Assessing the Environmental Potential of Hydrogen from Waste Polyethylene

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Abstract

In 2019, nearly 370 million tonnes of waste plastic were generated, an amount that has been steadily increasing over the years. Here we assess hydrogen production from waste polyethylene in the context of a circular economy of plastics. Based on the gasification of polyethylene waste (wPG), we performed a Life Cycle Assessment (LCA) study following the ReCiPe method. Our results show that the wPG process coupled with carbon capture and storage (CCS) performs very well environmentally relative to other H_2 production routes, outperforming steam methane reforming (SMR) with and without CCS and biomass gasification (BG) in the three endpoint impact categories.

Keywords: Hydrogen; Waste polyethylene; Circular economy; Life cycle assessment

1. Introduction

Every year, the global demand for single-use polymers increases and, with it, the generation of plastic waste. According to Geyer et al. (2017), as of 2015, 79 % of all plastic ever made had been disposed of in landfills or the environment. Although the percentage of polymer waste destined for recycling has been increasing over the years, millions of tonnes of residues are annually mismanaged globally. This continuous accumulation underlines the need for a circular economy that valorizes polymer residues.

The circular economy of plastics is based on the recycling, repurposing, refurbishing, and revalorization of the generated waste. Notably, valuable feedstocks to the chemical industry could be produced from waste polymers through chemical recycling, as pointed out by Pacheco-Lopez et al. (2021). For instance, waste polyethylene and polypropylene can be processed to recover their respective monomers through pyrolysis, and to produce synthesis gas (syngas), a key feedstock for chemicals production, through gasification (Saebeaa et al. 2020). While the first route would be ideally preferred due to the higher value of monomers, the second is significantly easier to implement due to the more mature gasification technologies.

Here we explore the benefits of recycling the hydrogen chemically stored in polymers via gasification of waste polyethylene (wPE). Hydrogen has attracted increasing attention as an energy carrier and low-carbon feedstock for various fields. Steam methane reforming (SMR), currently the standard and cheapest route for hydrogen production, relies on natural gas (Parkinson et al. 2019), which leads to large carbon emissions. Alternatives with lower emissions include SMR with carbon capture and storage (CCS) and electrolysis powered by renewable energies. Based on process modelling and LCA, here we investigate whether H_2 from recycled plastics is environmentally appealing, which at present remains unclear.

2. Methods description

2.1. Process description

We consider a hydrogen production process from waste polyethylene, alone or coupled with CCS, based on data collected from Saebeaa et al. (2020), Luyben (2018) and Susmozas (2015). The resulting block flow diagram is shown in Figure 1. The waste-polymer gasification (wPG) process consists of two main parts: syngas generation through steam gasification of wPE, and H_2 production and purification through water-gas shift (WGS) and pressure swing adsorption (PSA). CCS (wPG+CCS) is done on a CO_2-rich stream (95.6 mol%), which is compressed to 150 bar prior to injection. The WGS reaction is shown in Eq.(1).

$$CO + H_2O \leftrightarrow CO_2 + H_2 \quad (1)$$

The gasification takes place at 800 ºC and 1.013 bar with steam as the gasifying agent, as done in Saebeaa et al. (2020). The stream is then compressed to 32.5 bar with intercooling before entering the WGS section to meet the conditions in Luyben (2018). The syngas undergoes a high-temperature water-gas shift (HT-WGS) at 400 ºC with 88 % conversion and a low-temperature water-gas shift (LT-WGS) at 250 ºC with 95 % conversion, following the reaction in Eq.(1).

The H_2-enriched stream is cooled down to 40 ºC and flashed before being sent to the pressure swing adsorption (PSA) unit, obtaining H_2 at 99.9 mole% purity based on Susmozas (2015). The tail gas is decompressed and undergoes a combustion at 1300 ºC and 1.5 bar, covering the energy needs of the gasification. Combustion is performed with air and the post-combustion stream is vented after cooling and flashing at 40 ºC.

