



Technological learning and the future of solar H₂: A component learning comparison of solar thermochemical cycles and electrolysis with solar PV



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ABSTRACT

This analysis uses component learning curves to investigate the effect of policy support on the future potential of two methods of producing hydrogen using solar energy: solar thermochemical cycles and electrolysis with solar photovoltaics. The impact of policy support for photovoltaics, electrolysis, concentrated solar power, and thermochemical reactors is assessed. The rates of growth of the four technologies are taken as proxies for the degree of policy support. Key assumptions are identified and results are considered over the range of reasonable assumptions. Initially, electrolysis with PV will be the less expensive way to produce solar hydrogen. However, though it is initially more expensive, the thermochemical cycle has greater long-term potential for cost reductions from learning, and it is the faster route to \$2/kg hydrogen. Cost reductions in hydrogen from the thermochemical cycles are primarily driven by improvements in the thermochemical reactors, which, due to initially high costs, will only see growth through government support. Thus, policymakers must support the thermochemical cycles through their research, development, and early implementation stages in order to achieve these cost reductions. Though the details change when key parameters are varied over their range of reasonable values, the broad conclusions are unaffected.

1. Introduction

Climate change due to anthropogenic emissions of greenhouse gases is a serious threat that demands immediate and sustained changes in human behavior and consumption across all sectors (Pachauri and Meyer, 2014). Near term, many climate goals can be met with existing technologies—increasing capacity of renewables like wind and solar, a transition to more fuel-efficient and/or electric vehicles, and so on. However, stabilizing greenhouse gas concentrations in the atmosphere at 450 ppm CO_{2-e} or lower to try to keep global temperature increases below 2 °C will require significant emissions reductions in the second half of the century (Pacala and Socolow, 2004; Pachauri and Meyer, 2014). To do that, sustainably produced renewable fuels will likely be needed to meet the difference between electricity demand and production by a grid comprised increasingly of intermittent sources. Renewable fuels may also be needed to meet whatever transportation fuel needs cannot be met with electricity. Solar energy is by far the most significant renewable energy resource available, with a global technical potential of up to 100 times our current primary energy demand (IPCC, 2011). Using solar energy to produce fuels combines the enormous potential of solar energy with the flexibility and energy density of fuels.

Hydrogen (H₂), which produces only water when consumed, can be a clean and sustainable energy carrier if it is produced without the use

of fossil fuels. Both expert promoters and detractors of hydrogen agree that it will probably be an important part of the energy mix in a low-carbon energy future (Romm, 2004; Sperling and Ogden, 2004). It is a flexible fuel that can be used for electricity production (both distributed and centralized), transportation, and in industry. The objective of this analysis is to explore and compare the economic potential of two ways of producing solar H₂: solar thermochemical H₂ production cycles (specifically the Zn/ZnO cycle), and the electrolysis of water using solar photovoltaic (PV) electricity. Both PV and electrolysis are established technologies with decades of commercialization and development behind them, as well as areas of active engineering research (Jordehi, 2016; Wang et al., 2014). Water splitting via solar thermochemical cycles has been the subject of diverse and active research projects for about two decades (Loutzenhiser et al., 2010; Agrafiotis et al., 2015), but has not yet been commercialized. Most assessments of thermochemical cycles for fuel production focus on initial costs (Nicodemus et al., 2015; Steinfeld, 2002; Charvin et al., 2008). While that approach has the benefit of avoiding the uncertainties and assumptions inherent in forecasting the future, it cannot account for potential improvements in technology or cost reductions from the process of learning-by-doing. Similarly, though a number of studies have investigated the cost of electrolysis with renewable energy, none have investigated those how costs may change with experience (Saur, 2008; Schoots et al., 2008;

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Levene et al., 2007; Bockris and Veziroglu, 2007; Kolb et al., 2007). This assessment uses a component learning curve analysis to compare solar H₂ from the thermochemical cycle to that produced via electrolysis using solar PV electricity. By using the rates of growth of the four technologies as proxies for the degree of policy support, I explore the impact of policy support for photovoltaics, electrolysis, concentrated solar power, and thermochemical reactors on the cost of solar H₂. Key variables are identified and explored over a range of reasonable assumptions. This analysis is not meant to predict a winner or loser, but instead provide insight into the roles the two approaches may play in a low carbon future and the influence of policy support on costs.

2. Background

This component learning curve assessment of two methods of solar hydrogen production is based on a wide range of scholarship. Because the thermochemical cycle technology is lesser known and still in the research and development stage, this section begins with an explanation of the solar thermochemical cycles, specifically the Zn/ZnO cycle. The state of technology development research is necessary for contextualizing my assumptions about initial plant performance and size, and existing scholarship on thermochemical cycle costs serves as a basis for the initial cost estimates in this analysis. Next, I discuss research that has been done to estimate costs of H₂ from renewable electricity and highlight the lack of recent scholarship on the question. Third, I explain the concepts of learning curves, introduce scholarship on the use of component based learning curves, and discuss the strengths and weaknesses of using this type of analysis to estimate future costs. Finally, I summarize scholarship in which learning curves were applied to solar PV, electrolysis, or thermochemical cycles, highlighting knowledge gaps and the contributions of this work to the body of knowledge.

