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STUDIES ON THE PRODUCTION AND DELIVERY OF HYDROGEN FROM RENEWABLE RESOURCES

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Abstract

Work for the DOE Hydrogen Program in 1998 focused on determining the delivered cost of hydrogen from various production technologies. To that end, a computer module was built from earlier calculations, to identify the most economic storage and transportation option given the hydrogen production rate and transportation distance. Storage methods analyzed include compressed gas, liquid hydrogen, metal hydride, and underground storage. Modes of transportation included truck and rail transport for the compressed gas and metal hydride, and barge, truck, and rail delivery for the liquid hydrogen as well as pipeline delivery. To test the module, a previous analysis of hydrogen production by biomass gasification and steam reforming was revisited.

An earlier analysis of the economic feasibility of photoelectrochemical hydrogen production revealed the plastic housing unit to be a significant driver of total system cost. To remove some of the uncertainty in the analysis and to identify appropriate design targets, a detailed examination of the housing unit was made. The relevant properties of different polymer materials were compared, and vendor quotes were used to refine the cost of this component. Based on these new values, the selling price of the hydrogen produced by this technology was calculated.

This paper contains a summary of the input requirements and results from the storage and transportation computer module, the application of the module with the previous analysis of hydrogen from biomass via gasification, and a review of the results of the study of the PEC housing unit. Additionally, a description of ongoing work to evaluate the production of hydrogen from low-Btu coal is included. This last study is a joint effort between the NREL and FETC, and will include sequestration of CO_2 and recovery of coalbed methane, as well as coproduction of power with the hydrogen.

Determination of the Delivered Cost of Hydrogen

The determination of the economic feasibility of hydrogen production systems has typically been made in terms of gate price. That is, the cost to produce and purify the hydrogen would be included, but the cost to store and deliver it would be excluded. For the purpose of comparing the economics of the technology being studied to other methods, a gate price analysis is most appropriate since the goal is to compare the hydrogen selling price and to identify the components that account for the highest costs. However, this method does ascertain possible market penetrations or actual costs to future hydrogen fuel customers. It may be that hydrogen from technologies that are cheaper at the small scale can compete with conventional production systems that are more economic at large scales because of shorter transportation distances. Only by incorporating storage and transportation costs can future market scenarios for novel production methods be identified. For this reason, NREL has developed an Excel spreadsheet that will calculate the lowest cost option for hydrogen storage and transport. Details about the module can be found in the next section, while a test case to incorporate the module with a previous technoeconomic analysis is given later in this paper.

Computer Module for Determining Hydrogen Storage and Transportation Costs

The Excel computer module developed to determine the lowest cost method for a given production rate and delivery distance consolidates calculations for liquid, compressed gas, metal hydride, and pipeline delivery. Besides the cost data, other details, such as the number of trucks required, fuel consumption and electricity use, are calculated. Different assumptions, including the average unloading time, liquid hydrogen boil-off rate or weighted average cost of capital, can be changed to examine the effect on the hydrogen delivery cost. The module will be integrated with the standard discounted cash flow rate of return analyses performed on various production technologies to determine the total delivered cost of hydrogen. This work is an extension of that reported in Amos (1998).

To provide an example of the data the cost module provides, the following information was entered into the spreadsheet:

Production Rate = 100 kg/h
Delivery Distance = 200 km (one-way)
Minimum Onsite Storage = 12 h
Weighted Average Cost of Capital = 15%

This is the minimum amount of information that must be entered. From these data, the module uses a set of built-in assumptions to calculate the costs of all the different storage and delivery possibilities. The lowest-cost option is then highlighted.

In this case, onsite compressed gas storage with a metal hydride delivery truck was identified as the cheapest option. Metal hydride truck transport was included as an option because even though the metal hydride alloy is very expensive, the storage capacity per truck is much greater than for compressed gas storage, and no expensive liquefaction plant is required.

Table 1 compares liquid hydrogen, compressed gas and metal hydride truck delivery for this example. Twelve hours of onsite storage at the production site is also included in these costs. Note that there are two costs associated with the capital equipment: one based on the depreciation of the capital equipment or trucks and another based on the cost of capital, or revenue, returned to the investor. Depreciation periods vary for different pieces of equipment, leading to different depreciation charges for each method of storage and transportation. These results are shown graphically in Figure 1.

Table 1: Major Results for Different Hydrogen Delivery Methods

	Liquid	Comp. Gas	Metal Hydride
Total Delivered Cost	\$18.36/GJ	\$15.90/GJ	\$14.42/GJ
Compressor/Liquefier Cost	\$2.85/GJ	\$0.15/GJ	\$0.15/GJ
Onsite Storage	\$0.08/GJ	\$0.41/GJ	\$0.41/GJ
Trucks	\$0.93/GJ	\$1.68/GJ	\$3.40/GJ
Electricity	\$3.49/GJ	\$0.78/GJ	\$0.78/GJ
Heat/Steam	-	-	\$0.63/GJ
Cooling	\$0.08/GJ	\$0.01/GJ	\$0.04/GJ
Fuel	\$0.08/GJ	\$1.67/GJ	\$0.72/GJ
Labor	\$0.39/GJ	\$8.09/GJ	\$3.51/GJ
Cost of Capital	\$10.45/GJ	\$3.12/GJ	\$4.79/GJ
Total Capital Cost	\$8.2 million	\$2.5 million	\$3.8 million
Annual Op. Cost (No Cost of Capital)	\$0.9 million/yr	\$1.5 million/yr	\$1.1 million/yr
Annual Op. Cost w/Cost of Capital	\$2.1 million/yr	\$1.9 million/yr	\$1.7 million/yr
Truck Working Capacity	3,700 kg	200 kg	400 kg
Number of Trucks Required	1	4	2
Number of Trips per Year	186	4,700	2,100
Number of Drivers Required	1	8	4
Annual Fuel Consumption	7,700 gal	195,000 gal	84,000 gal
Annual Electricity Consumption	8,300,000 kWh	1,900,000 kWh	(18,000 MM Btu, 5,400,000 KWh as heat)
Minimum Storage	2 h	7 h	4 h
Labor Hours for Drivers	1,300 hr/yr	33,000 hr/yr	14,000 hr/yr