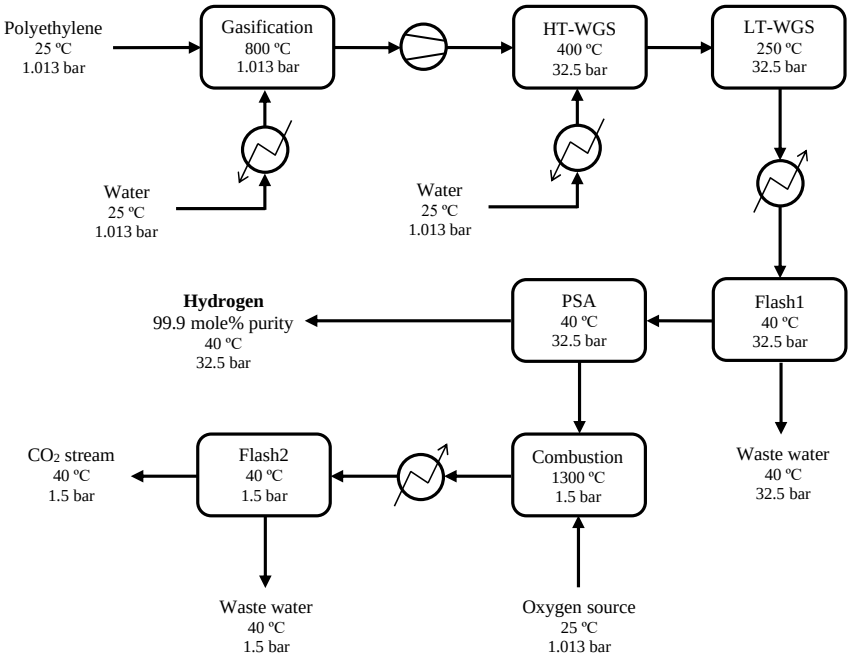

Figure 1. Block flow diagram of the process for hydrogen production from waste polyethylene.

For the process with CCS (wPG+CCS), oxy-combustion with a near stoichiometric O_2 ratio is considered at the same conditions as in wPG, obtaining a stream 95 mole% in CO_2 after cooling and flashing, which is compressed to 150 bar in four steps with inter-cooling and flashing, requiring 0.09 kW/kg CO_2 (Pipitone and Bolland of 2009). We considered that the flashed streams from this multi-stage compression are decompressed to 1.013 bar and undergo a final flash, recycling the gaseous stream to the combustion reactor. Therefore, no direct emissions are produced in the wPG+CCS process. The waste water streams from all flash units are sent to water treatment. Only cooling utilities are required.

2.2. Life cycle assessment (LCA) and scenarios definition

The environmental assessment was performed according to the ISO 14040 (2006). For each technology, the endpoint impacts on human health, ecosystems quality, and resource scarcity were calculated for 1 kg of hydrogen with the ReCiPe 2016 method using data from Ecoinvent 3.7 (global activities) in Simapro 9.2. The assessment follows a cradle-to-gate approach that considers the impacts from raw materials, electricity, process utilities, products, and direct emissions, disregarding the end-of-life of the plant infrastructure and use phase of the produced hydrogen.

We quantified the life cycle inventories (LCI) for wPG and wPG+CCS from the mass and energy balances of the process in section 2.1. Moreover, we expanded the system boundaries to account for the treatment of waste polyethylene. Hence, we assume that our process avoids the landfilling and incineration of wPE, considering the proportion that was destined to each alternative worldwide in 2015, showcased by Geyer et al. (2017): 55 % of wPE to landfills and 25.5 % to incineration. The impacts of the remaining 19.5 % waste that is recycled were omitted.

The wPG and wPG+CCS processes were compared to other hydrogen production routes: SMR with and without CCS, following Dufour et al. (2012); biomass steam gasification (BG) with and without CCS, based on Susmozas et al. (2016); proton exchange membrane (PEM) electrolysis powered by various energy sources, following Lee et al. (2010), i.e., bioenergy with CCS (BECCS), hydropower, nuclear power, solar power from photovoltaic cells, wind power and the electricity mix from the 2018 power grid.

3. Results and Discussion

Figure 2 displays the results of the endpoint environmental impacts of 1 kg of hydrogen for each of the 12 studied H_2 production routes. Regarding human health impacts, technologies involving the use of biomass coupled to CCS (PEM-beccs and BG+CCS) are found to be the most favourable alternatives, with negative impacts ($–7.88\times10^{–5}$ and $–7.43\times10^{–6}$ DALY/kg H_2, respectively), followed by wPG+CCS ($3.62\times10^{–6}$ DALY/kg H_2), PEM-nuclear ($3.95\times10^{–6}$ DALY/kg H_2), BG ($5.19\times10^{–6}$ DALY/kg H_2), PEM-hydro ($7.95\times10^{–6}$ DALY/kg H_2), wPG ($9.84\times10^{–6}$ DALY/kg H_2), SMR+CCS ($1.13\times10^{–5}$ DALY/kg H_2), PEM-wind ($1.40\times10^{–5}$ DALY/kg H_2), SMR ($1.46\times10^{–5}$ DALY/kg H_2), PEM-solar ($1.66\times10^{–5}$ DALY/kg H_2) and PEM-current mix ($8.62\times10^{–5}$ DALY/kg H_2).

