Renewable Hydrogen: A Cost and Policy Analysis

A Plan B Paper

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Abstract

The cost of hydrogen produced via the Zn/ZnO solar thermochemical cycle is compared to the cost of hydrogen produced via steam methane reforming and via electrolysis combined with wind and photovoltaic electricity. Prior work projects that H_2 produced by the Zn/ZnO cycle will cost between \$5 (7) and \$8 (28) per kilogram. In comparison, electrolysis combined with wind is calculated to cost between $\$4.76/kg$ and $\$5.60/kg$, and electrolysis with PV electricity is calculated to cost between $\$13.30/kg$ and $\$21/kg$. Hydrogen produced by SMR is found to cost between $\$2/kg$ and $\$4/kg$. The cost difference between H_2 produced via SMR and via the Zn/ZnO cycle is too great to be overcome with a carbon tax. Thus, policies that lead to public and private investment in the new technology will be necessary if the technology is ever to become cost competitive.

The time frame for the Zn/ZnO cycle to become economically viable is assessed through the use of experience curves under different policy scenarios. Future costs of hydrogen produced via the Zn/ZnO cycle are projected for progress ratios of 0.77, 0.82, and 0.87 using initial cost and batch sizes predicted in the literature (28). Future cost of hydrogen produced by SMR are predicted assuming increasing costs due to the rising cost of methane mitigated by a learning effect on the SMR plant operation and maintenance costs. Under the minimal input policy scenario, a small scale plant (producing $50\,\frac{kg}{hr}$) goes on-line in 2040 and a mid-sized plant (producing $250\,\frac{kg}{hr}$) goes on-line in 2070. Under this policy, and $PR = 0.82$, the Zn/ZnO cycle is expected to become cost competitive by 2070. Under the mid-range policy, the small scale and medium scale plants begin operating in 2025 and 2040, respectively. In this case, the Zn/ZnO cycle becomes cost competitive by 2050, again assuming $PR = 0.82$. Under the aggressive policy, the small scale plant begins operating in 2016, the medium scale plant goes on line in 2020, and a large scale plant (producing $792\,\frac{kg}{hr}$) goes on line in 2030. Under the aggressive policy scenario, the Zn/ZnO cycle becomes cost competitive in 2032. A sensitivity analysis on the assumptions used to predict these break even points indicates that the conclusions are relatively robust to 10% changes in the assumptions, with the exception of the progress ratio, which is accurate within 10 years given 5% changes in the assumed value.

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CHAPTER 1

Motivation and Objectives

We are living in an era of rising energy prices, exploding worldwide energy demand, rising temperatures due to increasing greenhouse gas emissions, and wars waged for control of non-renewable energy sources (1; 2). In addition, most scientists agree that in order to avoid some of the most serious consequences of climate change, atmospheric greenhouse gas (GHG) concentrations should be stabilized at or below an equivalent doubling over pre-industrial levels—approximately 500 ± 50 parts per million (1–3). This is a tremendous challenge to meet, and one that will require both bold policy action and continuing innovation in the field of renewable energy technology. Pacala and Socolow (1) have argued that this goal can be met by stabilizing emissions at 2004 levels through 2054, followed by a linear decline to about two thirds of 2004 levels by 2104. They argue that stabilization over the next 50 years can be achieved through the use of current technologies. However, to achieve the reductions necessary in the second half of the century, new and innovative renewable energy technologies will be necessary. Policies and technological development must strive to both meet near-term GHG reduction goals and plan and prepare for meeting long term goals. Using hydrogen as clean energy carrier is an appealing, though strongly contested, idea (4; 5). However, experts on both sides of the hydrogen debate agree that to meet long term goals of GHG emission reductions in the latter half of the century, hydrogen may need to part of the solution (4; 5).

One of the most powerful arguments made by hydrogen's detractors is that the energy input required to produce hydrogen exceeds the energy that you can get out of it (4; 5). However, in an ideal future in which a significant fraction of our energy comes from renewable sources, we will need a way to store and transport energy. A flexible energy carrier–a fuel–that can be used in vehicles, homes, off-grid sites, and to address the intermittent nature of much renewable electricity will be a vital aspect of that future energy sector. Another powerful point that detractors make is that the production method responsible for 95% of hydrogen produced in the US, steam methane reforming (SMR), is not renewable (5). Even in the ideal case, SMR results in the production of 5.5 times as much CO_2 as H_2 (on a mass basis)[1]. Clearly, steam methane reforming cannot be the hydrogen production method of the future if reduction of greenhouse gas emissions is an important societal goal.

This analysis explores the economic viability of one potential avenue for the production of hydrogen using renewable energy and the policy tools necessary to make it economically competitive. In this technology, concentrated solar energy is used to drive a two-step metal oxide reduction/oxidation cycle based on the zinc (Zn) and zinc oxide (ZnO) pair. Concentrated solar energy provides the heat required to split ZnO into Zn and oxygen (O_2), effectively storing the energy in that chemical reaction. In the second step, the Zn is reacted with steam (H_2O)–the Zn oxidizes to form ZnO, resulting in the production of hydrogen (H_2). The ZnO produced in the second step is recycled back to the first step. The net effect is the splitting of water with concentrated sunlight.

This process is the subject of engineering and physical science research around the world, and many technical issues remain to be resolved before the technology can move to commercial use (6–18). However, assuming that the technical and engineering issues are solved, will H_2 produced by this process be economically competitive? If not initially, what policies would be needed to make this process economically viable in the long term?

In this paper, the cost of hydrogen produced using this two-step Zn/ZnO solar thermochemical cycle (which will be referred to as the "Zn/ZnO cycle" for simplicity) will be compared to the cost of hydrogen production via traditional methane reforming (SMR) and via electrolysis of water using electricity generated from solar photovoltaic (PV) cells and wind. The effect of accumulating experience on the cost of H_2 produced by the Zn/ZnO cycle will be predicted and three policy scenarios used to estimate the time frame for the accumulated experience. The projected costs will be compared to the cost of H_2 produced via SMR assuming natural gas price increases with time. The impact of a carbon tax policy on the price of SMR H_2 is also calculated. Policies that would make solar hydrogen cost competitive with hydrogen produced by steam methane reforming will be discussed.

This analysis will not consider issues of storage, transportation, distribution, or the status of fuel cell technology. While these issues are very important technically and politically, they are not the focus of this study. How these issues play out will have significant impacts

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[1] Calculated based on the stoichiometry of SMR reactions and molar masses of H_2 and CO_2.

on the time frame in which hydrogen starts being utilized and its relative importance in the overall energy portfolio, but they will have a lesser effect on how that hydrogen is produced. In addition, the goal of this study is not to advocate for policies or to advocate for this technology over other methods of producing H_2, or for the use of H_2 over other energy storage technologies. Doing so would be very premature, as this technology has not been commercialized. Rather, this study stems from an interest in the solar Zn/ZnO cycle, and its potential as a part of long term renewable energy portfolios. Thus, the goal of this study is to explore the economics of the Zn/ZnO H_2 production cycle in comparison with SMR and electrolysis combined with renewably generated electricity. In addition, the goal is to identify and discuss policies that would help the Zn/ZnO cycle become competitive with steam methane reforming.

CHAPTER 2

Background

2.1. The Zn/ZnO solar thermochemical process for hydrogen production

Hydrogen production from sunlight is a very appealing concept—water (H_2O) is split into oxygen (O_2) and hydrogen (H_2) and the only energy input is solar energy. Water can be directly dissociated into H_2 and O_2 at very high temperatures (above $3500\,K$), bu the challenge of reaching these temperatures in solar reactors and the difficulties in separating the H_2 and O_2 at these temperatures make the process unrealistic. However, thermochemical cycles that use multiple steps to split water allow for both lower operating temperatures and easier product separation. In general, a process with more chemical reaction steps requires lower temperatures but also loses efficiency at each step (7). Thus, a two step process is highly desirable.

One potential two-step process for hydrogen production is a metal/metal-oxide cycle in which the metal-oxide is dissociated (to produce the oxygen and the metal or lower valence metal oxide) at high temperatures in a concentrating solar reactor. The metal or lower valence metal oxide is subsequently reacted with steam to produce hydrogen and the original metal oxide. Some pairs that have been investigate are ZnO/Zn, Fe_3O_4/FeO, TiO_2/TiO_x, Mn_3O_4/MnO, and Co_3O_4/CoO (7). The ZnO/Zn pair is especially interesting, because ZnO dissociates at lower temperatures than many of the other pairs. The ZnO/Zn cycle is shown in schematic form in Figure 2.1. The first, endothermic step, is the dissociation

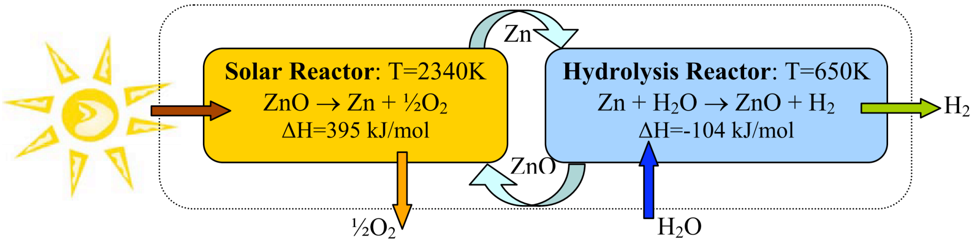

FIGURE 2.1. The Zn/ZnO thermochemical cycle uses concentrated sunlight to produce hydrogen from water

of ZnO at approximately $2300\,K$, a temperature achievable at the focal point of solar concentrating systems with concentration ratios, C^1, of approximately 5000 suns or higher (7). This step has been shown to be feasible in prototype reactors (6; 8–10). The products of this step, $Zn(g)$ and $O_2(g)$ are separated by rapidly quenching (cooling) the gasses to below the saturation temperature of Zn, $690\,K$. The Zn vapor condenses, while the O_2 remains gaseous, thereby efficiently separating the products (6; 8–10). Recovery of the heat energy used in the quenching process is desirable to maintain high efficiency in the overall cycle.

In the second, exothermic step, Zn is hydrolyzed with steam to produce ZnO and hydrogen. This exothermic step can be carried out whether or not the sun is shining, whenever and wherever it is useful. Ideally, the product ZnO can be completely recycled back to the first step, so that the net effect is the splitting of water. Work has been done on improving the efficiency of this second step (11–18), but it remains the main barrier to implementation. The second step may require additional heat input, as temperatures above $650\,K$ are favorable for the hydrolysis reaction. However, if some of the heat lost in quenching in the first step is recovered, it may be useful in the driving the reaction in the second step.

Solar concentrating tower systems consist of a receiving tower surrounded by an array of heliostats that track the sun on both axes and reflect sunlight to the focal point of the receiving tower. These solar power towers have concentration ratios of several hundred to several thousand suns. Secondary concentrators, usually compound parabolic concentrators (CPC), further increase the concentration ratio to 5000 suns and higher. This high radiation flux allows for the conversion of solar energy to heat energy at $2000\,K$ and higher (7). CPCs are a composite of two parabolas that reflect beam radiation at a range of incidence angles, defined by an acceptance angle, into a receiving cavity at the intersection of the two parabolas (19). A CPC with an acceptance angle of 10° would provide a concentration ratio of 11.5. Thus, a CPC can provide a ten-fold increase in the concentration ratio of the concentrating solar tower when the beam radiation being collected by the CPC is being directed to it from the focal point of the concentrating solar tower.