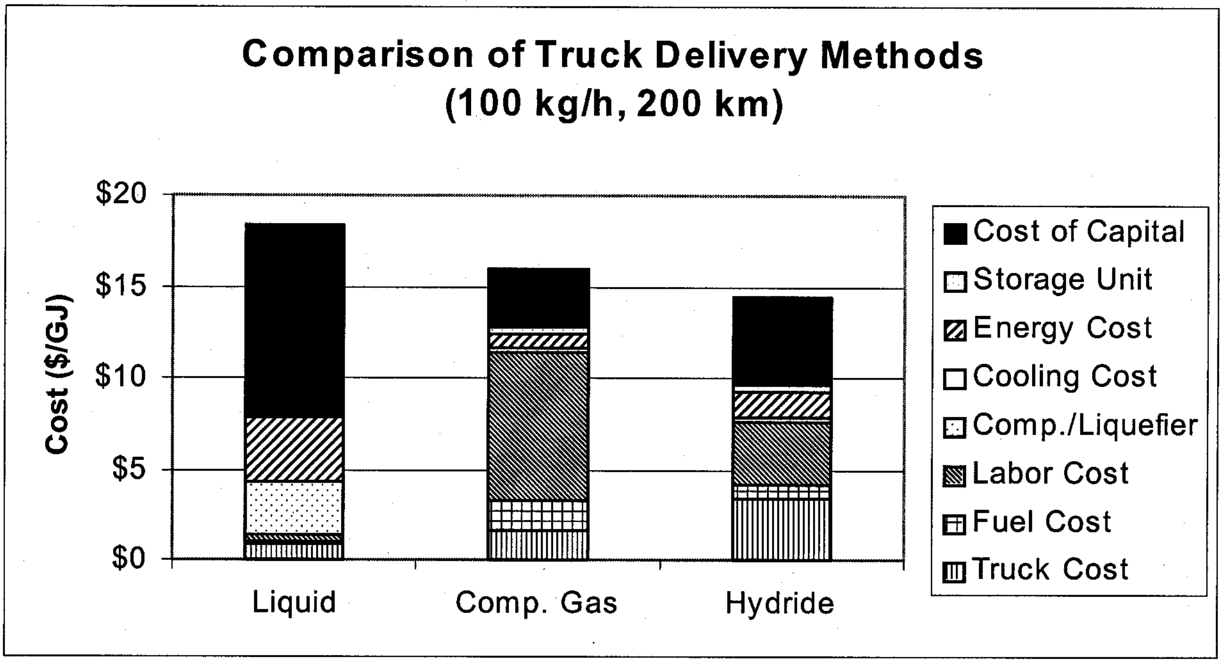


Figure 1: Comparison of Different Hydrogen Delivery Costs

The costs associated with onsite storage and delivery vary depending on the production rate and the delivery distance. To complicate matters, the cheapest method of delivery will also vary with the production rate and distance. For example, at high production rates and short distances, pipeline delivery of gas is almost always the lowest cost alternative, but for distances of a few hundred kilometers, the lowest cost method of delivery depends on the production rate. Figure 2 shows how the lowest cost delivery method changes with the delivery distance and production rate for a given set of assumptions.

The graph agrees with what we might expect: to justify the large capital investment in a pipeline or liquefaction plant, one must be producing large quantities of hydrogen, otherwise, compressed gas transportation and storage is the best option. It is interesting to note that there is a region between compressed gas delivery and liquid hydrogen transport where metal hydride transport by truck might make sense depending on the alloy cost, desorption energy requirements and the amount of hydrogen that can be transported by each truck. Underground storage costs are also estimated by the cost module, but this method of storage is only available at sites with the proper geology.

An important reason for using the cost module for determining transport costs is that delivery cost does not vary linearly with delivery distance. One simple method of estimating delivery costs uses a flat cost of so many cents per mile per pound of hydrogen. Figure 3 shows, however, that the delivery and storage costs have sections that increase sharply, then level out. This is because the lowest-cost delivery method changes.

