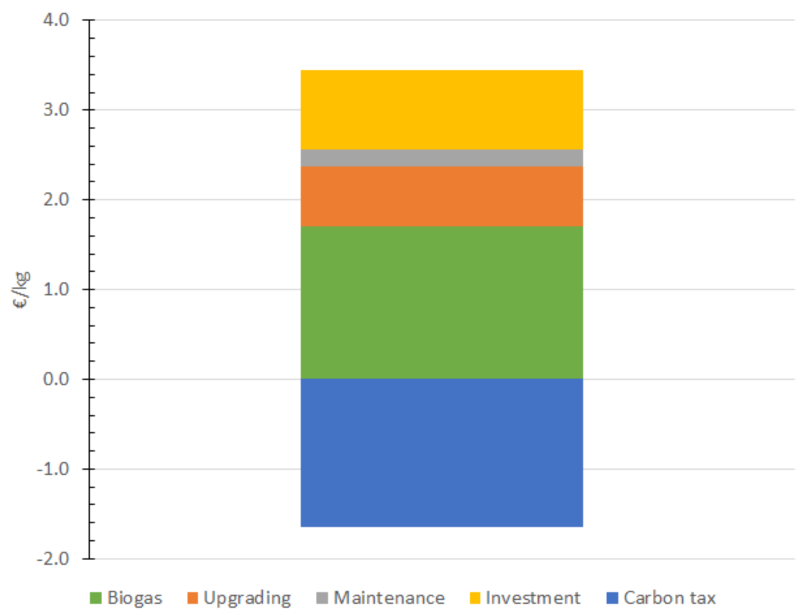

Figure 2. Levelized cost breakdown of golden hydrogen for MSW from 500,000 inhabitants.

The cost model considered in this work is based on in-situ production, that is, SMR facility is close to the landfill where organic fraction of MSW is converted in biomethane. However, other business models are possible, based on origin guarantee certificates. So, a PPA contract can be signed with a set of biomethane producers and install the SMR facility in a convenient location of the natural gas grid close to a geological CO_2 storage or an industrial consumer. This might be a successful model to extrapolate this technology to other feedstocks with lower absolute biomethane productions, or to small towns, allowing to account for the sum of their MSW in a virtual way.

3.2. Case study A: decarbonizing urban public buses

If the hydrogen produced by a municipality can be used locally, transport and distribution costs would be reduced. So, the use of the hydrogen from MSW has been assessed in the public urban buses in the city of Madrid. The consumption of a typical bus [15] ranges from 10 to 14 kg H_2 per 100 km. In Madrid, urban bus service consists of 212 lines with 2,049 buses which run 100,475,522 km in a year [16]. Assuming that all the buses are powered by fuel cell with an average consumption of 12 kg H_2/100 km, an annual production of 12,057 tones of hydrogen would be required. Taking into account the population of Madrid (3,334,730 inhabitants [11]), the production of hydrogen from MSW would be 12,705 tons of hydrogen per year, thus enough to meet the consumption of the buses.

A key factor of the use of hydrogen in mobility is its low density, what leads to its storage at high pressures. Typical buses [15] store hydrogen as compressed gas in vessels at 350 bar. The electrical consumption required for the compression up to 500 bar is about 3.2 kWh/kg [17]. If that consumption is considered to be supplied by means of a fuel cell with an electrical efficiency of 50% , an additional quantity of 2.3 kg of hydrogen is required to run 100 km.

Regarding the CO_2 emissions retired from the atmosphere by using the golden hydrogen, these would sum up 110,155 tons of CO_2 in a year, which can be accounted to compensate diffuse sectors or sold in the renovated Emissions Trading System (ETS) to compensate unavoidable emissions. Such emissions represent 1,040 g CO_2 per kilometer driven by one bus, which would allow to compensate the emissions of up to 10 cars which emit 95 g CO_2/km, according with the current limit established by EU.

So, the hydrogen production from the organic fraction of the municipal solid waste of a big city (Madrid) is enough to meet the demand of the entire fleet of its urban buses, allowing each bus to compensate the CO_2 emissions of up to 10 modern cars (95 g CO_2/km) due to the negative CO_2 emissions if they are captured in a centralized way while golden hydrogen is produced.

3.3. Case study B: blending of hydrogen

Although the most efficient conversion of the hydrogen takes place in a fuel cell, many applications are now paying attention to its use as a mere fuel replacing the current fossil fuels in furnaces and other combustion equipment. Such replacement requires technical development as combustion with hydrogen differs from the one with natural gas. For this reason, in the short term the use of hydrogen in combustion applications is foreseen to take place by blending it with traditional fuels, up to 50% in volume [18].