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[1] The solar concentration ratio, C, is defined as the ratio of the solar flux intensity achieved after concentration to the normal beam radiation from the sun ($1000\frac{W}{m^2}$). Though it is a dimensionless number, it will be reported here in units of "suns".

FIGURE 2.2. PS-10 in Seville Spain, built by Abengoa Solar, has an 11MW installed capacity and is the first commercial solar power tower in the world.

Solar One and Solar Two are the first and second iteration of a concentrating power tower demonstration project in the Mojave Desert in California. Solar One was built in 1981 and had an installed electricity production capacity of 10 MW_e. The heliostat array consisted of 1818 mirrors, each $40\,m^2$, resulting in a total collection area of $72720\,m^2$. From 1982 to 1986, Solar One was used to demonstrate the viability of using concentrated solar energy to run a steam turbine generator. In 1995, Solar One was converted into Solar Two, a demonstration project for the use of molten salt as a storage medium. The conversion to Solar Two also included the addition of more heliostats, resulting in a total collection area of $82750\,m^2$. The salt used in Solar Two–a mixture 60% sodium nitrate ($NaNO_3$) and 40% potassium nitrate (KNO_3)–melts at 220°C and is stable up to 600°C. Thus, the solar radiation was stored as heat in the molten salt. The stored heat is then transferred to water to produce steam and run a steam turbine (20; 21).

Solar concentrating systems of this kind are already being built for commercial use. PS-10, an 11 MW_e installed capacity solar concentrating power plant went on line in Seville, Spain in 2007 (see Figure 2.2). The tower at PS-10 is approximately 100 m high. The plant has 624 heliostats that are each $120\,m^2$ and sits on 150 acres of land. With a total collection area of $74880\,m^2$ and a receiving aperture area of $65\,m^2$, C is approximately equal to 1156 suns. PS-20 is currently under construction adjacent to PS-10. With a total collection area of $150,600\,m^2$, it is likely to achieve even higher concentration ratios than PS-10. The larger plant will have an installed capacity of $20\,MW_e$.

2.2. Other hydrogen production methods

The cost of producing hydrogen via the two-step thermochemical Zn/ZnO cycle will be compared to the costs of hydrogen production by traditional steam methane reforming and the cost of hydrogen production by electrolysis using solar photovoltaic and wind electricity. Methane reforming accounts for about 95% (22) of the hydrogen produced in the United States, and is therefore likely to be the most significant non-renewable competition for the Zn/ZnO solar thermochemical cycle. Electrolysis from renewably generated electricity is the only technology available today for the renewable production of hydrogen. Though wind electricity is significantly less expensive than solar photovoltaic (PV) electricity, solar PV is more directly comparable to the two-step thermochemical production of hydrogen, as both are only likely to be used in regions of high solar and low wind resources.

Approximately 8.5 billion kilograms of H_2 is produced annually by steam methane reforming (SMR) in the United States. Currently, that H_2 is used primarily for production of chemicals and refining petroleum (23). The process occurs in two steps. In the first, methane (CH_4) is reacted with steam at 750 to $800°C$ to produce synthesis gas, or syn-gas, a mixture of H_2 and carbon monoxide, CO. The ideal reaction in the first step is

$$CH_4 + H_2O \rightarrow CO + 3H_2. \tag{2.1}$$

In practice, some carbon dioxide (CO_2) is produced in this step as well. The second step is known as the water gas shift reaction. The carbon monoxide produced in the first step reacts with steam in the presence of a nickel (Ni) catalyst to form more H_2 and CO_2:

$$CO + H_2O \rightarrow CO_2 + H_2. \tag{2.2}$$

The second step occurs in two temperature stages. The first, high temperature shift occurs at $350°C$, while the second, low temperature shift occurs at 190 to $210°C$ (24). In the idealized process 2.005 kg of methane is consumed and 5.501 kg CO_2 is produced for every kilogram of hydrogen produced.

In water electrolysis, an electric current is passed through water via two submerged electrodes, resulting in the decomposition of water into hydrogen and oxygen. Hydrogen is drawn to the negatively charged electrode (the cathode), where electrons are pumped into the water, and oxygen is drawn to the positively charged electrode (the anode). At 100% efficiency, 8.9 liters of water and 39 kWh are required to produce one kilogram of H_2. However, commercial electrolyzers are 56 to 73% efficient (25), so 53 to 71 kWh are required to produce one kilogram of H_2.

2.3. Regulating CO_2 emissions

Experts generally agree that in order to avoid some of the more catastrophic effects of climate change, atmospheric greenhouse gas concentrations should be stabilized at or below an equivalent doubling over pre-industrial levels—approximately 500 ± 50 parts per million (1; 3). Because greenhouse gasses other than CO_2 contribute to global warming, their radiative forcing effect must be considered as well. A doubling of the CO_2 concentration over pre-industrial levels produces a radiative forcing of $4.4\,W/m^2$. Therefore, an equivalent doubling can be produced by any combination of greenhouse gasses that produces the same radiative forcing. These other greenhouse gasses—methane, nitrous oxide, and halo-carbons—are likely to contribute $1.3\,W/m^2$, limiting the radiative forcing due to CO_2 to $3.1\,W/m^2$. This corresponds to an atmospheric concentration of 450 ppm (3). World population growth and the industrialization of developing countries ensure that greenhouse gas emissions will well exceed these target values without significant policy intervention (3).

Much climate change mitigation policy fits into two categories. First, incentive policies aim to increase the implementation of renewable energy and energy efficient technologies and practices by making them more economically competitive and/or decreasing investment risk. These incentive policies include direct financial support for research, development, demonstration and even initial commercial projects, and indirect support through tax incentives for renewable energy projects, purchase guarantees, or low interest rate loans (26). These incentive policies are especially useful in the early stages of technology market penetration, as they encourage investment in technologies that might not otherwise be economically competitive. As the technology matures it becomes more economically competitive. Ideally, technologies eventually become cost competitive without incentives.

The other important form of climate regulation involves internalizing the cost of carbon emissions through a carbon tax or a cap and trade program. By putting a price on carbon emissions, this type of policy makes all renewable and efficient technologies more cost competitive. Models calculate that a tax of \$100 per tonne of Carbon (tC), increasing to $\$325 - 450/tC$ in 2050 and $\$750 - 1200/tC$ in 2100 could lead to CO_2 concentrations stabilized at $450\,ppm$ (3). Carbon tax and cap and trade policies are generally considered the most economically efficient way to increase the market share of renewable energy. Under these policies the market operates to identify and implement the least expensive CO_2 reduction methods first, only implementing more expensive technologies after the less expensive options have been exhausted. The danger in relying solely on these market based CO_2 reduction strategies is that not enough resources may be put into development of future technologies—technologies like the Zn/ZnO cycle—that have potential to be important energy sources in the future.

Rai et al. (26) explored the government inputs that have proven necessary in the implementation of technologies with high capital costs and uncertain revenue steams. Though their goal was to use analogous technologies to analyze future deployment of carbon capture and sequestration (CCS), the lessons they learn are also potentially relevant to the Zn/ZnO cycle. They analyze the development of the US nuclear power industry, the US SO_2 scrubber industry, and the global liquid natural gas (LNG) industry, because these technologies, like CCS and the Zn/ZnO cycle, have very high capital costs and uncertain revenue streams. They make three main observations. First, government involvement was crucial in the early development of all three technologies, providing direct backing for research and development (R&D) and demonstration projects. Government support also created niche markets and opportunities for these technologies. Second, continued development of these technologies after demonstration relied on incentives for industry to invest in commercial projects. Initially, government involvement in the early commercial projects was very direct, but as the technology became more reliable and as experience accumulated, government involvement shifted to indirect support in the form of tax breaks, purchase guarantees, portfolio/performance standards and low interest rate loans. Third, in some cases, the expectation that increased experience leads to reduced costs did not hold. In the case of nuclear power, implementation proceeded too rapidly for successive plants to learn from the experience of those that came before, and prices actually increased, rather than decreased, as cumulative installed capacity grew. In the case of the LNG industry, a market structure with limited competition and price guarantees resulted in little reduction in cost as experience increased. However, in the case of SO_2 scrubbers, costs did decline as expected with experience once the technology had been shown to be effective and reliable and industrial scale investment was underway (26). They conclude

> Policymakers must remain mindful that cost reduction is not automatic—it can be derailed especially by non-competitive markets, unanticipated shifts in regulation, and unexpected technological challenges. At the same time, there may be some inevitable trade-offs, at least for a period, between providing credible mechanisms to reduce commercial risk, such as promises of assured demand for early technology providers, and stimulating market competition that can lead to lower costs. History suggests that government-backed assurances are essential to creating the market for capital-intensive technologies; yet those very assurances can also create the context that makes it difficult for investors to feel the pressure of competition that, over successive generations of technology, leads to learning and lower costs. (26)

Thus, though incentivizing specific technologies or technology classes is not the most economically efficient path to reduce GHG emissions, history shows that some important technologies require direct and indirect government support, especially in R&D, demonstration, and early commercialization. However, to keep the technology on a path in which increased experience leads to decreased costs, policies should be clearly defined and consistent, diffusion of the technology should not be excessively rushed, and a way to transition to a competitive market structure should be planned into the policy.

It should be noted that there are strong and logical arguments against policies that favor particular technologies—that the market should decide which technologies succeed, not policy makers (27). Picking technology winners may result in a less than optimal use of funds, especially if the technology is picked for political reasons, rather than scientific or environmental reasons. This paper is not intended to advocate for “picking” the Zn/ZnO cycle, rather it is an exploration of the policy and economic factors that would be required for the technology to succeed.

CHAPTER 3

Analysis

3.1. Hydrogen production costs

Solar thermochemical production of hydrogen. The cost of hydrogen production via the the two-step Zn/ZnO thermochemical cycle has been previously analyzed by Seinfeld (7) and Charvin et al. (28). Both studies account for the efficiencies of the process, losses due to re-radiation in the solar collector, and losses due to the thermodynamic irreversibility of the chemical reaction. Both studies also include the cost of the solar power plant, the reactor, and annual costs, and assume that all costs associated with GHG emissions are external (i.e. not included in the analysis).

Steinfeld finds that H_2 produced via the Zn/ZnO cycle would cost of $\$5.02/kg$ based on the lower heating value (LHV) of hydrogen, $241\,kJ/mol$ and assuming a solar concentration ratio, C, of 5000 suns. In this study, no pump or other external work input is assumed, none of the heat lost when the Zn and O_2 are quenched is assumed to be recovered, and the separation step is assumed to be perfect (i.e. no recombination of the Zn and O_2 into ZnO). In addition, none of the heat generated in the exothermic hydrolysis step is assumed to be recovered or used, and the hydrolysis step is assumed to be complete (i.e. the Zn is completely reacted and the maximum possible amount of H_2 is generated). He assumes a $34\,MW_e$ solar thermal power plant with a $155172\,m^2$ heliostat array costing $\$150/m^2$. The total capital cost is found to be \$55.08 million, and total annual costs are \$9.36 million. Steinfeld also includes a thermodynamic analysis of the efficiency of the cycle, and finds the overall efficiency of the process to be 29%. Table 1 includes a summary of these assumptions and findings.

