A review of hydrogen production pathways, cost and decarbonization potential

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Overview

Climate change poses significant risks. The long residence time of CO_2 in the atmosphere (on the order of hundreds to thousands of years) implies that stabilizing global temperature requires near-zero anthropogenic carbon emissions and deep decarbonization of energy systems. Deep decarbonization in the transportation sector requires near-zero-carbon fuels. Hydrogen, when used in fuel cell electric vehicles (FCEVs) is ideal for long-range and heavy-duty applications. Hydrogen FCEVs achieve high efficiency and zero emissions (except water vapor). Furthermore, hydrogen has near-zero carbon emissions when produced using renewable energy sources. In addition to mobile uses, stationary applications of fuel cells can produce electricity and heat with zero emissions. We review estimates in the literature for life cycle greenhouse gas emissions and cost of all major hydrogen production pathways and identify key trends, concensus findings, and areas of largest uncertainty.

Methods

In this review, we consider representative hydrogen production technologies studied in the literature. We address five fundamental chemical and biological processes to produce hydrogen: (1) thermal-chemical processes (reforming, gasification, and decomposition) of fossil fuels, biomass, and biofuels, (2) electrolysis, (3) thermal-water splitting, (4) photo-electrochemical process (phtoelectrolysis or photolysis), and (5) biological processes (photolysis, fermentation, and electrolysis that happen in micro-organisms). Figure 1 presents the simplified diagram of these processes. For each fundamental process, there are multiple technologies that use different engineering designs. Furthermore, the same technology can be distinguished by hydrogen feedstock, energy input, production scale, and whether it is central or distributed production. Therefore, we define a *pathway* as a way of making hydrogen using a specific technology of a chemical or biological process that uses specific hydrogen feedstock and energy inputs at a certain scale. For instance, thermal-chemical conversion of natural gas via steam methane reforming (SMR) using natural gas as feedstock and process fuel at a large-scale central facility is the most common hydrogen production pathway.

As illustrated in Figure 1, the primary energy sources of hydrogen production processes can be grouped into 3 broad categories: fossil fuels, nuclear energy (fission), and renewable energy. The renewables are all derived directly (solar power) or indirectly (biomass and wind) from the sun. Similarly, the feedstock of hydrogen comes from 3 broad categories: fossil fuels, water, and biomass. Whereas fossil fuels and biomass can serve both as primary energy sources and feedstock, water is only used as a feedstock, and another energy source is needed to power the process.

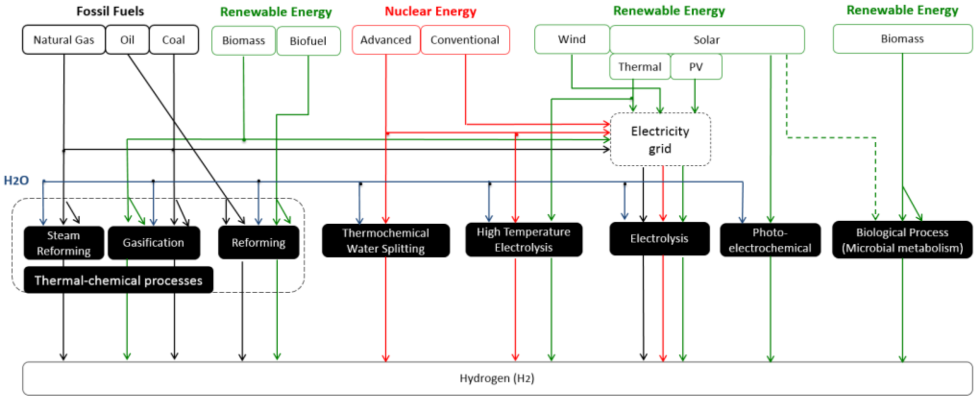

Figure 1. Hydrogen production pathways included in this review.

Results

We summarize the body of literature with regard to levelized production cost and life cycle greenhouse gas (GHG) emissions of hydrogen production pathways. In Figure 2, we plot literature estimates of levelized hydrogen production cost and life cycle GHG emissions of hydrogen production pathways. In this review, we compare the GHG emissions and production costs for 1 kg of high-purity hydrogen delivered to the end use. For GHG emissions, both direct and indirect emissions related to delivering hydrogen at fueling pumps are included, such as hydrogen production, transportation, delivery, dispensing, resource extraction and transport to produce primary energy and feedstock used in hydrogen production. For production cost, both capital cost for equipment purchase and replacement and operation and maintenance cost such as fuel cost, feedstock cost, and labor cost are considered.