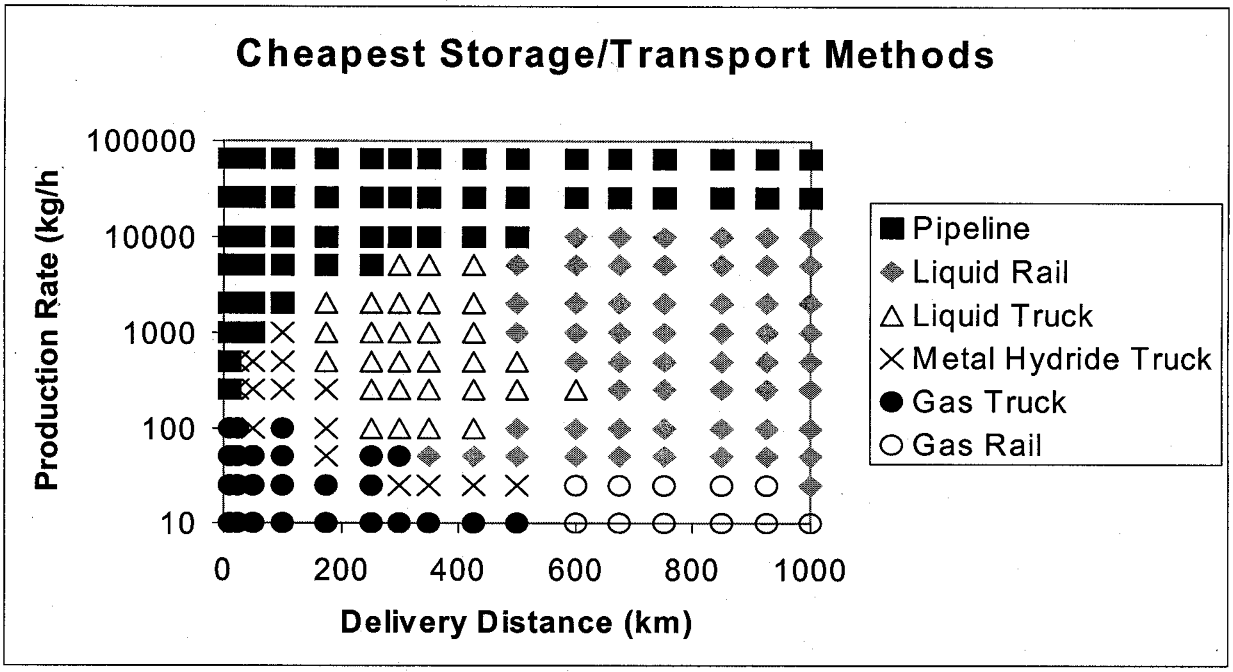


Figure 2: Lowest Cost Hydrogen Storage and Delivery Combination

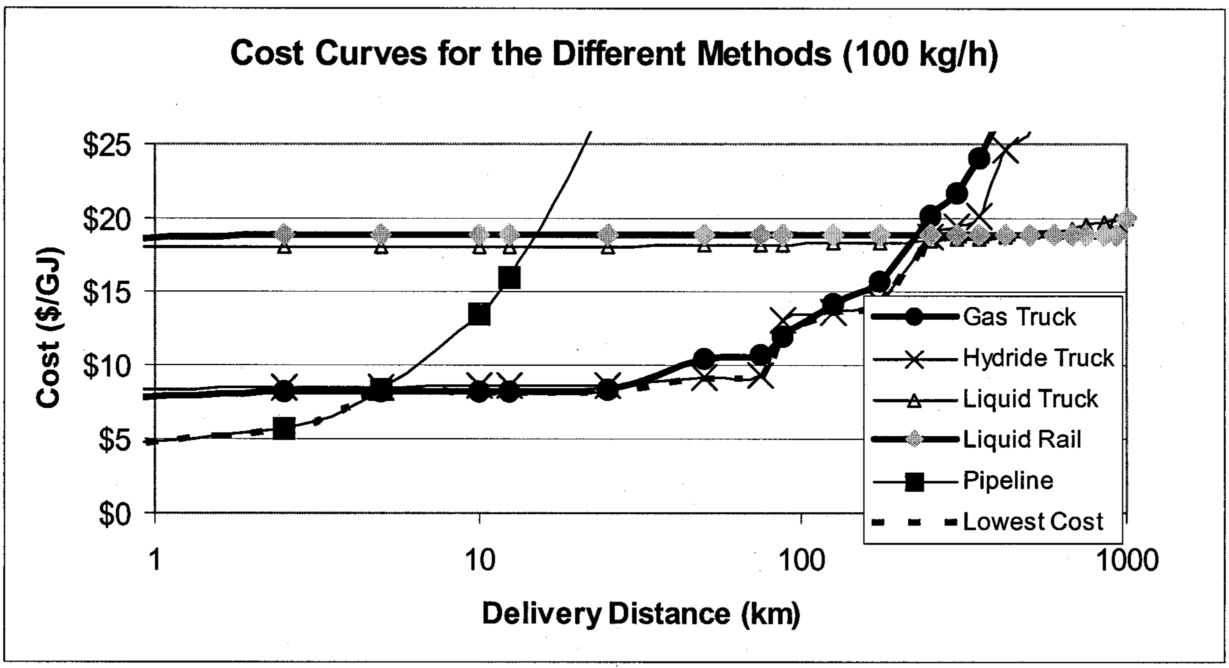
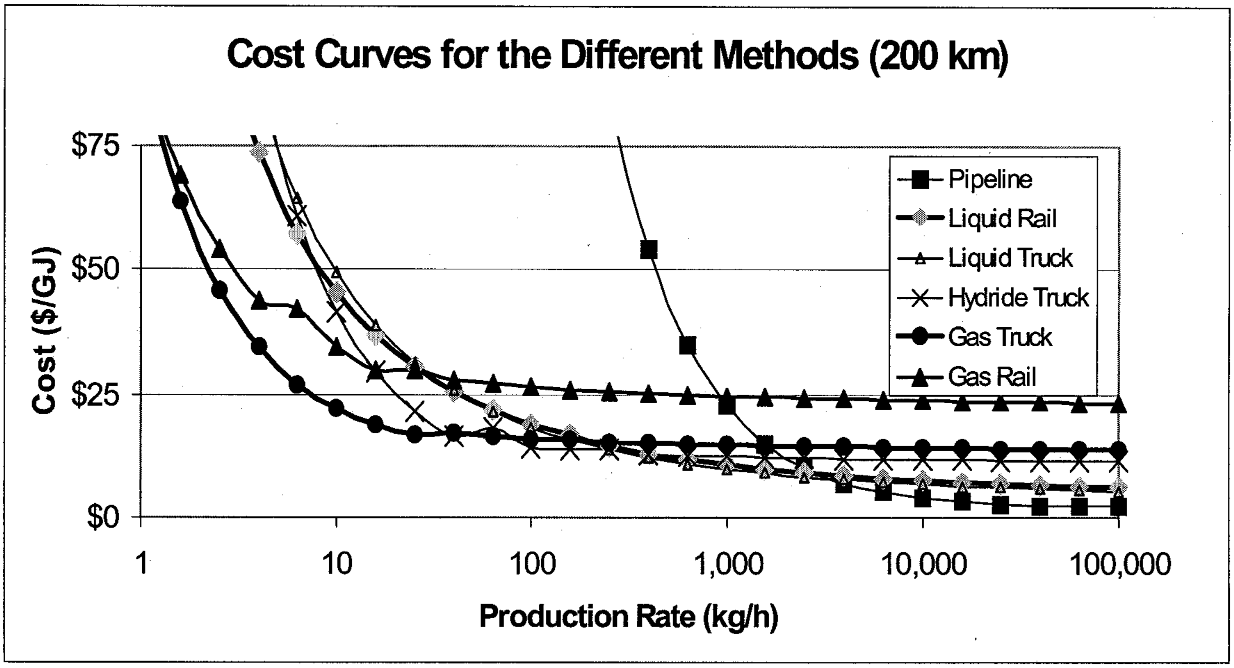


Figure 3: Delivery Cost Does Not Vary Linearly with Distance.

Another important consideration when calculating delivery costs is how many trips each truck can make per day. Delivery costs will decrease considerably when the distance is short enough for one truck to make multiple trips on the same day. This way, the capital cost of each truck is spread out over more hydrogen. Eventually, the costs level out once a truck is no longer sitting idle and it is making deliveries around the clock. This is shown in Figure 4 for a fixed delivery distance of 200



km.