Charvin et al. (28) more recently undertook a similar analysis of the cost of hydrogen produced via the Zn/ZnO cycle. They project the cost of hydrogen to be $\$7.28/kg$. Though their efficiency and cost assumptions tend to be slightly more optimistic than those in Steinfeld, they assume a significantly smaller scale operation, resulting in higher estimated

TABLE 1. Major assumptions and findings for cost and efficiency of the Zn/ZnO cycle

	Steinfeld (7)	Charvin et al. (28)
Plant size, energy and mass flows		
Concentration ratio, C	$5,000$ suns	$5,000$ suns
Solar plant size (power input to solar reactor) $[MW_{th}]$	90	75
beam irradiation $kWh_{th}/m^{2} \cdot yr)]$	2300	2000
Heliostat area $[m^2]$	$155,172$	$54,800$
Efficiencies		
Optical efficiency of solar concentration system, η_{optics}	58%	68.4%
Cycle efficiency, η_{cycle}	29%	30.4%
global efficiency, η_{global}	17%	20.8%
Assumptions		
Pump or work input	none	none
Solar step temperature $[K]$	2300	2000
Reactor re-radiation losses	accounted for	accounted for
Endothermic reaction losses	accounted for	accounted for
Heat recovery in separation by quenching after first step	no heat recovery	heat recovery
Recovery of heat released in exothermic reaction	no heat recovery	complete heat recovery
Efficiency of separation of Zn and O_2	complete, no recombination	20% recombination
Efficiency of hydrolysis step	complete hydrolysis	complete hydrolysis
Hydrogen energy content $[kJ/mol]$	241(LHV)	286 (HHV)
Costs		
Heliostat field [M\$, assuming \$150/m^2]	23.28	8.22
Land [M\$, assuming \$1/m^2]	not included	0.28
Tower [M\$]	3.60	1.5
Tower reflector and CPCs [M\$]	5.30	not included
Solar receiver-reactor + periphery [M\$]	7.00	2.00
Quencher [M\$]	3.00	not included
Hydrolyzer [M\$]	4.00	1.00
Balance of plant, indirects, contingency [M\$]	8.90	2.00
H_2 storage	not included	1.00
Total capital cost for solar H_2 [M\$]	55.08	16.00
Annual Cost		
Annual fixed charge rate [M\$]	15%	not included
Capital cost for solar H_2 [M\$]	8.26	not included
O&M cost for solar H_2 [M\$]	1.10	1.01
Total annual cost for solar H_2 [M\$]	9.36	1.01
Hydrogen production rate **$[kg/hr]$**	792	250
Hydrogen cost **[\$/kg]**	5.02	7.98

hydrogen costs. As in Steinfeld, no pump or other external work input is assumed and the hydrolysis step is assumed to be complete. However, this study assumes that the heat lost in the quenching step can be recovered using heat exchangers, and used to heat the reactants in the second step and for preliminary heating of the ZnO in the initial, solar step. They also assume that the heat released in the second, exothermic hydrolysis step is not lost, it is used to maintain the temperature of the Zn and H_2O at temperatures favorable for the hydrolysis reaction. However, they do not assume perfect separation during quenching after the first step–instead, a 20% recombination is assumed. The assumptions and major findings of their analysis is compared to those in Steinfeld in Table 1.

These two analysis make different assumptions and result in slightly different cost predictions; \$5.02/kg (7) versus \$7.98/kg (28). In this analysis, the average of these two values–\$6.50/kg hydrogen–will be assumed as the cost of hydrogen produced via the Zn/ZnO solar thermochemical cycle. This is more than double the department of energy's (DOE) target cost of \$3/kg for renewably produced hydrogen (25). However, the comparison of these costs to other renewable hydrogen production methods will provide insight into how this technology measures up to others in striving to meet that target goal.

Renewable electricity plus electrolysis production of hydrogen. The cost of production of hydrogen by electrolysis depends on the efficiency and costs of the electrolyzer and the cost of the electricity. The total cost is the capital cost, the fixed operation and maintenance (O&M), and the cost of electricity. The capital and fixed operation and maintenance costs can be assumed to be \$1.53 and \$0.56 per kg of hydrogen, respectively, assuming an electrolysis plant that produces 1000 kg per day (29). Typical commercial electrolyzer systems require 53.4 to 70.1 kWh_e to produce one kilogram of hydrogen (25; 30). Electricity generated by solar PV costs \$0.27/kWh_e (commercial) to \$0.21/kWh_e (industrial)[1]. Electricity cost per kg of H_2 is then \$11.21/kg to \$18.93/kg. Thus, even assuming the minimum electricity cost, the total cost of hydrogen produced by PV electricity is \$13.30/kg of hydrogen. However, hydrogen produced by wind electricity is significantly less expensive. Assuming the same electrolyzer capital and O&M costs and \$0.05/kWh_e for wind electricity, the total cost of hydrogen produced by electrolysis using wind energy is \$4.76/kg to \$5.60/kg hydrogen. This is less expensive than either solar hydrogen production method. However,

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[1] http://www.solarbuzz.com/SolarPrices.htm

the Zn/ZnO cycle is surprisingly competitive. It should be noted that wind electricity and electrolysis are current and proven technologies, whereas the Zn/ZnO cycle is still in the research and development stage. Thus, the costs estimated here for H_2 produced by wind electrolysis is a near term or current cost, whereas the predicted cost of H_2 produced by the Zn/ZnO cycle are based on assumptions of significant technological advancements that in reality have yet to occur.

Steam methane reforming production of hydrogen. Hydrogen produced in a steam methane reforming plant that produces 22000 kg of hydrogen per day has been calculated to cost \$2.40/kg or \$4.10/kg assuming natural gas prices of \$7/GJ and \$15/GJ, respectively (31). Other analysis finds H_2 production by SMR to cost between \$1.25 and \$3.50 when natural gas costs \$6/GJ, depending on the size of the SMR plant. In addition, natural gas cost comprises 52 to 68% of the total cost of hydrogen production in the larger scale plants (32). Thus, assuming a plant size that produces hydrogen for \$2/kg in which 60% of the cost is due to natural gas costs, an increase in natural gas cost from 6 to 10 \$/GJ will result in hydrogen costs increasing to \$2.80/kg. A further increase in natural gas cost to \$15/GJ would result in hydrogen costs of \$3.80. Even hydrogen produced at the largest scale plant, which can produce H_2 at \$1.25/kg when natural gas costs \$6/GJ, would cost \$2.53/kg when methane costs \$15/GJ. In July, 2008 the price of natural gas was \$13.84/GJ, and in March of 2009, natural gas cost \$9.23/GJ (22). Clearly, natural gas prices are volatile and hard to predict. However, given recent prices, near term cost of natural gas can be expected to be between ten and fifteen dollars per GJ, and hydrogen produced by steam methane reforming is expected to cost two to four dollars per kilogram, near term. Given the range in costs for SMR production of hydrogen based on the SMR plant size and natural gas cost, for this analysis, the base cost of hydrogen produced by SMR will be taken to be \$3/kg. The current best estimates of the costs of hydrogen production by the Zn/ZnO cycle, PV combined with electrolysis, wind with electrolysis, and SMR are compared in figure 3.1. The error bars in this figure represent the range of cost estimations reported.

A simple analysis of the internalized cost of carbon required to make the Zn/ZnO cycle competitive with SMR can be done based on the relative costs discussed above and given that in the ideal case, 5.5 kg CO_2 are emitted for every kilogram of hydrogen produced

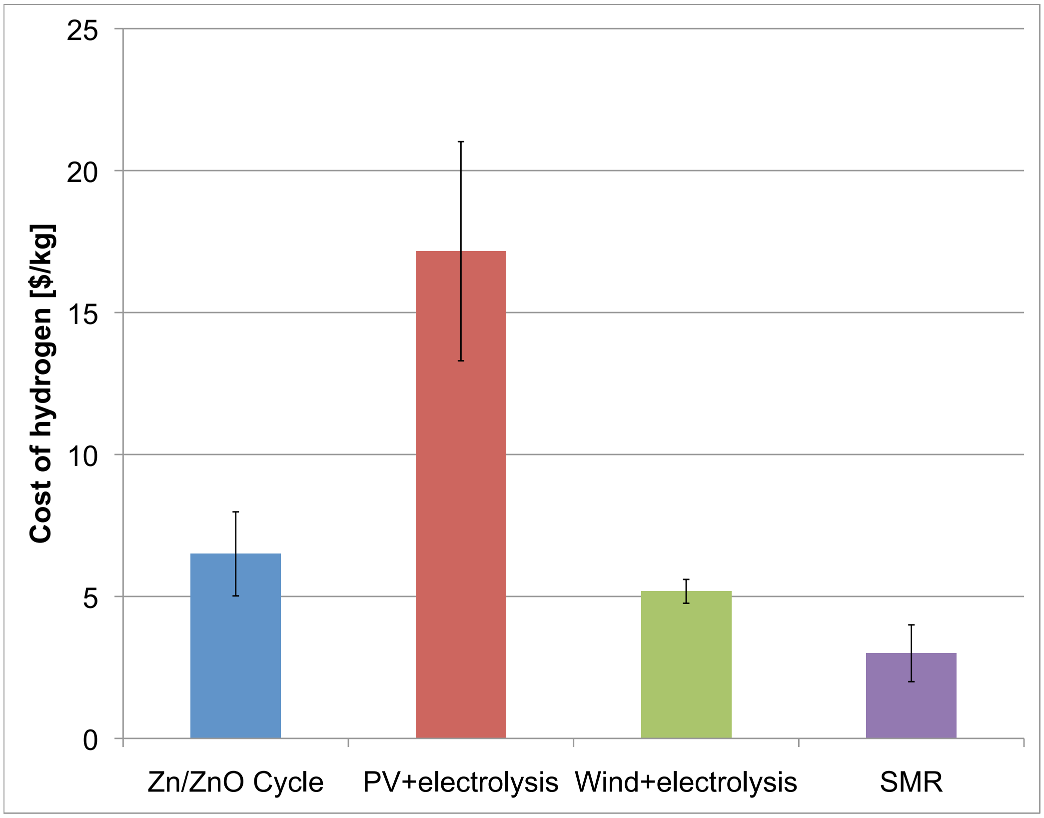

FIGURE 3.1. The costs of hydrogen production via the Zn/ZnO cycle, PV combined with electrolysis, wind electrolysis, and SMR

by steam methane reforming. Because the reaction does not proceed perfectly, it should be noted that CO_2 emissions of $5.5\,kg$ is a conservative estimate. In order to increase the cost of hydrogen produced via SMR from \$3.00 to \$6.50, the cost of carbon would need to be \$636 per metric ton of CO_2. This corresponds to a carbon tax of approximately \$2300 per metric ton of carbon. Clearly, this level of carbon tax is not likely. However, as technologies mature, the experience curve effect brings costs down. Assuming some initial implementation of the Zn/ZnO cycle, the cost of hydrogen produced by this method will fall as the technology matures. In addition, the cost of natural gas is likely to continue to increase with time, driving up the cost of hydrogen produced by SMR. Thus, in the long term, the costs of solar hydrogen and SMR hydrogen may become more similar.

3.2. Cost projections

Zn/ZnO **cycle experience curve.** Experience curves, or learning curves, are graphical representations of the effect of learning-by-doing on prices in manufacturing and technology. Experience curves are based on the hypothesis that the costs of a technology decrease by a constant fraction with every doubling of the cumulative production or installed capacity. The fraction by which the cost decreases with every doubling is called the learning rate (LR). It is often more useful to discuss the experience curve in terms of the progress ratio (PR), which is the fractional multiplier by which the price drops. For example, if a technology with $PR = 0.75$ costs \$100 at time, $t = t_1$, it will cost $\$100 \cdot PR = \$75$ after twice as much of the technology has been produced. The learning rate and the progress ratio are related as $PR = 1 - LR$. 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 (33; 34).