The low LHV of hydrogen in molar basis (3 kWh/Nm^3) compared with methane (9.92 kWh/Nm^3) makes it difficult to reach high percentages of reductions in CO_2 emissions by the use of blending up to 50% in volume. The dashed line in Figure 3 shows 23% of CO_2 reduction when green hydrogen (CO_2 emissions free) is used in a blend with 50% of hydrogen share in volume. Such value is reduced to less than 7% when the share of hydrogen in the blend is 20% in volume, as it is currently set out in existing natural gas grid. Former numbers discourage the use of green hydrogen blending as decarbonization technology. However, the so-called *hard to abate* sectors require a carbon free fuel able to reach high temperatures in combustion processes, while the use of pure hydrogen is not currently possible. Such dilemma might be solved with the use of golden hydrogen, due to its negative CO_2 emissions. The solid line in Figure 3 shows the percentage of reduction in CO_2 emissions with golden hydrogen blending, reaching more than 16% for 20% of share in volume and more than 53% for 50% of share in volume. As it can be seen in that figure, when hydrogen share exceeds 71.8% in volume, golden hydrogen enables the total decarbonization of the combustion with natural gas and even more, negative emissions release takes place that may be used to compensate unavoidable emissions of other sectors. Figure 4 assesses this fact, reaching a maximum value of 260 g CO_2/kWh-LHV of negative emissions if pure golden hydrogen could be burned, as it is expected to happen in the medium term.

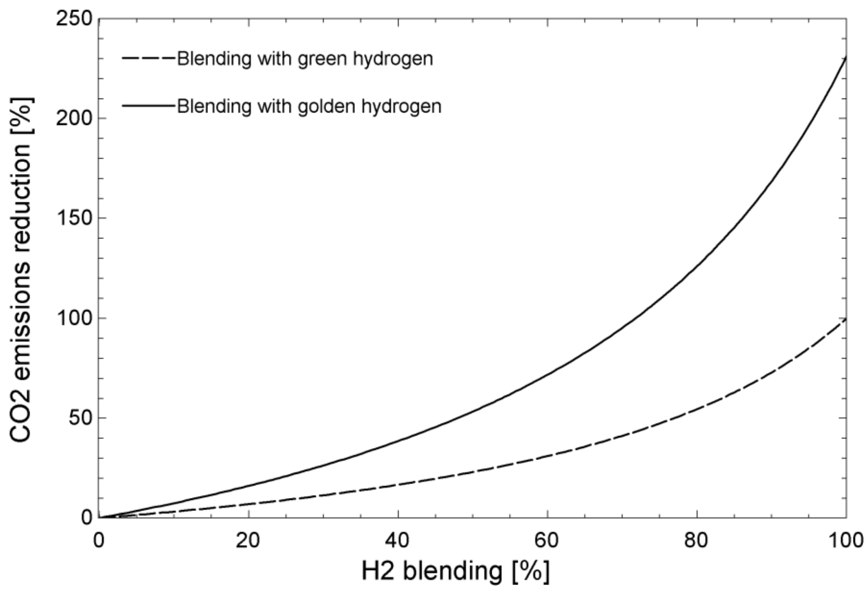

Figure 3. CO_2 emissions reduction in combustion processes burning hydrogen blends (percentages in volume).

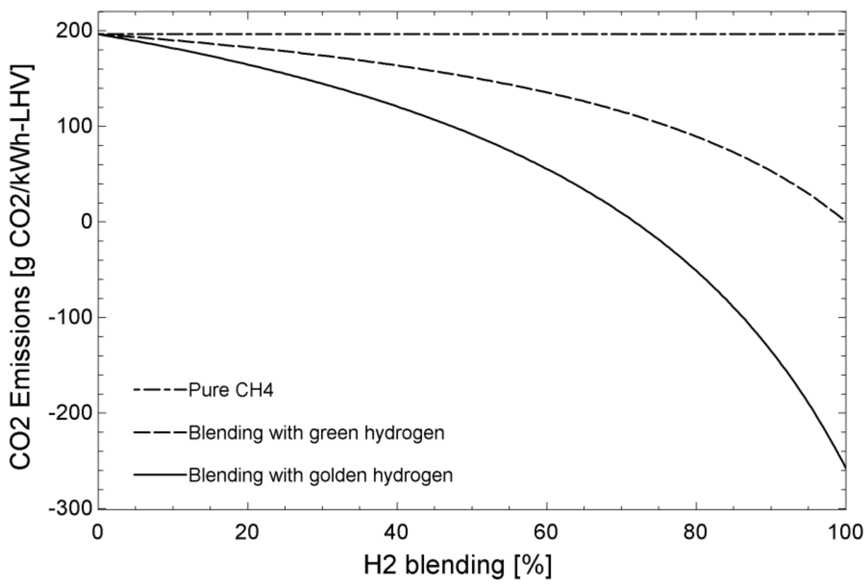

Figure 4. CO_2 emissions in combustion processes burning hydrogen blends (percentages in volume).

4. Conclusions

Although hydrogen from renewable electrolysis is currently the main focus of attention as a way to produce green hydrogen, other production routes are possible. One of these routes is the steam methane reforming, which has been the main procedure to produce hydrogen from natural gas for many years. Thus, such procedure can be undoubtedly considered a mature technology. Further, for more than 20 years carbon capture has been added to this technology in order to reduce carbon emissions. Nowadays, renewable gases coming from wastes are called to play a key role in the energy transition towards a decarbonized economy. Biogas can be produced by anaerobic digestion from many kinds of organic wastes, being the organic fraction of municipal solid waste an interesting feedstock in order to reduce the volume of wastes dumped into the landfill, avoiding the need of degasification and methane leakages. This work sets out the use of the organic fraction of municipal solid waste to produce biogas which, once upgraded to biomethane, is fed to a SMR unit with carbon capture to produce the so-called golden hydrogen (renewable hydrogen with negative CO_2 emissions).