High temperature solar thermochemical cycles are an exciting avenue for producing renewable hydrogen using solar energy. In these cycles, a metal oxide is completely or partially split into metal and oxygen when exposed to the very high temperatures (generally higher than 2000 K) present at the focal point of a solar concentrator. These high temperatures are achievable in modern solar concentrating facilities with concentration ratios of 5000 to 10,000 suns. The metal (or reduced metal oxide) is then reacted with steam to produce H₂ and reform the original metal-oxide, which is cycled back to the solar step. The net reaction is the splitting of water with sunlight. For this analysis, details are obtained from analyses of the well-studied zinc/zinc-oxide (Zn/ZnO) cycle. In the solar step of the Zn/ZnO cycle, which occurs at 2300 K, ZnO is split into Zn and oxygen (O₂):



The gaseous products are then rapidly cooled, or quenched, to re-solidify the Zn, enabling the separation of the Zn from the O₂. The resulting Zn is then reacted exothermically with water in an oxidizer to produce H₂ and ZnO:



Ideally, all of the Zn produced in the solar step would be recovered for use in the oxidizer and all of the Zn would fully react to produce the maximum possible amount of hydrogen. Additionally, in an ideal case, all heat from quenching and the exothermic reaction would be recuperated and used in the process. In the ideal case, the maximum theoretical efficiency of the process is 36% (Steinfeld, 2002). However, in reality, recombination of some of the Zn with O₂ in the quencher, incomplete conversion in the oxidizer, and challenges with heat recovery in both steps significantly reduce efficiencies (Nicodemus et al., 2015; Venstrom and Davidson, 2011; Koepf et al., 2016). A recent pilot scale plant (100 kW_{th}) achieved 44% yield of Zn from the quencher (Koepf et al., 2016), while a prototype scale reactor/quencher achieved

61% yield (Müller and Steinfeld, 2008) and experimental reactors have achieved up to 85% yield (Schunk et al., 2008). Conversion in the oxidizer depends largely on the process. Aerosol processes, which have the benefit of potentially being continuous, have achieved no more than 20% conversion of the aerosolized Zn to ZnO (Melchior et al., 2009; Funke et al., 2008). Packed bed and vapor phase reactions can achieve much higher reactions (approaching 100%), but have other engineering challenges and are batch processes (Stamatiou et al., 2013; Lindemer et al., 2017). Heat recuperation also remains an important engineering challenge that some experimental reactor designs attempt to overcome (Ermanoski et al., 2013), but significant work remains.

Several studies have estimated the cost of H₂ produced via the Zn/ZnO cycle (Steinfeld, 2002; Charvin et al., 2008; Nicodemus et al., 2015). Two of those studies estimated H₂ costs for ideal or nearly ideal processes and for specific plant sizes, and found that H₂ from the Zn/ZnO cycle would cost between \$14.75/kg (Charvin et al., 2008) and \$5.02/kg (Steinfeld, 2002), depending primarily on the plant size. A subsequent analysis focused on the production and cost of syngas (a mixture of hydrogen and carbon monoxide) via the Zn/ZnO cycle. In that paper, we investigated syngas cost as a function of plant size, yield from the quencher, conversion in the oxidizer, heat recovery, solar resource, and water (and CO₂) feedstock cost, oxidation temperature, and the fraction of H₂ in the syngas mixture, providing a more complete analysis of how those factors influence the cost of solar fuels (Nicodemus et al., 2015). By all assessments, initial costs of solar fuels from thermochemical cycles far exceed economic competitiveness, especially when the analysis reflects current challenges with quencher yields and oxidizer conversion factors (Nicodemus et al., 2015).

A more technologically mature approach to producing H₂ with solar energy is to use solar electricity from PV cells to renewably power an electrolyzer, which splits water into hydrogen and oxygen. Electrolyzer technology is well established though not widely used, as there are often cheaper ways of producing hydrogen with fossil fuels. The cost of electrolysis depends strongly on the cost of the electricity used. At the time of many past analyses, solar electricity was very expensive relative to conventional forms of producing electricity. Thus, analyses concluded that producing hydrogen via electrolysis using solar electricity was not economically viable (Saur, 2008; Schoots et al., 2008; Levene et al., 2007; Bockris and Veziroglu, 2007; Kolb et al., 2007). However, installed capacity of solar PV has increased dramatically in the last decade—global cumulative installed capacity has increased from 8.6 GW in 2007 to 303 GW in 2016—while the price of solar electricity has rapidly dropped and is approaching or has reached grid parity in favorable markets (Schmela, 2016). Costs will continue to fall with continued industry growth. Similarly, increases in installed capacity of electrolyzers for use with conventional electricity slowly bring down electrolysis costs. Thus, the question of how the price of solar hydrogen is likely to change with increased cumulative capacity of both electrolysis and solar PV is worth exploring.

The price decreases observed as installed capacity grows can be described by learning curves, which are graphical representations of the effect of learning-by-doing on costs or prices in manufacturing and technology sectors. They are based on the premise that the cost of a technology decreases by a constant fraction, the learning rate (*LR*), with every doubling of the cumulative production or installed capacity. There is extensive empirical support for the existence of this relationship between experience and cost from a wide range of industrial fields, including technologies that transform or use energy (IEA, 2000; Schoots et al., 2008; Ferioli et al., 2009; de La Tour et al., 2013; Parente et al., 2002; Poponi, 2003; Rubin et al., 2007; McDonald and Schratzenholzer, 2001). Learning curves are generally expressed as

$$c(t) = c_0 \left(\frac{I(t)}{I_0} \right)^{-E} \quad (3)$$

where $c(t)$ is the cost of the technology at time t , c_0 is the reference cost

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