Experience curves can be expressed as

$$c_t = c_\circ \left(\frac{P_t}{P_\circ}\right)^{-E}, \tag{3.1}$$

where c_t is the cost of the technology at time, t, $c_\circ$ is the cost of the technology in the first batch of production (at $t = 0$), P_t is the total cumulative production at time t, $P_\circ$ is the number of items in the first production batch, and E is the learning index. E is related to PR by $PR = 2^{-E}$. Production can be expressed in a variety of units, including MW, GJ, kg, etc. Experience curves are generally plotted with cost, c_t, as a function of cumulative production, P_t, on a double-logarithmic scale. In this scale, the curve is linear with a negative slope (33; 34).

Generally, experience curves are used to analyze past data on technology production and costs, and predict future trends. However, in the case of the Zn/ZnO cycle, there are no past data to analyze. Because the technology is still firmly in the research and development stage, there are no data on the initial cost of the first batch of hydrogen produced via this method, nor data on how that cost changes with production. Thus, in order to estimate future costs of H_2 produced via the Zn/ZnO cycle, I will estimate costs over a range of assumed values for the initial conditions and the progress ratio. The conclusions that I draw from this analysis can therefore be considered relevant within the bounds of the assumptions made.

In order to identify appropriate progress ratios for this technology, I will use a combination of progress ratios observed for solar thermal power towers and two-step chemical reactors. Little data exists on the cost evolution of electricity generated by solar power towers, but one study estimates that the progress ratio for this technology is 0.9 ± 0.05. Part of the learning rate for this technology is attributable to the effect of accumulated experience in the tower, receiver, and heliostat technology, while part is attributable to the learning rate of the steam turbine electricity generation system. It would not be accurate to assume that the PR for solar power tower is the same as that for the Zn/ZnO cycle, because the main difference in the Zn/ZnO cycle is that it employs a very technical, two-step chemical reactor instead of the steam turbine generating electricity. Thus, it will be important to try to understand how this technology difference might affect the progress ratio.

The total progress ratio for the solar power tower, PR_{PT}, is assumed to be due to a combination of the progress ratio of the solar receiver, tower, and heliostats, PR_{solar}, and the progress ratio steam turbine electricity generation system, PR_{elec} as

$$PR_{PT} = f_{solar} \cdot PR_{solar} + f_{elec} \cdot PR_{elec}, \tag{3.2}$$

where f_{solar} and f_{elec} are the fraction of costs due to the solar components and electricity generation components, respectively. In PS-10, 46.8% of the total cost of the power tower was due to the steam turbine and electrical power generation system (35), so for this analysis $f_{elec} = 0.468$ and $f_{solar} = 0.532$. In addition, PR_{elec} is taken to be 0.965 ± 2 (36). The progress ratio for the solar components of the power tower, PR_{solar}, is calculated for the stated values of f_{solar} and f_{elec} and the stated ranges for $PR_{elec}$and PR_{PT}. The progress ratio for the tower, heliostat, and receiver technology is found to be from 0.74 to 0.95.

Similarly, the total progress ratio for the Zn/ZnO cycle, $PR_{Zn/ZnO}$, is a combination of PR_{solar} and the progress ratio of the Zn/ZnO reactors, heat exchangers, etc., $PR_{reactor}$, as

$$PR_{Zn/ZnO} = f'_{solar} \cdot PR_{solar} + f_{reactor} \cdot PR_{reactor}, \tag{3.3}$$

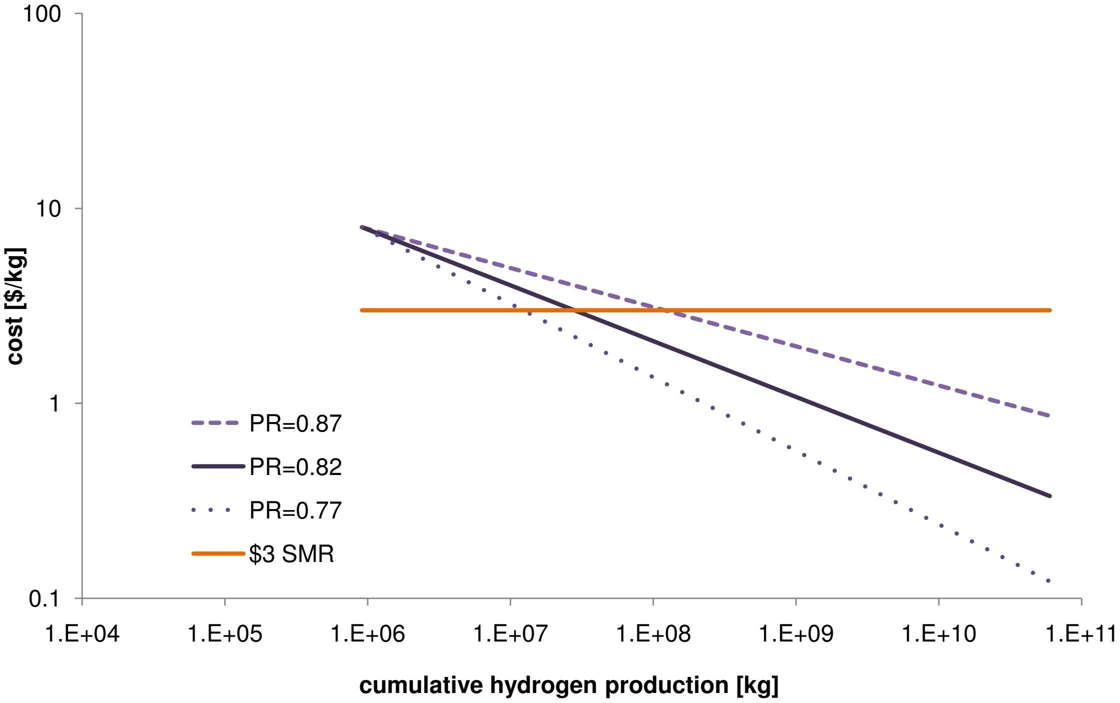

FIGURE 3.1. Learning curves for the production of hydrogen via the Zn/ZnO cycle assuming progress rates (PR) of 0.87, 0.82, and 0.77, an initial cost of $\$8/kg$, and an initial batch size of $574900\,kg$.

where $f_{reactor}$ is the fraction of cost due to the Zn/ZnO cycle reactors and periphery. Both Steinfeld (7) and Charvin et al. (28) predict that approximately 25% of the total cost of the Zn/ZnO cycle will be due to the reactors, heat exchangers etc., so in this analysis $f_{reactor} = 0.25$ and $f'_{solar} = 0.75$. No data exists on the progress ratio of the Zn/ZnO reactors, so the progress ratio for steam methane reforming (0.73 ± 0.05) will be assumed here. SMR is chosen because it, like the Zn/ZnO cycle, is a two-step chemical reaction. Using $0.74 \leq PR_{solar} \leq 0.95$ and $0.68 \leq PR_{reactor} \leq 0.78$, $PR_{Zn/ZnO}$ is found to be between 0.73 and 0.91. The middle portion of that range, $0.77 \leq PR_{Zn/ZnO} \leq 0.87$, is reasonable to assume. Thus, in this analysis I explore $PR_{Zn/ZnO} = 0.77$, 0.82, and 0.87.

In addition to choosing reasonable values of PR, I must also assume some cost and size of an initial production batch, $c_{\circ}$ and $P_{\circ}$. Figures 3.1, 3.2, and 3.3 show the experience curves for the Zn/ZnO cycle under three different sets of assumptions about the initial cost and batch size, using $PR = 0.77$, 0.82, 0.87 for each. The experience curves are highly sensitive to assumptions about initial cost and batch size; the uncertainty of that information is therefore a major weakness in this analysis.

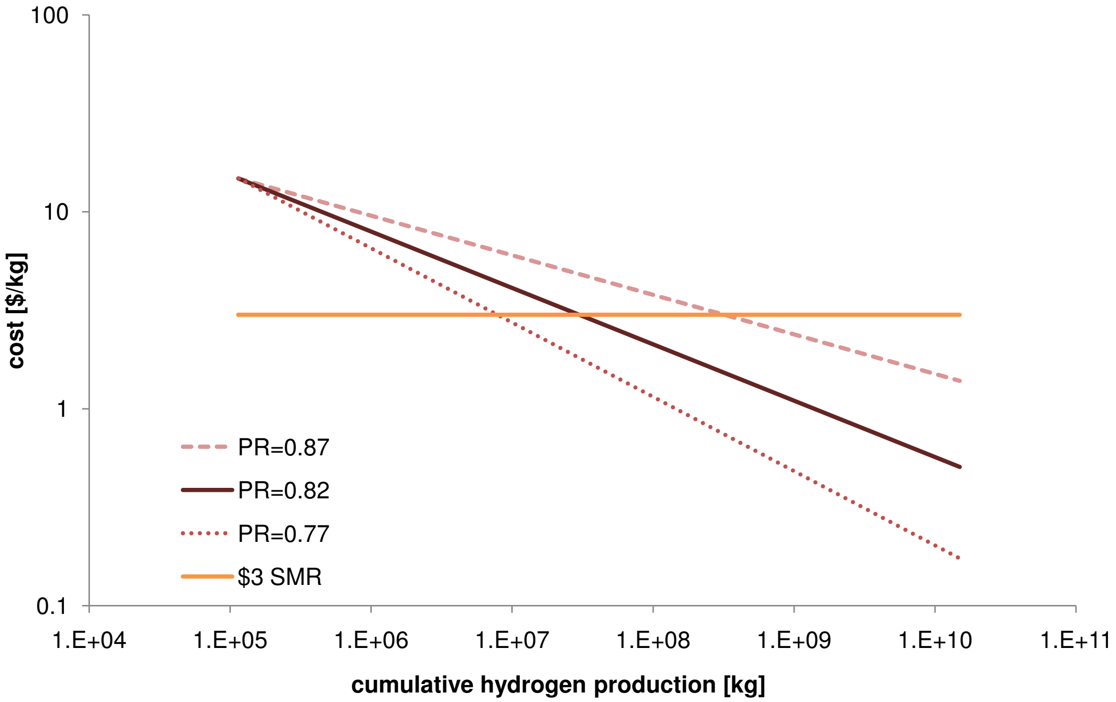

FIGURE 3.2. Learning curves for the production of hydrogen via the Zn/ZnO cycle assuming progress rates (PR) of 0.87, 0.82, and 0.77 and an initial cost of $\$15/kg$ and initial batch size of $115000\,kg$.

The experience curve analysis shown in Figure 3.1 is based on Charvin et al.'s (28) cost estimation for the Zn/ZnO cycle (discussed in section 3.1), because that analysis is based on a smaller scale plant than the analysis in Stienfeld (7). Thus, the cost per kg of H_2 predicted in that study ($\$8\,/kg$) was used as the initial cost, and the initial batch size was assumed to be $574900\,kg$ H_2, which is the amount of H_2 produced in one year at the production rate assumed in the study ($250\,kg/hr$). This annual H_2 production is approximately enough to run 1000 cars[2]. While this set of assumptions may represent a point on the experience curve, it is unlikely to actually be the starting point. In their analysis, Charvin et al. (28) assumed a fair amount of technological improvements in order to estimate a reasonable cost of hydrogen produced by the Zn/ZnO cycle. Thus, the experience curves in Figure 3.1 do not tell us very much about the public and private investments required to bring the technology to that stage. They do show what additional investment would be needed to make the technology economically competitive with SMR (assuming current natural gas

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[2] Based on the approximate equivalence of the heating values for H_2 and gasoline, average vehicle miles traveled of $14000\frac{miles}{yr}$, and average gas mileage of $25\,\frac{miles}{gallon}$.