PEM-nuclear generates the lowest impacts on ecosystems quality ($6.63\times10^{–9}$ species.y/kg H_2), followed by wPG+CCS ($9.16\times10^{–9}$ species.y/kg H_2), PEM-wind ($1.91\times10^{–8}$ species.y/kg H_2), SMR+CCS ($2.44\times10^{–8}$ species.y/kg H_2), wPG ($2.92\times10^{–8}$ species.y/kg H_2), PEM-hydro ($3.51\times10^{–8}$ species.y/kg H_2), SMR ($3.93\times10^{–8}$ species.y/kg H_2), PEM-solar ($4.12\times10^{–8}$ species.y/kg H_2), BG+CCS ($5.33\times10^{–8}$ species.y/kg H_2), BG ($9.43\times10^{–8}$

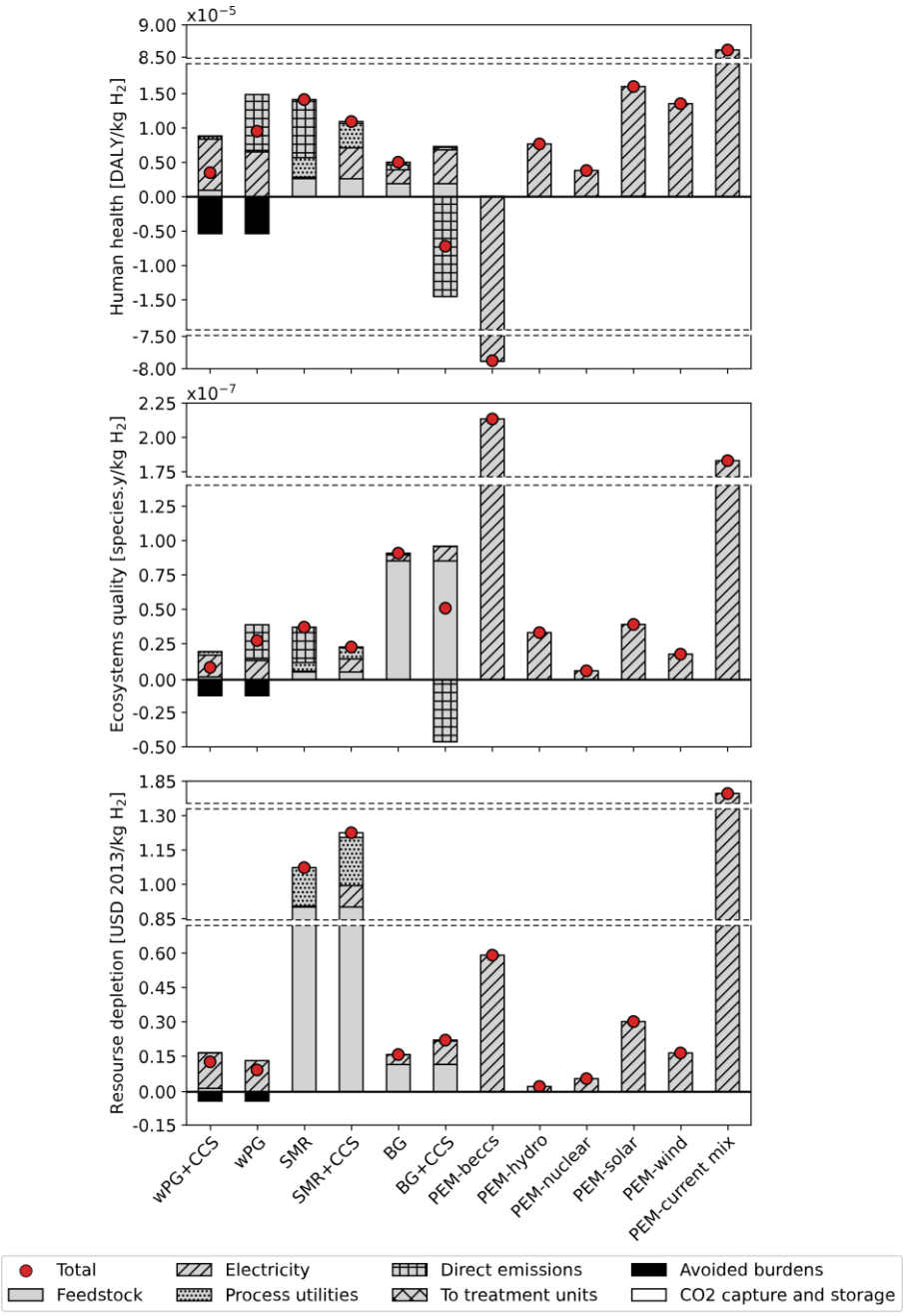

Figure 2. Endpoint environmental impacts of the hydrogen production routes assessed in this study, broken down by process components. The electricity term corresponds to the impacts of the energy sources used in the process (different for each PEM scenario). The following acronyms are employed: wPG: waste polyethylene gasification; CCS: carbon capture and storage; SMR: steam methane reforming; BG: biomass gasification; PEM: proton exchange membrane electrolysis; beccs: bioenergy with CCS; hydro: hydropower; nuclear: nuclear power plant; solar: photovoltaic energy; wind: wind power; current mix: electricity from the power grid of 2018.

species.y/kg H_2), PEM-current mix (1.82×10^{-7} species.y/kg H_2) and PEM-beccs (2.13×10^{-7} species.y/kg H_2).

PEM-hydro and PEM-nuclear generate the lowest impacts on resource availability (0.02 and 0.06 USD 2013/kg H_2 respectively). wPG (0.10 USD 2013/kg H_2), wPG+CCS (0.13 USD 2013/kg H_2), BG (0.17 USD 2013/kg H_2), PEM-wind (0.18 USD 2013/kg H_2), BG+CCS (0.23 USD 2013/kg H_2), PEM-solar (0.32 USD 2013/kg H_2), PEM-beccs (0.62 USD 2013/kg H_2), SMR (1.09 USD 2013/kg H_2), SMR+CCS (1.24 USD 2013/kg H_2) and PEM-current mix (1.79 USD 2013/kg H_2) follow.

wPG H_2 with and without CCS outperform SMR H_2 in all three endpoint categories. Moreover, except for technologies involving biomass coupled with CCS (PEM-beccs and BG+CCS), wPG+CCS has the lowest impact on human health among the studied routes.