We find a few pathways such as natural gas steam methane reforming (SMR) with carbon capture and sequestration (CCS), coal gasification CCS, and biomass gasification CCS, can achieve low carbon emissions at a cost of $2-4/kg, or in an energy equivalent measure, $2-4 per gallon of gasoline. However, if CCS is not available in the near- or mid-term, thermal-chemical pathways without CCS (natural gas SMR, coal gasification, and biomass gasification) are more likely to achieve low cost than to achieve low emissions.

Other pathways such as electrolysis powered by renewable electricity, solar photo-electrochemical (PEC), high-temperature electrolysis (powered by nuclear or solar), thermal watersplitting (TWS) (powered by nuclear or solar), and biological pathways have the potential to achieve near-zero carbon emissions. However, in each case the hydrogen production costs remain high or the technology is still a long way from practice. Electrolysis powered by renewable electricity is mature right now, but there are systems issues to deal with, including the intermittency and variability of renewable energy sources and integration challenges with the electricity grid and energy systems at large. With that said, the performance and economics of renewable energy sources (such as wind turbine, solar PV) and energy storage technologies have been progressing rapidly in the past decade and are likely to continue to improve in the near future.

The potential to produce hydrogen with low-cost and near-zero emissions via solar PEC, high-temperature electrolysis and TWS (powered by nuclear or solar), and biological pathways, on the other hand, face steeper challenges. Theoretically, advanced nuclear reactors are ideal to produce cheap and clean hydrogen on a large scale. But in more than two decades there has not been significant progress in the R&D and deployment of nuclear reactors in the U.S. Solar-driven pathways (PEC, high-temperature electrolysis, and TWS) do not face as serious constraints as nuclear, but the cost of such pathways are unlikely to be low, and their deployment may be limited in areas with abundant land resources and good solar irradiance. Finally, biological pathways are still in the early scientific research and laboratory testing stage. To become viable pathways at scale, these technologies need to demonstrate hydrogen production over a long period of time and increase production rate to an acceptable threshold.

Conclusions

Overall, we find that while estimates of some pathways suggest low emissions and comparable costs relative to existing petroleum fuels, all hydrogen pathways have practical issues. Thus more R&D and deployment of hydrogen pathways are needed. Moreover, we find that for thermal-chemical pathways (natural gas SMR, coal gasification, and biomass gasification), there is a worse-performance-over-time trend: studies published in recent years generally found *higher* cost and *higher* emissions estimates compared to studies published in early 2000s. In other words: the tendency is for each study to project lower cost and emissions in the future, yet estimates of cost and emissions increase over time in new studies. We find that a few key factors may explain this unexpected trend. First, the system scopes used to quantify emissions and production costs have expanded over time because of scientific and analytical progress. Second, these trends reflect unrealistic over-optimism in early studies.

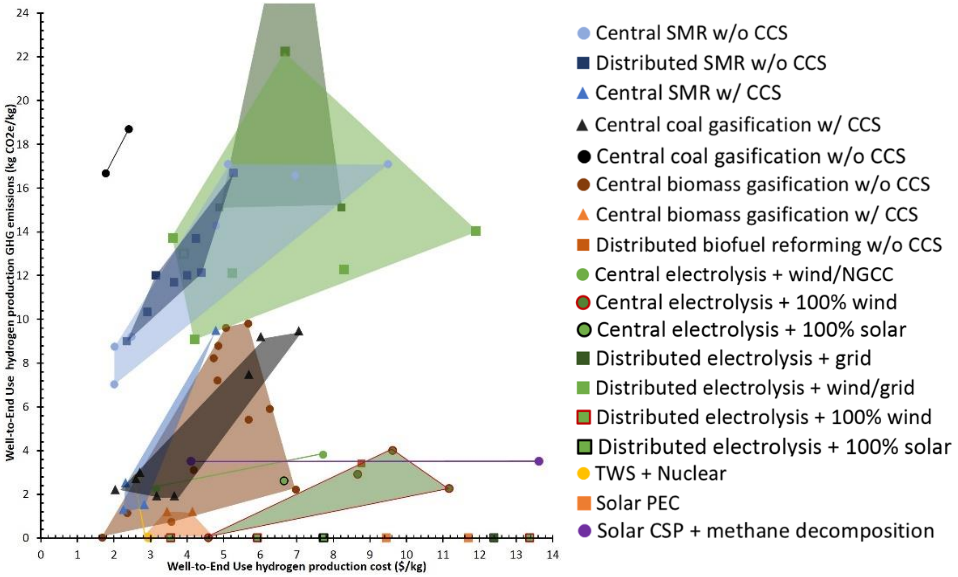

Figure 2. Summary of estimates from the literature of levelized production cost and life cycle GHG emissions of hydrogen production pathways.