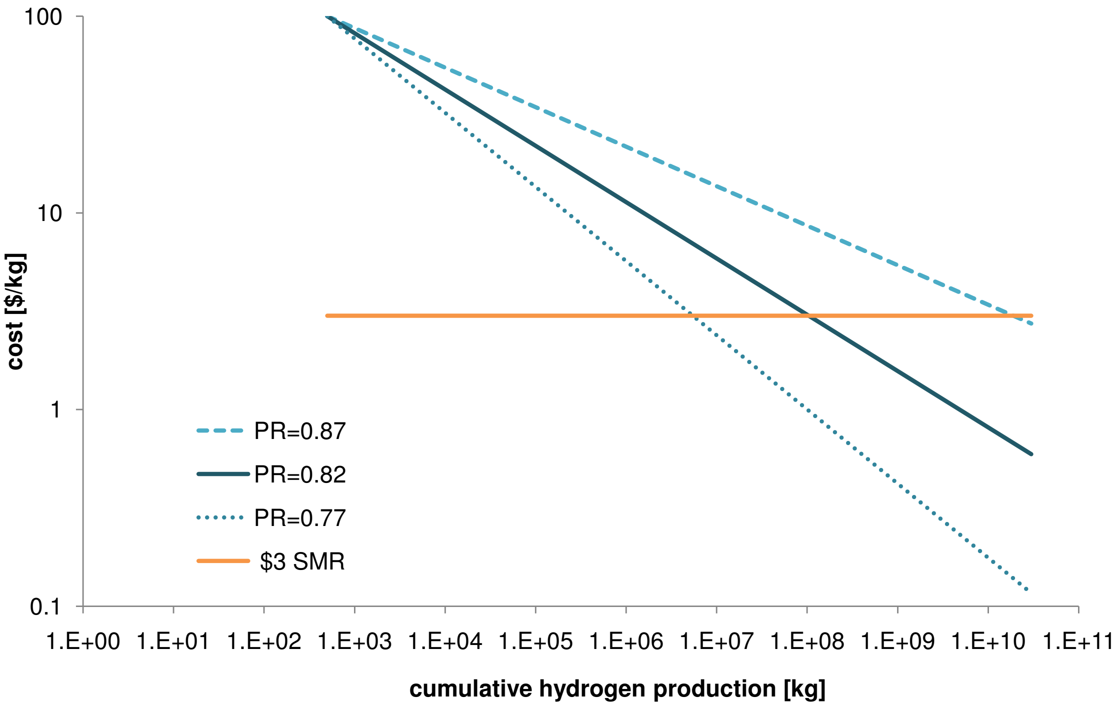

FIGURE 3.3. Learning curves for the production of hydrogen via the Zn/ZnO cycle assuming progress rates (PR) of 0.87, 0.82, and 0.77 and an initial cost of \$100/kg and initial batch size of 500 kg.

prices). The additional investment needed assuming $PR = 0.8$ and these initial conditions is the area between the experience curves and the SMR line in Figure 3.1; it is approximately \$15 million. This does not represent the cost of developing and building solar concentrating facilities or hydrogen reactors, rather it is the incremental cost of using the Zn/ZnO cycle instead of steam methane reforming to produce H_2. In addition, this cost does not include any of the investments that would have come before the moment the plant began producing $250\,\frac{kg}{hr}$.

In their cost analysis, Charvin et al. (28) also discuss the cost of a smaller plant—one that produces H_2 at a rate of $50\,\frac{kg}{hr}$. The cost of H_2 produced by this smaller plant was estimated to be \$14.75/kg . The experience curves shown in Figure 3.2 use those values for the initial cost and batch size. The initial batch of hydrogen produced is assumed to be $115000\,\frac{kg}{yr}$. If the assumptions of initial conditions and PR are accurate, the public and private investment predicted by this model is approximately \$29 million. Again, this is the difference between the predicted cost of H_2 produced by the Zn/ZnO cycle and what it would have cost to produce that H_2 by SMR, and it does not include any prior investment.

TABLE 2. Cumulative H_2 production necessary for the Zn/ZnO cycle to become economically competitive under three sets of initial condition assumptions given $PR = 0.77$, 0.82, 0.87.

	$c_\circ = \$8,\ P_\circ = 574900\,kg$	$c_\circ = \$14.75,\ P_\circ = 115000\,kg$	$c_\circ = \$100,\ P_\circ = 500\,kg$
$PR = 0.77$	$7.8 \times 10^6\,kg$	$7.9 \times 10^6\,kg$	$5.5 \times 10^6\,kg$
$PR = 0.82$	$1.8 \times 10^7\,kg$	$3.0 \times 10^7\,kg$	$1.1 \times 10^8\,kg$
$PR = 0.87$	$7.6 \times 10^7\,kg$	$3.2 \times 10^8\,kg$	$1.9 \times 10^{10}\,kg$

Finally, the experience curves in Figure 3.3 assume a much smaller initial batch and a much higher cost for that batch. In this analysis, the initial batch is assumed to be $500\,kg$ at a cost of $\$100\,/kg$. This assumption corresponds to a small-scale early demonstration project costing \$50000. This is a reasonable price for testing a reactor in the later stages of academic or private research, not including the costs of earlier research efforts. The amount of public and private investment needed to bring the technology down the experience curve to $\$3\,/kg$ predicted given these assumptions is \$112 million. These initial conditions are arbitrary, though reasonable; under this model, H_2 would cost \$5 to \$8 at cumulative production levels of 10^6 to 10^7 kg of hydrogen—on the order of production levels assumed by Steinfeld (7) and Charvin et al. (28).

The levels of cumulative H_2 production required for the Zn/ZnO cycle to compete economically with SMR H_2 at $\$3\,/kg$ are listed in Table 2 for each of the three assumed sets of initial conditions and each of the three assumed progress ratios. First, under the assumption of $PR = 0.77$, all three models predict similar break even points. This gives weight to the assertion that the assumptions in the models are reasonable. However, when PR is taken to be 0.87 the three models predict significantly different levels of production required to reach $\$3\,/kg$. However, a progress ratio of 0.87 corresponds to a learning rate of 13%—it is unlikely that such a new and emergent technology would have such a low learning rate. The lower progress ratios of 0.82 and 0.77 are more reasonable given the early development stages of all aspects of the technology (from the reactor to solar power towers) (33). For the sake of making conservative estimates, the proceeding analysis will be based on $PR = 0.82$. The two orders of magnitude difference between $PR = 0.77$ and $PR = 0.87$ for the third case ($c_\circ = \$100$) illustrates the sensitivity of the results to the assumed value of the PR. Because the initial conditions assumed in the third case do not come from the literature and because of the increased sensitivity to PR assumptions, the third case should be considered the least informative. Thus, in the following analysis, the initial conditions assumed will correspond to the small-scale plant, with $c_\circ = \$14.75$ and $P_\circ = 115000\,kg$ (28).

Policy: determining the rate of implementation. Though experience curves are clearly related to time—it takes time to increase production—they do not specify the time frame in which the prices drop, they simply explain how cost decreases with increasing cumulative production. The time in which the increased cumulative production occurs could be anything from 1 year to 100 years, and it would not affect the experience curve. However, the implementation time frame of the Zn/ZnO hydrogen production technology clearly matters. If we chose not to invest anything in the technology until the year 2100, it is unlikely to make any difference in mitigating climate change. On the other hand, if we invest heavily in this technology, at the expense of other interesting technologies, it may be competitive much sooner, but other valuable technologies would be floundering. If the H_2 produced by the Zn/ZnO cycle is to ever be a part of the energy market, Figures 3.1, 3.2, and 3.3 show that significant public and private investments are required. Both public and private investment in new technology is largely dependent on policy. Thus, I will explore three possible policy scenarios for implementation of the Zn/ZnO cycle: a minimal input policy, a mid-range policy, and an aggressive policy.

All three policy scenarios require the same amount of public and private investment to reach economic competitiveness, as the required investment is determined by the experience curve. The differences in these policies are in the rate at which these investments are made (i.e. the rate of technology demonstration and commercialization). The minimal input policy assumes that few resources are used to encourage the implementation of this technology in the short or mid term. In this policy scenario, either few resources are put to renewable energy in general, or the resources are directed almost entirely to near and mid-term technologies, while few resources are allocated for long term technologies like the Zn/ZnO hydrogen production cycle. The mid-range policy scenario assumes a moderate level of resources being devoted to demonstration and small scale implementation of the technology in the near to mid term, with the goal of economic viability by mid century. The Zn/ZnO cycle is assumed to be one of many long term technologies being cultivated. The aggressive policy scenario assumes high levels of resources devoted to the technology

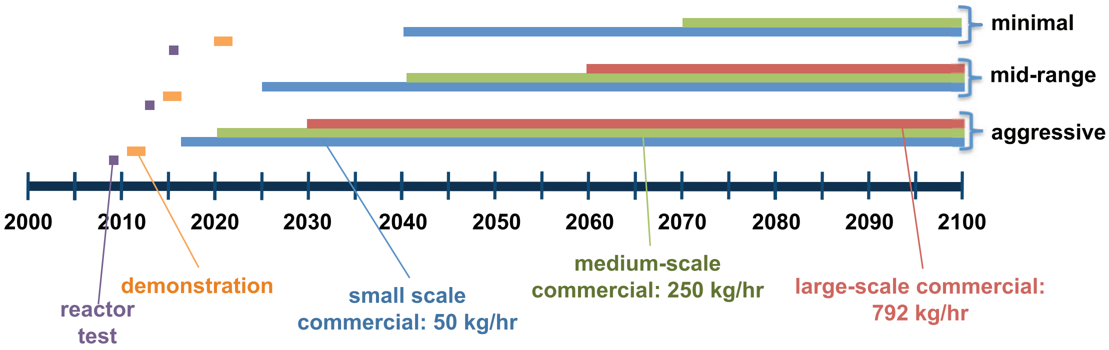

FIGURE 3.4. Time line for implementation of Zn/ZnO cycle technology under the three policy scenarios.

early on, with the goal of making the technology economically competitive well before mid-century. Under this policy scenario, either very significant resources are being devoted to renewable energy in general, or the Zn/ZnO cycle is receiving a disproportionate share of the funding.