Figure 4: Delivery Costs versus Production Rates

Further work on the cost module will focus on verifying some of the assumptions with industry, and running sensitivity analyses to determine which variables have the greatest effect on the overall costs. All future technoeconomic cost estimates will use this module to determine both the gate cost and the delivered hydrogen price.

Incorporating Storage and Transportation Costs into a Previous Analysis

Last year, a technoeconomic analysis of the thermochemical conversion of biomass to hydrogen using the Institute for Gas Technology (IGT) direct-fired gasifier was performed (Mann *et al*, 1998). The results showed the plant gate hydrogen selling price for a 300 bone dry megagram/day plant to range from $25-$29/GJ for a feedstock cost of $0 to $46/dry tonne. For the same feedstock prices, the hydrogen cost decreases to $17-$22/GJ for a 1,000 bone dry Mg/day plant size. This is the cost for producing purified hydrogen but does not include any storage or distribution costs. To determine the effect of storage and transport on the delivered cost of hydrogen, the following scenarios were examined and incorporated into this previously completed IGT analysis. These represent six likely scenarios for using hydrogen.

Storage and transportation scenarios studied:

1. bulk delivery: 16 km one-way
2. bulk delivery: 160 km one-way
3. bulk delivery: 1,610 km one-way
4. on site consumption: 12 hours of storage; no transport.
5. gas station supply: weekly hydrogen delivery; driving distance of 160 km round trip; supplying multiple stations along the way; hydrogen use of 263 kg/day per gas station.
6. pipeline: 3 km to the nearest pipeline infrastructure; no storage; an additional 160 km pipeline for hydrogen delivery to end user for which the cost is shared by 5 companies.

For each scenario, the most economical mode of storage and delivery was identified for both the 300 and 1,000 Mg/day plants. The hydrogen production capacities of these plants were 22,232 kg/day and 74,106 kg/day, respectively. Each plant was assumed to operate at a 90% capacity factor with the purified hydrogen coming out of the plants at 22 C and 3 MPa. Table 2 shows the cheapest storage and delivery method for each production size, along with the associated costs.

Table 2: Cheapest Storage and Transport Type and Cost

Plant size (Mg/day)	Scenario	Storage type	Transport type	Storage cost (\$/GJ of H_2)	Transport cost (\$/GJ of H_2)	Total storage & transport cost (\$/GJ of H_2)
300	1	gas	pipeline	1.53	1.79	3.32
	2	gas	metal hydride truck	1.53	8.73	10.26
	3	liquid	liquid rail	9.97	2.04	12.01
	4	gas	none	1.53	none	1.53
	5	gas	metal hydride truck	1.53	6.03	7.56
	6	none	pipeline	none	3.94	3.94
1,000	1	gas	pipeline	1.23	0.55	1.78
	2	gas	pipeline	1.23	5.44	6.67
	3	liquid	liquid rail	7.95	1.98	9.93
	4	gas	none	1.23	none	1.23
	5	gas	pipeline	1.23	5.44	6.67
	6	none	pipeline	none	1.26	1.26

Note: The numbers in this table are for the specific hydrogen production rate from each plant size and should not be scaled to other production rates.

The total storage and delivery cost must be added to the hydrogen production cost to get the total delivered cost of hydrogen. Figure 5 shows the total delivered cost of hydrogen for each of the six scenarios examined for the 300 Mg/day plant assuming a biomass feedstock cost of \$46/dry Mg.