Although the mere renewable hydrogen production from wastes is important (from the whole MSW of Spain 30% of the current hydrogen demand could be produced), the potential of golden hydrogen to compensate unavoidable emissions is a key point in this proposal. This procedure takes advantage of the CO_2 retired from the atmosphere in the photosynthesis, overtaking to hydrogen from renewable electrolysis in the decarbonization performance. The production of hydrogen from MSW is 3.81 kg/pax-year, with -8.67 kg CO_2/kg H_2 emissions. If these negative emissions are sold in a renovated ETS, a LCOH lower than 2 €/kg can be obtained for populations larger than 300,000 inhabitants, which is well below current costs for green hydrogen from electrolysis. The maximum CO_2 captured in the golden hydrogen production from the whole MSW generated in Spain would be comparable to the CO_2 captured from just one coal power plant, so no issues regarding the storage or the utilization of that CO_2 are expected.

Two case studies have been analyzed, one for public urban buses and another for hydrogen blending. In the former, the entire hydrogen demand of the fleet can be met from the MSW of the population, compensating with each kilometer driven the CO_2 emissions of 10 modern combustion cars (besides the emissions avoided by replacing single cars by public bus). In the later case study, the compensation ability allows to reach reasonable rates of decarbonization in blending, with CO_2 credits available for additional uses once the share of hydrogen in the blend is higher than 71.8%.

In conclusion, golden hydrogen has revealed as an alternative to green hydrogen from electrolysis, being competitive when both are compared and with the extra benefit of supplying CO_2 compensating resources, in line with BECCS technology. Electrolysis opens opportunities for long term storage of electricity, making possible the increase of the share of renewable energies in the electricity mix, but golden hydrogen encourages circular economy and provides an extra help to compensate unavoidable emissions. Both technologies should complement each other to go ahead in the transition towards a decarbonized economy.

Acknowledgements

Authors acknowledges to Rafael Mariño Chair in New Energy Technologies its support to carry out this research.

References

[1] Hydrogen Science Coalition (2021). Manifesto.
[2] L. Nelson, J. Lin, et al. (2020). Green Hydrogen Guidebook, *Green Hydrogen Coalition*.
[3] Ministry for Ecological Transition and Demographic Challenge (MITERD) (2020), Hydrogen roadmap: a bid for renewable hydrogen, *Ministry for Ecological Transition and Demographic Challenge (MITERD)* [in Spanish]
[4] Ministry for Ecological Transition and Demographic Challenge (MITERD) (2021), Biogas roadmap (draft), *Ministry for Ecological Transition and Demographic Challenge (MITERD)* [in Spanish]
[5] A. Picardo, V.A. Soltero, M.E. Peralta, R. Chacartegui (2019). District heating base don biogas from waste water treatment plant. *Energy*, 180, 649-664
[6] A. Feliu, X. Flotats (2020). Renewable gases. An emerging energy vector, *Naturgy Foundation*, 34
[7] IEAGHG (2017). Techno-Economic Evaluation of SMR Based Standalone (Merchant) Plant with CCS, *IEAGHG*.
[8] T.E. Lipman (2004). What will power the hydrogen economy? Present and future sources of hydrogen energy. Institute of Transportation Studies – Davis. University of California. Final Report UCD-ITS-RR-04-10.
[9] IRENA (2020). Hydrogen Cost Reduction: Scaling up Electrolysers to Meet the 1.5ºC Climate Goal, *International Renewable Energy Agency*, Abu Dhabi.
[10] J. Cuesta (2015). Biogas from municipal solid waste for grid injection. Bachellor Disertation. *Universidad Carlos III de Madrid*. [In Spanish]
[11] National Statistics Institute. Official population figures from municipal census review at January first. [In Spanish]
[12] J.M. Martínez-Val (Coord.) (2008). The future of coal in the Spanish energy policy. *Energy Studies Foundation*. [In Spanish]
[13] N. Petchers (2002). Combined Heating, Cooling & Power Handbook: Technologies & Applications: An Integrated Approach to Energy Resource Optimization. *Farimont Press*.
[14] A. Bejan, G. Tsatsaronis, M. Moran (1996). Thermal Design & Optimization, *John Wiley & Sons*.
[15] Mercedes-Benz (2009). The Citaro FuelCELL Hybrid. Generation Zero Emission. EvoBus GmbH.
[16] EMT Madrid (2018). Management report. *EMT*.[In Spanish]
[17] Howden (2019). Pure hydrogen delivered at 1000Bar. Compressor solution for fuelling stations.
[18] M.Mayrhofer, M. Koller, P. Seemann, R. Prieler, C. Hochenauer (2021). Assessment of natural gas/hydrogen blends as an alternative fuel for industrial heat treatment furnaces. *International Journal of Hydrogen Energy*, 46, 21672-21686.