The three policy regimes are applied to the learning curve data by assigning each a different time frame for implementing the Zn/ZnO cycle technologies. Under each scenario, implementation of the technology occurs in five stages. First, the reactor is tested, and second, a larger scale reactor is demonstrated in a process that occurs over two years. Because there is no data on the cost or scale of these steps, they cannot be included in the experience curve analysis. However, they will be used in the policy time-line for reference. Third, an initial, small commercial plant goes on line, producing H_2 at a rate of $50\,kg/hr$, corresponding to the small plant analyzed in Charvin et al. (28). Second, a mid sized plant goes into operation. Corresponding to the larger plant size analyzed in Charvin et al. (28), this mid-sized plant is assumed to produce H_2 at $250\,kg/hr$. Finally, a large scale plant goes on line, producing H_2 at a rate of $792\,kg/hr$, as analyzed in Steinfeld (7). The time line of implementation assumed for each policy scenario is depicted graphically in Figure 3.4. Under the aggressive policy, additional research and development funds push reactor testing and demonstration to 2009 and 2011-2012, respectively. The small, medium, and large scale solar H_2 production plants are rapidly built and implemented, so that the large scale plant goes on line in 2030. Under the mid-range policy scenario, the reactor is tested in 2012 and demonstrated in 2015 and 2016–time scales that the current level of research is on track to meet. The commercial plants are deployed steadily, with the small-scale plant starting

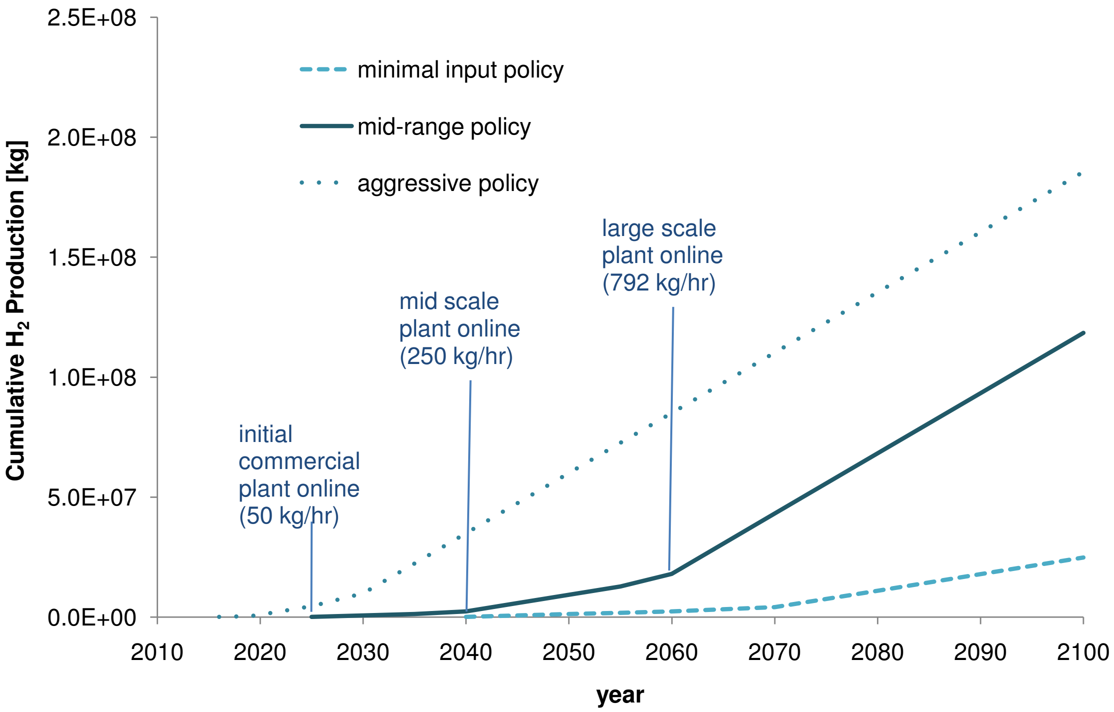

FIGURE 3.5. Cumulative H_2 production under an aggressive policy scenario, a mid-range policy scenario, and a minimal policy scenario for the Zn/Zno cycle technology.

operation in 2025, the mid-scale plant in 2040, and the large scale plant in 2060. Under the minimal input policy, the reactor is not tested until 2015 or demonstrated until 2020. Deployment of the small scale reactor only occurs once the need for solar fuels becomes acute, assumed here to be 2040. The medium sized reactor is built for operation in 2070, once the learning associated with the small scale plant brings prices down to economically competitive levels. A large scale reactor is not assumed to be built in this century under the minimal input policy scenario. If all three plants are in operation, these plants would produce a total of $3.8 \times 10^6\,kg$ of H_2 annually, roughly equivalent to the amount required to run 7000 cars each year[3].

Figure 3.5 shows the cumulative H_2 production by the Zn/ZnO cycle under each of the three policy scenarios. Bends in the production trends correspond to the addition of the small, medium, and large scale plants. These bends are labeled for the mid-range policy scenario. Through the use of the policy scenarios I have tied the cumulative production

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[3] Based on the approximate equivalence of the heating values for H_2 and gasoline, average vehicle miles traveled of $14000\frac{miles}{yr}$, and average gas mileage of $25\,\frac{miles}{gallon}$.

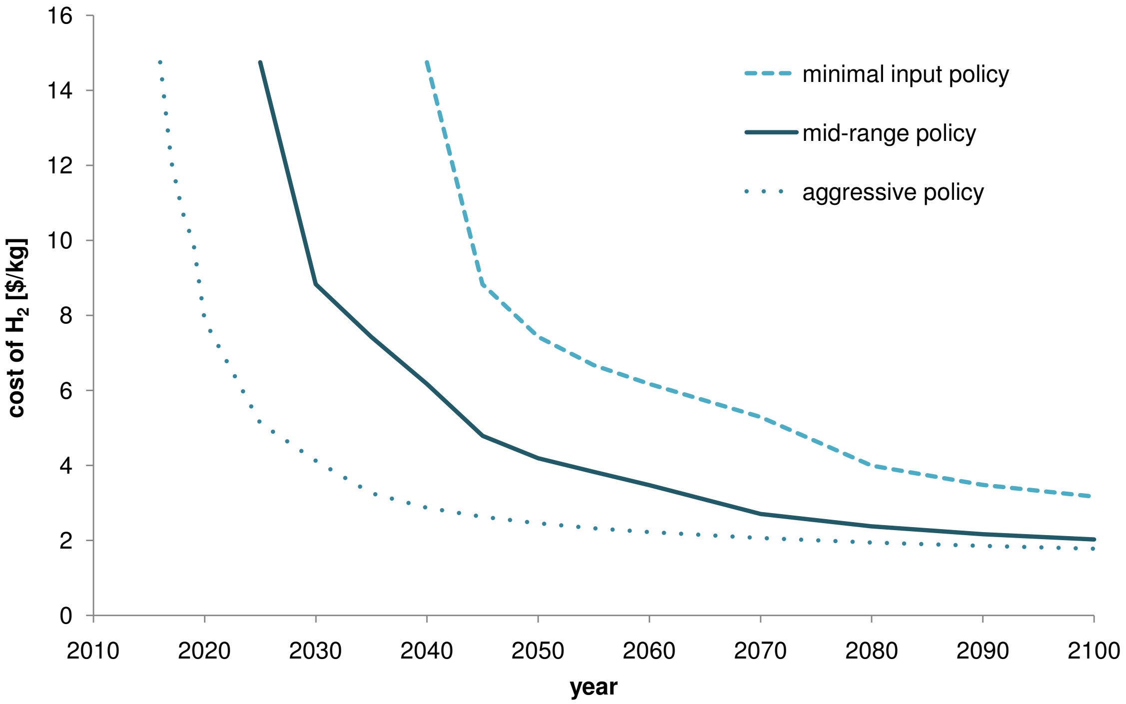


FIGURE 3.6. Cost of H_2 produced via the Zn/ZnO cycle under the three implementation policy scenarios.

to a time frame. Because experience curve expressions give the price of H_2 in terms of cumulative production, they can now be used to find the price of H_2 with time, under the different policy scenarios, as shown in Figure 3.6. It should be noted that these policy scenarios do not include assumptions about additional H_2 production plants, though they are likely to be built once the technology becomes economically competitive. Additional plants are not included in this analysis simply because their construction will be motivated by economic factors, not policy.

Effect of methane cost increases. To determine at what point H_2 produced by the Zn/ZnO cycle becomes cost competitive with that produced by SMR, the price of H_2 produced by the traditional, non-renewable method must also be predicted. As stated previously, 52 to 68% of the cost of H_2 produced by SMR is due to the cost of the natural gas (methane) used in the process. The remaining cost is due to the cost of the plant and its maintenance and operation. This 48 to 32% of the cost is subject to an experience curve effect of its own with $PR = 0.73$ (36). Thus, the cost of H_2 produced by SMR is predicted based on increasing costs of methane and decreasing O&M costs due to the learning effect.

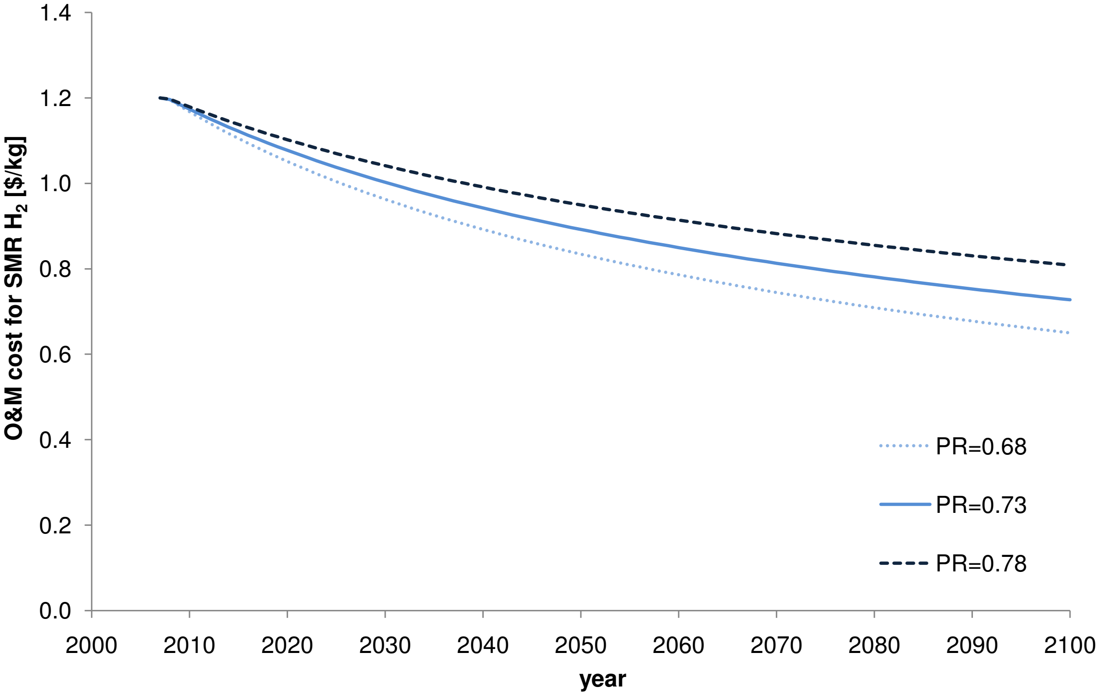


FIGURE 3.7. Predicted cost per kilogram of H_2 produced by SMR that is due to the plant operation and maintenance costs, assuming $PR = 0.68$, 0.73, and 0.78.

The cost of H_2 produced by SMR for each year is calculated as

$$c_t = (b \cdot c_{t-1})i_t + (1 - b) \cdot c_{O\&M} \tag{3.4}$$

where c_t is the cost of H_2 produced by SMR at time, t, c_{t-1} is the cost a year before year t, b is the fraction of the cost due to the cost of natural gas, $c_{O\&M}$ is determined from the SMR experience curve, and i_t is the annual percent increase in the cost of natural gas for the corresponding year. The first half of the right hand side (RHS) of equation 3.4 is the portion of the cost due to the price of natural gas, it changes every year at the same rate as the price of natural gas. The second half of the RHS of equation 3.4 represents the plant and operational costs, which decrease with cumulative experience.