wPG and wPG+CCS perform differently for various reasons. wPG+CCS requires 14 % more electricity and 78 % more cooling water per kg of H_2 than wPG due to the CO_2 compression unit. Additionally, wPG+CCS includes the impacts embodied in the oxygen feedstock for oxy-combustion, avoided in the standard wPG route that uses excess air as the oxygen source and where the post-combustion stream is vented. Overall, wPG+CCS is worse in resource depletion and better in human health and ecosystems quality.

In terms of ecosystems quality, wPG+CCS is the second least harmful route, only behind PEM-nuclear. The technologies involving biomass and CCS, which performed very well in human health, are the most harmful to the ecosystems. This is due to the significant land requirements of biomass plantations (i.e., poplar).

As for resource depletion, PEM-current mix presents the highest impact because the 2018 energy mix is heavily reliant on fossil resources, as reported by the IEA 2019 World Energy Outlook. SMR with and without CCS follow, as they require natural gas as feedstock, representing 83 % of the total impact for SMR and 73 % from SMR+CCS for this category.

Interestingly, PEM-solar and PEM-wind are never the preferred option in any category. This is because their life-cycle impacts, linked to the manufacture of photovoltaic panels and wind turbines, are high compared to those associated with other energy sources.

4. Conclusions

Our work assessed the potential environmental benefits of producing hydrogen from waste polyethylene. Our results show that wPG+CCS outperforms SMR (business as usual) and SMR+CCS in the studied impact categories. Moreover, wPG+CCS performs better in human health than biomass (BG) and electrolytic H_2 (PEM) powered by renewable energy sources, excluding BECCS. It also shows lower impacts on ecosystems quality than most processes (except for PEM-nuclear). The processes using waste polyethylene as a feedstock also display lower impacts on resource availability than SMR and BG with and without CCS.

Overall, our results suggest that hydrogen production based on plastic waste via wPG+CCS is environmentally appealing. This technology would help realize the circular economy concept in chemicals production by recycling polymer residues that would otherwise end up in landfills or incineration facilities.

Acknowledgments

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