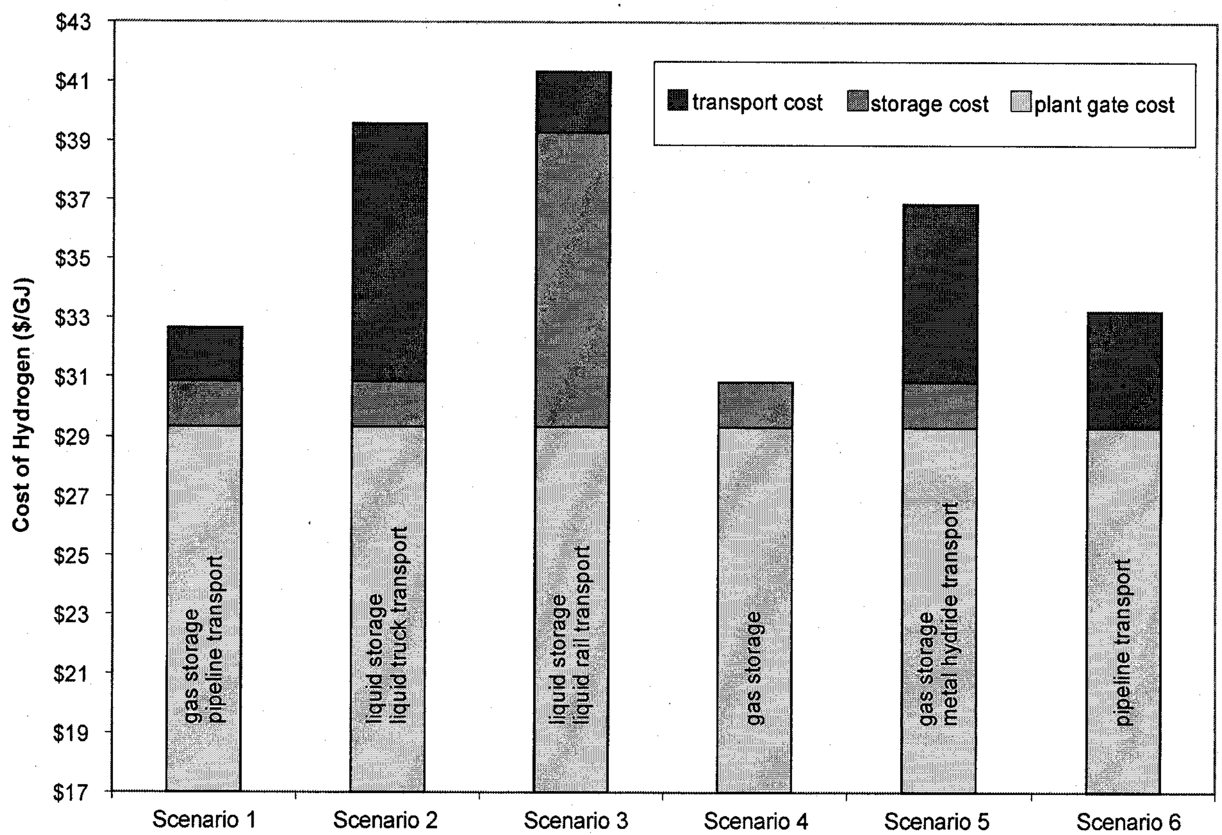


Figure 5: Cost of Delivered Hydrogen for IGT Analysis

The most economical mode of storage and delivery (e.g., liquid, compressed gas, metal hydride or pipeline delivery) varied depending on the production rate and transport distance. For example, for scenario two (bulk delivery of hydrogen to a customer 160 km away), compressed gas storage and metal hydride truck delivery was the cheapest option for the 300 Mg/day plant size. For the 1,000 Mg/day size, however, gas storage and pipeline delivery were the most economical. These six scenarios show that the cost for storage and transport could be as little as $1/GJ or as much as $10/GJ for this production technology. Ultimately, the cost of storing and transporting hydrogen depends on the amount of hydrogen the customer needs and how far their site is from the production facility.

Evaluation of Hydrogen Production from Low BTU Western Coal Augmented with Coalbed Methane Recovery Induced by CO_2 Sequestration

Hydrogen production via gasification of low sulfur western coal is being evaluated in a joint effort between the National Renewable Energy Laboratory (NREL) and the Federal Energy Technology Center (FETC). This work differs from past evaluations because it focuses on sequestering CO_2 and recovering coalbed methane. The off-gas stream, containing primarily CO_2, that is produced during hydrogen purification, is used to displace methane from unmineable coalbeds. This methane is then utilized within the gasification-to-hydrogen system. Processing schemes are being evaluated for maximizing hydrogen production or co-producing hydrogen and electricty.

Wyodak coal was selected as a suitable coal for this type of operation. This is a low rank Western coal that is inexpensive to produce and is available in abundant supply. Additionally, the state regulations in Wyoming permit the extraction of coalbed methane, making this site attractive for CO_2 sequestration and coalbed methane recovery. The elemental analysis and heating value of the Wyodak coal being used for this work are shown in Table 3 (EIA, 1995).

Table 3: Wyodak Coal Analysis

Ultimate Analysis	(Weight %, dry basis)
Carbon	67.6
Oxygen	17.7
Hydrogen	4.8
Nitrogen	1.2
Sulfur	0.8
Ash	7.9
Moisture, as-received (wt%)	26.6
Heat of combustion, HHV ,as-received	20,073 J/g (8,630 Btu/lb)

The Destec gasifier, which is a two-stage entrained, upflow gasifier, is being used for this analysis. The gasifier is currently being demonstrated under FETC's Clean Coal Technology Program at the Wabash River Coal Gasification Repowering Project in West Terre Haute, Indiana. The gasifier operates at a temperature of 1,038 C (1,900 F) and a pressure of 2,841 kPa (412 psia). For hydrogen production, the gasifier must be oxygen blown in order to minimize the amount of nitrogen in the syngas. Nitrogen, like hydrogen, is not strongly adsorbed onto the catalyst in the pressure swing adsorption (PSA) unit, and therefore reduces the hydrogen recovery rate for the same purity. The feed is a coal/water slurry containing 53 wt% solids. Table 4 shows the syngas composition exiting the gasifier:

Table 4: Syngas Composition

Component	N2	Ar	H_2	CO	CO_2	H_2O	CH_4	H_2S	NH_3	COS
mol %	0.6	0.7	27.7	27.4	16.5	26.6	0.0939	0.1399	0.2	0.0061
Heat of combustion, HHV, = 419 J/g (180 Btu/lb)										

Two options are currently being evaluated for this study. Option 1 aims for maximum hydrogen production, while Option 2 is designed to co-produce hydrogen and power, with the hydrogen being produced from the syngas and the power from recovered methane. See the simple block flow diagrams shown in Figures 6 and 7 for graphical descriptions of these options. The shaded blocks are the process steps that differ between the two options. Time permitting, other options for co-production of hydrogen and power will be analyzed. In order to compare the economics as well as the overall CO_2 emissions from each option, the base case analysis will include only the process steps associated with coal gasification, shift, and hydrogen purification (i.e., none of the steps associated with CO_2 sequestration or coalbed methane recovery will be included in the base case). All of the options studied in this joint venture will be compared to this base case.