The operation and maintenance costs were predicted using $PR = 0.73$. Future cumulative production levels of H_2 produced by SMR were extrapolated from data presented in Schoots et al. (34), in which SMR production increased by approximately 9.1% each year. The cost is projected starting in 2007, assuming costs of $\$3/kg$ for H_2 produced by SMR, and 2007 cumulative production of$4.18 \times 10^{10}\,kg$ (34). Figure 3.7 shows the decreasing cost

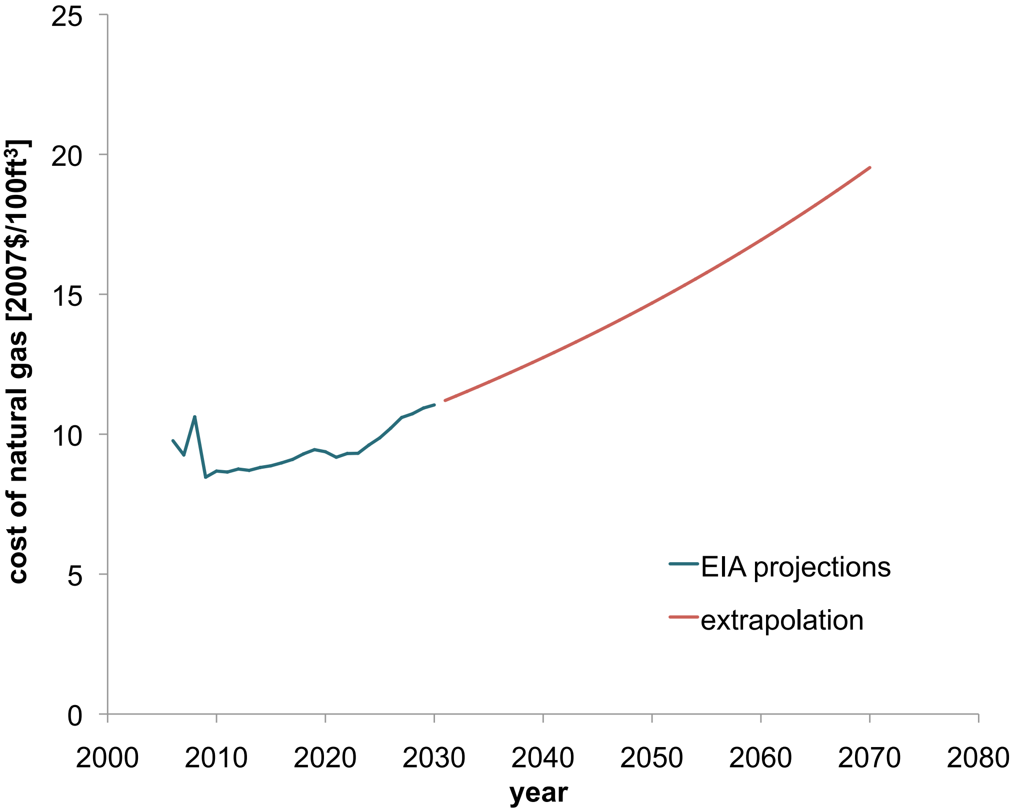


FIGURE 3.8. Projected cost of natural gas. Data through 2030 projections made my the EIA. Data for 2031 through 2070 are based on the average percent growth in the EIA data for 2015 through 2030.

of the plant operation and maintenance with time under $PR = 0.73 \pm 0.05$.

The price of natural gas from now until 2030 has been predicted by the Energy Information Administration (EIA). I used the average annual increase from 2015 to 2030 in the EIA's predicted costs to extrapolate natural gas price for the rest of the century, as shown in Figure 3.8. The resulting total projected costs of H_2 produced by SMR are shown in Figure 3.9.

The assumptions made in order to predict future costs of H_2 produced via the Zn/ZnO cycle are numerous. I have assumed a range of three values for initial conditions and the progress ratio. The progress ratio assumptions were based on progress ratios for similar technologies and reflect the range expected for this technology (33; 35–37). The assumptions about initial conditions were chosen to reflect values estimated in prior studies of the cost of H_2 produced via the Zn/ZnO method (7; 28) with the understanding that those predicted

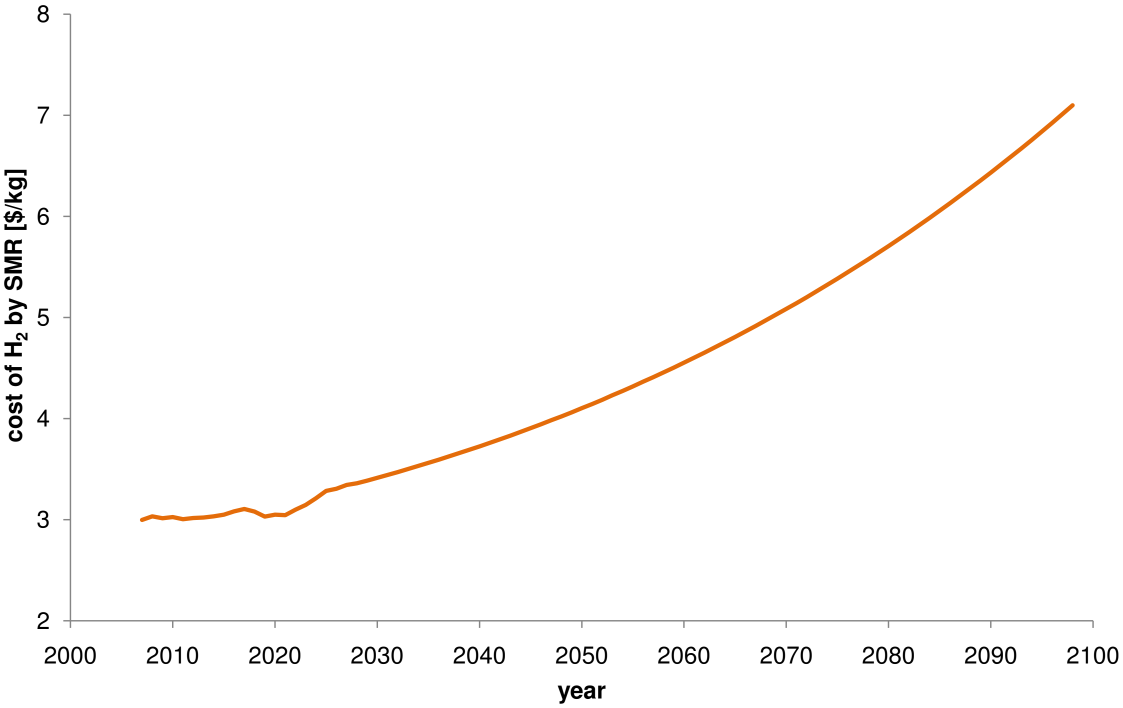


Figure 3.9. Projected cost of hydrogen produced by SMR assuming the overall cost of H_2 is 60% due to the cost of natural gas and the O&M progress ratio is 0.73.

costs assumed significant prior experience and so may represent points farther down the learning curve. A progress ratio of 0.82 was chosen as it is in the middle of what is likely for this technology. In addition, in order to tie cost to a time frame, implementation scenarios associated with different policy scenarios, were also assumed. Finally, in order to predict the cost of H_2 produced by SMR, assumptions were made about the fraction of cost due to the cost of natural gas. These assumptions are reasonable, but they remain educated guesses. Thus, this analysis must be understood as valid only under the conditions assumed. Under different conditions, this analysis can be useful as a reference point.

In addition to the assumptions that were necessary in the preceding calculations and analysis, three major premises underlie this work. First, this analysis is based on the theory that the experience curve effect will occur with this technology. There is ample evidence that shows that costs drop with increased cumulative production in most renewable technologies (33). However, in some markets in which policies were used to push technology deployment, the lack of competitive market or the overly rapid expansion of the sector caused prices to remain constant, or even increase, despite increasing cumulative production

(26). Thus, one important caveat to this analysis is that it only holds if the learning effect occurs. Second, it should be noted that the projected costs of natural gas from the EIA, which were used and extrapolated to predict natural gas costs through the end of the century, should not be assumed to be correct, rather a "best guess". Finally, this analysis relies on the Zn/ZnO H_2 production costs predicted by Steinfeld (7) and Charvin et al. (28). All three initial condition scenarios were chosen to keep their predicted costs approximately on the experience curve. The validity of this analysis therefore depends in part on the accuracy of those cost predictions.

CHAPTER 4

Results and Discussion

The intersections of the cost curves for H_2 produced by the Zn/ZnO cycle with the cost curves of H_2 produced by SMR are the points at which the solar H_2 becomes economically competitive. Figure 4.1 shows the cost of H_2 produced by both methods from 2010 through the end of the century. The cost of H_2 produced by SMR is shown both without a carbon tax, and with a carbon tax that increases with time. The carbon tax is assumed be $\$50\,/tC$ starting in 2012, increasing to $\$100\,/tC$ in 2025, $\$250\,/tC$ in 2050, and $\$500\,/tC$ in 2075. As can be seen in Figure 4.1, an increasing carbon tax combined with the aggressive policy, results in solar H_2 becoming competitive in 2032, the carbon tax combined with the mid-range policy results in H_2 becoming competitive by 2050, and carbon tax combined with