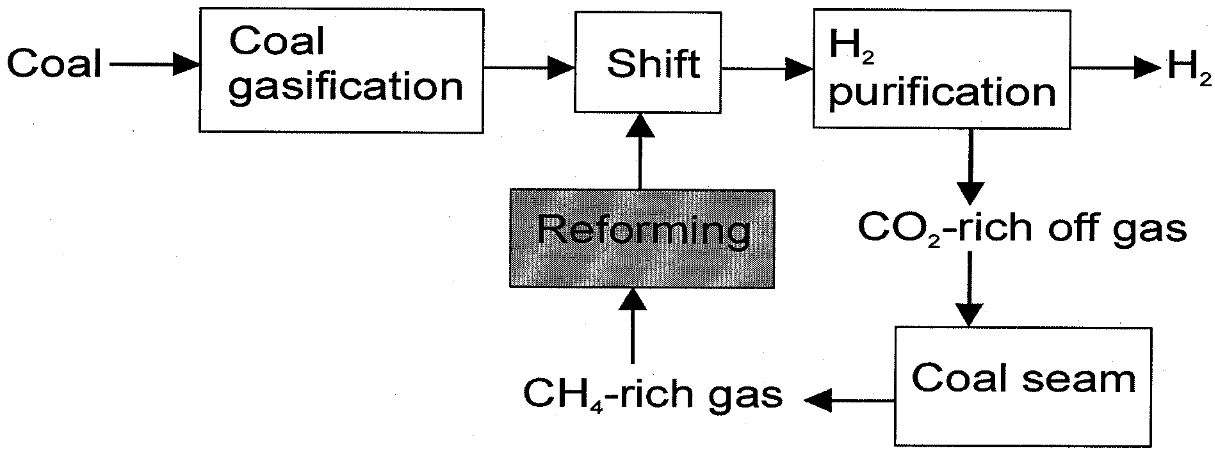


Figure 6: Option 1 - Maximum H_2 Production

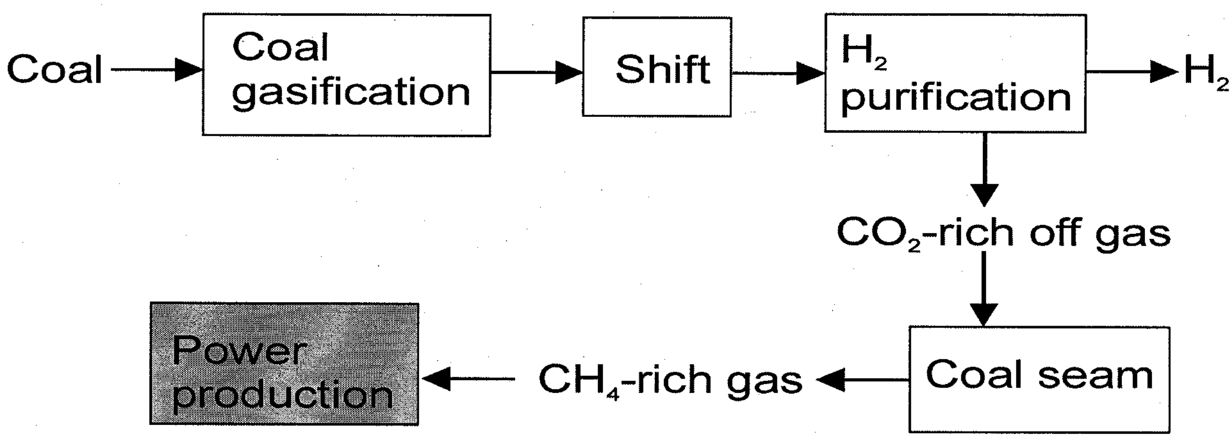


Figure 7: Option 2 - H_2 Production from Syngas &Power Production from Recovered CH_4

Because the syngas from the gasifier contains approximately 1,400 ppm H_2S, the sulfur must be removed prior to shift conversion. The high temperature shift catalyst can tolerate concentrations up to 200 ppm but typically operates at lower amounts. Sulfur strongly poisons the low temperature shift catalyst, requiring a reduction in H_2S levels below 0.1 ppm. Figure 8 is a schematic of the hydrogen/power co-production case showing the sulfur removal scheme. Hot gas clean up (HGCU) followed by a ZnO bed is being used for all cases examined.

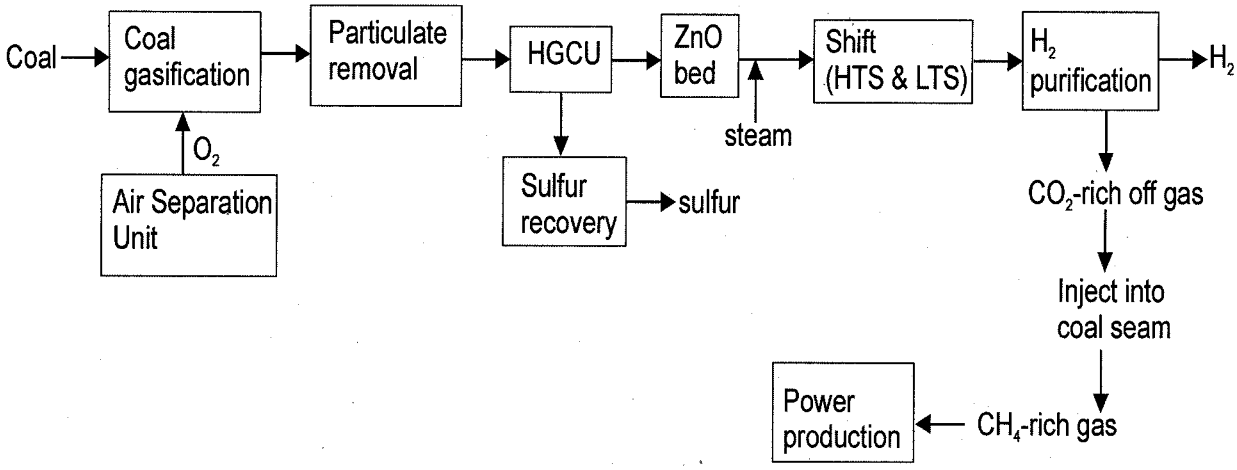


Figure 8: Sulfur Removal Using Hot Gas Clean Up

While defining the scope of this analysis, other sulfur removal schemes that incorporate a combination of cold gas clean-up and "dirty" shift catalyst were examined. However, none of these schemes are more economical than HGCU. For instance, using cold gas clean up prior to shift conversion not only requires cooling and reheating of the syngas but it results in condensing out the steam that is required for shift conversion.

The syngas leaving the gasifier contains entrained particles of char and ash. Particulate removal will be performed through cyclone separators and ceramic candle type hot-gas filters. Hydrogen purification will be done using a PSA unit. Because this unit operates at a pressure considerably lower than the coal seam, the CO_2-rich off-gas must be compressed prior to injection. Based on data from previous studies (Gunter *et al*, 1996 and Hendriks, 1994) the analysis assumes that two molecules of CO_2 are injected for every one molecule of CH_4 released from the coalbed. The off-gas from the hydrogen purification unit, which contains about 68 mol% CO_2, must be compressed from 2.7 MPa (392 psi) to the pressure generally found in coalbed methane reservoirs, about 3 - 14 MPa (500- 2,000 psi) (American Association of Petroleum Geologists, 1994).

Once the hydrogen production cost is determined, several likely scenarios for storing and transporting hydrogen will be examined. These expenses will be added to the hydrogen production cost in order to determine the delivered price of hydrogen. The cost of storing and transporting hydrogen depends on the amount of hydrogen the customer needs and how far their site is from the production facility. In each case, the lowest cost storage and delivery method (i.e., liquid, compressed gas, metal hydride or pipeline delivery) will be determined based on several factors including production rate, transport distance, and end use.

Evaluation of the Cost of a PEC Housing Unit

An economic evaluation conducted in 1998 of photoelectrochemical (PEC) hydrogen production identified the housing material as a key cost component with significant uncertainty (Mann *et al*,

1998) . The long-term (~2020) projections found that construction and assembly of the housing material could represent 23% of the total capital costs, assuming that the housing assembly will cost \$7/m of length (\$2.13/ft). The near-term (~2000) and mid-term (~2010) analyses predicted that the housing unit could make up 19% and 20% of the total capital, respectively. This assumes housing assembly costs of \$12/m and \$9/m, respectively. PEC has the potential to be an important source of future renewable hydrogen, but cannot currently compete against fossil-based systems and even some renewable systems. Therefore, efforts to reduce the uncertainty in predicting the ultimate costs are important in identifying which cost components should be given research priority.