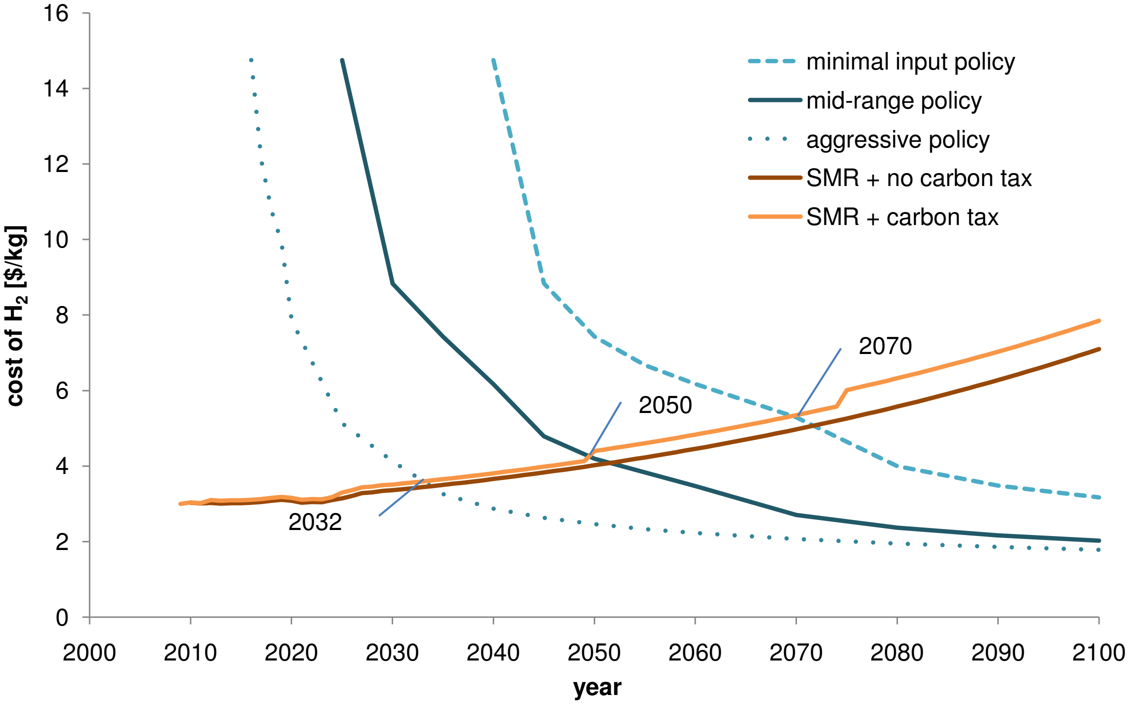


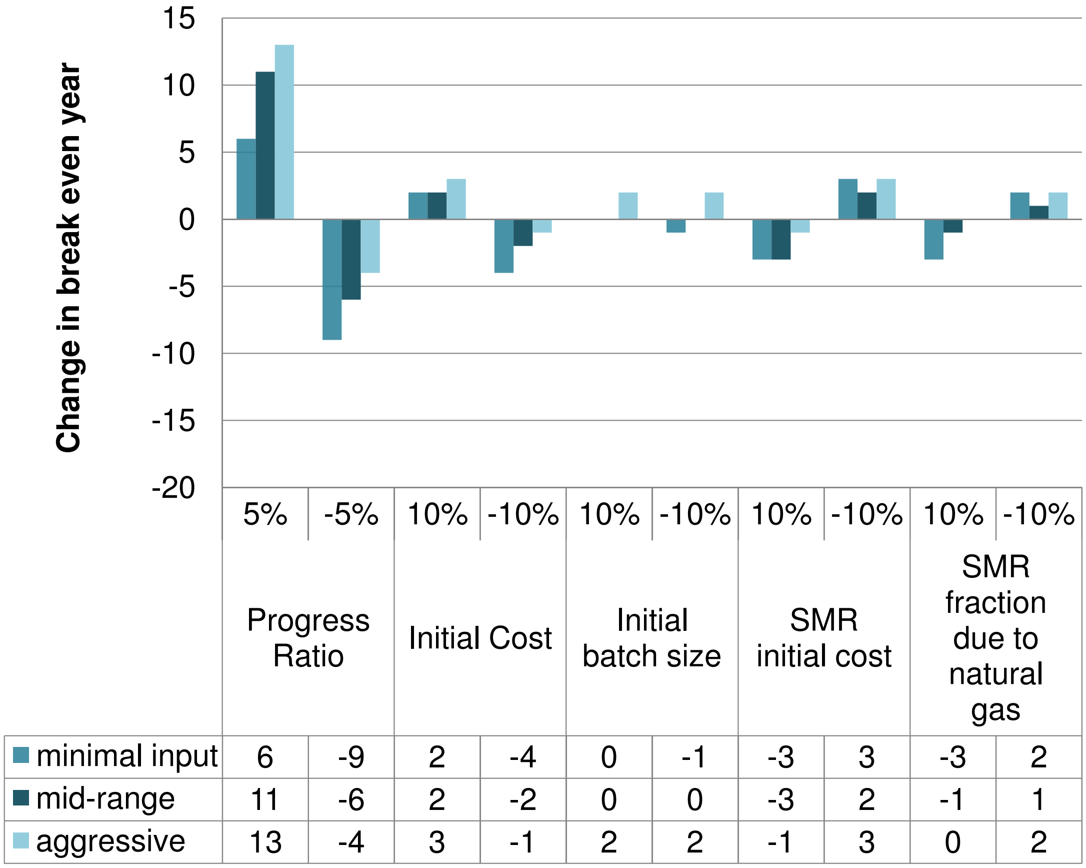
FIGURE 4.1. The cost of hydrogen produced via the Zn/ZnO cycle and SMR under different policy scenarios and with and without a carbon tax. The points at which solar H_2 becomes competitive is indicated for each policy scenario combined with a gradually increasing carbon tax.

the minimal input policy results in the technology becoming competitive in 2070. Without the carbon tax, the corresponding dates are 2034, 2052, and 2072.

The results of the cost projections on hydrogen produced via the Zn/ZnO cycle and steam methane reforming indicate that with public and private investment in the Zn/ZnO technology, even at a relatively slow investment pace, it can become economically viable in the latter part of the century. However, a more proactive approach (i.e. the mid-range policy) should help to ensure that the technology is economically competitive before mid-century. The year 2050 is often used as a bench mark for climate change policy, a time by which we should have stabilized the carbon in the atmosphere and after which we should start to reduce atmospheric concentrations of CO_2 and other greenhouse gases (1). Thus, it would be prudent to invest in long term solutions like the solar H_2 process, so that by the time we get to 2050 we have a wide range of economically competitive renewable energy technologies. Direct government support for R&D, demonstration, and early commercialization will be required for the technology to reach economic competitiveness with hydrogen produced by SMR. Further commercialization will depend on incentive policies such as tax breaks, purchase guarantees, and low interest rate loans (26). In addition, to help ensure that additional experience has the expected effect on cost, incentive policies must be clearly defined and consistent and include a pathway for transition to a competitive market structure (26).

The aggressive policy scenario is the most successful at quickly making the Zn/ZnO cycle cost competitive, but it should be considered carefully. If the aggressive approach to this technology is at the expense of other potential renewable energy technologies, then it may be counter to the overall goal of reducing greenhouse gas emissions. However, in a scenario in which renewable energy technologies are being pursued aggressively across the board, the aggressive policy may be appropriate. In that case, it would be important to consider that rapid investment and deployment of a technology can result in costs actually going up with experience, rather than down, as happened initially with nuclear electricity plants in the US (26).

It is interesting to note the relatively small effect of the carbon tax on the time at which the solar H_2 process becomes economically competitive. The 5.5 kg of CO_2 emitted per kg of hydrogen produced corresponds to 1.5 kg of carbon. A tax of \$100 per metric ton of



	Progress Ratio 5%	Progress Ratio -5%	Initial Cost 10%	Initial Cost -10%	Initial batch size 10%	Initial batch size -10%	SMR initial cost 10%	SMR initial cost -10%	SMR fraction due to natural gas 10%	SMR fraction due to natural gas -10%
minimal input	6	-9	2	-4	0	-1	-3	3	-3	2
mid-range	11	-6	2	-2	0	0	-3	2	-1	1
aggressive	13	-4	3	-1	2	2	-1	3	0	2

FIGURE 4.2. The sensitivity of the predicted "break even" year to the five major assumptions

carbon results in an additional \$0.15 added to the cost of a kg of H_2 produced by SMR. At the same time, the cost of solar H_2 is decreasing from approximately \$15 in 2025 to approximately \$4 in 2050. Thus, the effect of experience on the price of solar H_2 is much more significant than the effect of the price of carbon on H_2 produced via SMR. This is due to the emergent nature of the Zn/ZnO technology. The cost of a more mature technology would decrease much more slowly, closer to the order of magnitude of the carbon tax.

Five major assumptions were made in this analysis: the value of the progress ratio, the initial cost and batch size of H_2 produced by the Zn/ZnO cycle, the initial cost of H_2 produced by SMR, and the fraction of the cost of SMR H_2 that is due to the cost of natural gas. A sensitivity analysis on these assumptions was conducted, and the results are summarized in Figure 4.2.

The effect of a 5% increase or decrease in the progress ratio (PR) and a 10% increase or decrease the other four assumed values on the year in which the solar H_2 becomes competitive with SMR H_2 is shown. I use a smaller percent difference for PR, because assuming 10% change would result in values of PR that are outside the bounds of reasonable values to assume. As can be seen in Figure 4.2, the results are more sensitive to PR than anything else. A 5% increase in PR results in a predicted "break even" point $6 - 13$ years later, and a 5% decrease in PR results in the predicted break even point decreasing by four to nine years. The effect of a 10% change in the initial cost, initial batch size, SMR initial cost, and SMR cost fraction due to natural gas all result in changes in the predicted break even point of less than five years. Thus, this analysis is relatively robust, as changes in the assumptions do not result in significant changes in the predicted break even point.

CHAPTER 5

Conclusions

This study focused on the economic viability of H_2 produced via the Zn/ZnO cycle under different policy scenarios. Under the assumptions used in this analysis and given policies that lead to an initial, small scale Zn/ZnO hydrogen production plant in operation in 2025 and a mid-sized plant in operation in 2040, hydrogen produced using this technology should be competitive by mid-century. At that pace, the Zn/ZnO cycle would be positioned to produce a solar fuel to help meet goals of reducing atmospheric greenhouse gas concentrations during the second half of the century. Under a slower policy scenario, in which a small scale plant is in operation by 2040, the Zn/ZnO cycle is estimated to be able to competitively produce hydrogen by 2070, just after initiation of a mid-sized plant. Thus, the Zn/ZnO thermochemical cycle has the potential to help reduce greenhouse gas emissions in the second half of the century.

Estimations of near term costs of hydrogen produced by SMR (31; 32), electrolysis plus wind electricity (25; 29; 30), and electrolysis plus photovoltaic electricity (25; 29; 30) compared with projected costs of hydrogen produced by the Zn/ZnO cycle from the literature (7; 28) make clear that a reasonable level of carbon taxation would not be sufficient to make the Zn/ZnO cycle (or either electrolysis method) competitive with SMR. Thus, for hydrogen produced by the Zn/ZnO cycle to become cost competitive with hydrogen produced by steam methane reforming, public and private investment in the technology will be required. Direct government support for research, development, and demonstration projects and early commercialization followed by policies that provide incentives for private investment in the Zn/ZnO cycle technology—such as tax breaks, purchase guarantees, and low interest rate loans—will be crucial in bringing the cost of H_2 produced via the Zn/ZnO cycle down to levels competitive with H_2 produced by SMR. Incentive policies are often required for emerging energy technologies, in which the capital costs are high and the revenue steam may be uncertain, and many present day technologies initially relied on this type of government support (26). However, history also shows that if the most economically efficient path to cost competitiveness is desired, very rapid implementation of the technology or policies that result in non-competitive markets can undermine the learning effect for a technology (26). Thus, the benefits of rapid implementation should be weighed against the potential economic inefficiencies resulting from rapid deployment in policy design.

The most striking conclusion that comes out of the experience curve analysis is the relatively low investment needed to bring the technology to cost competitiveness. As the experience curve analysis shows, the public and private investment needed to become cost competitive is \$29 million, starting with construction of the first, small scale plant. This number does not include any investment in research, development and demonstration that occurred prior to the construction of the initial small plant, and it is only the investment above what it would have cost to produce the same amount of H_2 by SMR at $\$3/kg$. It is perhaps more intuitive to think about how many concentrating solar thermal Zn/ZnO plants need to be built in order to reach cost competitiveness. Under all three policy scenarios, the technology is projected to become cost competitive shortly after the second, mid-sized plant begins operation. The small and mid-sized plants are projected to cost \$5.7 million and \$16 million to build, respectively, and \$0.42 million and \$1 million for annual operation and maintenance, respectively (28). Thus, for this technology, economic viability is essentially two power plants away. Given that two (generally coal) power plants begin operation every week in China[1], building two solar Zn/ZnO plants seems eminently achievable, assuming there is the will. This is a very hopeful conclusion for this, and other, renewable energy technologies.

There are matters not explored in this study that would be important to consider if the Zn/ZnO thermochemical cycle proves to be an economically and technically attractive method of producing H_2. This cycle requires both excellent solar resource and a reliable water supply. In the United States, the suitable solar resource is primarily in the south west, where water is scarce. The two steps can be split up, so that the solar dissociation of ZnO occurs in a region of high solar resource and the hydrolysis step is carried out in a location with plentiful water supply. However, in that case, the Zn and ZnO would need to be transported back and forth between sites. Siting and water use are therefore two issues beyond the initially high costs that will need to be addressed in order for the Zn/ZnO

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[1] http://news.bbc.co.uk/2/hi/asia-pacific/6769743.stm, accessed 7/13/2009

cycle to be viable. Further, as water becomes more scarce, we will need to either address the question of whether it should be used to make fuels or design reactors that can accommodate salt water.

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