PEC water splitting represents an alternative to PV/electrolysis systems by combining a semiconductor and an electrocatalyst into a single device. Researchers in this field are working to develop a stable, cost effective, semiconductor-based system that will collect solar energy and electrolyze water in one step to produce hydrogen, with sunlight as the only energy input. Two configurations are being studied: single gap systems and multijunction systems. The theoretical lower heating value efficiency of dual junction systems is 32% while single bandgap systems have an upper limit on the order of 24%. Practical systems could achieve 20% and 10% efficiencies for multijunction and single bandgap systems, respectively. Current efforts are focused on understanding the fundamental mechanisms of reaction, improving yield, and protecting the photocatalyst from surface oxidation. More information on this research can be found in Kocha *et al* (1996), Kocha *et al* (1997), and Rocheleau *et al* (1996).

Housing Unit Design

The housing unit contains the PEC cell (based on the design of a photovoltaics cell without interconnects and wiring), immersed in a weakly acidic or basic electrolyte solution. An ion-porous membrane is set on both sides of the cell. The shape of the housing is designed to concentrate the incident light by a factor of about five or more; the amorphous silicon-based cells can tolerate up to about 10-12 suns. This assessment assumes that the cheapest design will be based on standard extruded plastic tubes. However, a reduction in the amount of materials may make an integrated housing unit concept more economic.

Optics calculations determined the relationship between the radius of curvature of the unit and the distance between the surface and the target plane. Figure 9 shows the parameters that were included in the calculations. The incident sunlight was assumed to fall on the unit in perfectly parallel rays. Additionally, a concentration ratio of five was assumed, with the cell width specified at 2 cm; this forces the aperture width to be 10 cm. Finally, the index of refraction of the electrolyte medium was assumed to be 1.4. The Excel spreadsheet function that was used to calculate D is: R+(4/(TAN(ASIN(5/R)-ASIN(5/(1.4*R))))-SQRT(R*A19-25)).

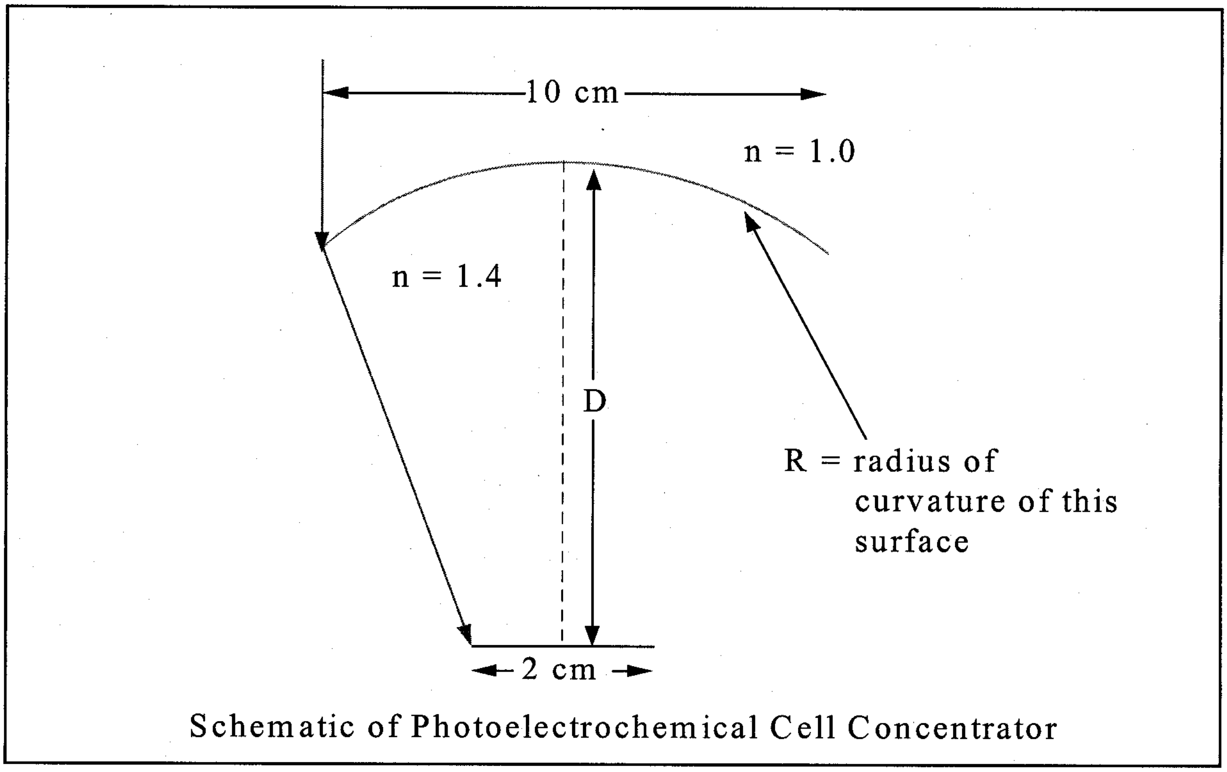


Figure 9: Schematic of Top of PEC Housing Unit

Based on these optics calculations, a few simple test reactors were constructed from acrylic. If the radius of curvature on the lens side of the concentrator is kept small enough (about 4" diameter depending on reflective losses and the index of refraction of the electrolyte solution), the focal point is actually contained within a cylinder. Therefore, standard extruded cylinders could be used for the reactor, resulting in lower prices.

Although the design for the PEC housing unit was addressed in the 1998 study, materials of construction were not optimized based on cost. The chosen material should meet the following criteria:

Able to resist attack from the electrolyte solution
Stable in an aqueous environment
Transparent to light from 400 - 1000 nm
UV stable
Able to withstand the expected range of operating temperatures
Low hydrogen permeability
Low cost

Summary of Material Options

The clear thermoplastic resins, which may work for this application, fall into three cost and characteristic categories. The low cost materials, styrene acrylonitrile (SAN), crystal polystyrene, and clear acrylic butadiene styrene (ABS), range from $0.36-1.00/lb of raw pellets. The next class of resins costs between $0.90 - 2.00/lb, and includes acrylic, PETG (a glycol modified type of polyethylene terephthalate), and polycarbonate. These materials have better impact resistance and tolerance for higher temperatures than the cheaper resins. The highest grades are the fluoropolymers, which have excellent corrosion resistance, temperature capabilities and transparency, but can cost upwards of $6.00 - 12.00/lb of raw pellets.

Table 5 shows the major properties relating to this application, for several different polymers. Most of the potential candidates are quickly discarded based on the stated criteria. Data for this table were taken from several sources, including Brandrup and Immergut (1989), Miller (1981), SRI International (1997), and the Modern Plastics Encyclopedia (1998).

Polystyrene and polypropylene, while being some of the least expensive materials, have poor UV stability and are not likely to survive long outdoors. Nylon, while being well-suited for high temperature work, does not do well in the presence of acids/alkali and is rated only fair for UV stability. Polycarbonate (Lexan) will not handle the electrolyte solution very well. Clear, rigid PVC remains an option, although its transparency is rather low. Finally, if we can stay away from polysulfone and the fluorinated compounds, we are much more likely to come up with a cost-effective solution.

The remaining possibilities are SAN, clear ABS, acrylic, and PET or PETG. SAN rates only fair for UV resistance and the transparency is lower than desired. Clear ABS is similarly quite low on transmissivity. PETG, has recently been modified to improve its UV resistance and may prove useful in this application. Injection molding of these materials, such as employed in soda bottle production, is quite inexpensive. Acrylic (more commonly known as Plexiglass), displays good-to-excellent acid and alkali solution resistance, high transparency, and good UV resistance. However, although it has better UV stability and bondability than PET or PETG, it is expected to have a higher price based on the cost of the raw resin pellets. To better define the cost and characteristic trade-offs, investigations of the cost of a finished product using acrylic, PET, and PETG were carried out.

It is important to note that many applications of polymers involve layered or coated materials to impart the required characteristics. In this case, almost any material can be coated or lined to overcome weaknesses in the base material. The possibilities are endless, and typically develop as one formulation demonstrates inadequacy in one area or another. Often these specialized formulations are more expensive, but economy of scale will play a strong role in reducing the cost of an individual unit. As actual units are built and weaknesses of the material are identified in field trials, coatings can be further investigated. Good sources of information on this subject are: Gacher and Muller (1990), Milewski (1987), Flick (1986), and Plastics Design Laboratory (1994).

To test the optics of these systems, bases were bonded onto several acrylic cylinders of different diameters, and the units were filled with water. For both the four and the five inch O.D. tubing, the

Table 5: Properties of Clear Thermoplastic Resins

Type of Polymer	Resistance to acid/alkali	Water absorption, %/24hr@73 C	Transparency	UV resistance	Hi temp., F	Hydrogen permeability, 10^{-9} ml cm/cm^2 s cm Hg	Cost per sq ft	Cost per pound	Bond-ability	Process-ability	Specific Gravity	Notes
Styreneacrylo-nitrile (SAN)	V. Good/ V. Good		Good, 85-89%	Fair	210			$0.94-1.16		Excellent	1.07	
Crystal polystyrene	Fair/Good		Good, 87-92%	Poor	170	2.26		$0.36-.39/lb		Excellent	1.1	
Clear Acrylic butadiene styrene (ABS)	Fair/Good		Fair, 72-88%	Good	160				Excellent	Good		
Polypropylene (Nalgene)	Good/Exc.	0.03	Translucent	Poor	200	4.12	$0.05/3 mil	$0.40	Poor		0.9	Adhesives don't work, must be welded/molde
Nylon	Poor/Fair	1.6-9.5	Translucent depending on thickness	Fair	325	0.5-6.0	$0.07/2 mil	$2.00-2.40	Good		1.1-1.2	
Polymethylmeth-acrylate (acrylic; Plexiglas)	Good/Exc.	0.20%	Clear 88-92% 92%	Good	165	0.15	$1.24/ 1/8"	$0.89-.94	Excellent	Good	1.19	
PETG	Good/ Good		Clear	Fair	240			$0.44	Good			
Polycarbonate (Lexan)	Good/ Poor	0.15%*24	Transparent 86-89%	Good Excellent	250 158	0.5-20 1.2	$0.21/5 mil	$1.48-1.63	Good	Fair	1.2	Embrittles with continuous exposure to hot water
Rigid PVC	Exc.		Fair, 76-82%	Good Excellent	148	0.36			Good	Fair		
Polysulfone (Udel)	Exc.			Good	325	0.5-20	$0.55/5 mil	$3.50-6.00	Good		1.24-1.37	
Teflon	Good/Exc.		Transparent if thin, 92%	Fair	400+ 260 206	2.0	$0.40/1 mil, Type A (FEP)	$6.70 (PVDF)	Poor	Poor	2.1	
Tedlar, Poly (vinyl fluoride)				Good	225		$0.27/2 mil		Good			
Tefzel				Good	400+		$0.27/2 mil		Good			

focal point using pure water was slightly behind the back wall of the tube. The use of 3M sulfuric acid or 1M sodium hydroxide will increase the index of refraction a bit and bring the focal point somewhat further in. For a 4" tube, the highest concentration achieved was ~1:10. For the 5", it could theoretically get to 1:12, ignoring the optical losses. It's important to note that considerable reflection of light was observed. Means to reduce the reflection through coatings or other means may be needed to maximize hydrogen production. As mentioned earlier, the highest concentration that the low-cost amorphous-silicon cells can tolerate is approximately 1:10.

Price

Information on the price of raw pellets and the extruded tubes was obtained from several manufacturers. Although there was a great deal of discrepancy between quotes for the same materials, acrylic was generally found to be the more expensive choice. PET and PETG are approximately equal in price. Tables 6 and 7 show the prices obtained. Values that are in bold-face type are those obtained directly from the manufacturer. Others are calculated.

Table 6: Prices Obtained for 4" Acrylic Tubes with 1/8" Wall Thickness

Source	Price ($/m)	Price ($/ft)	Notes
Universal Plastics, Inc.	11.50	**3.50**	
Ono Industries / Ace Plastics Co.	4.43	**1.35**	Extremely large scale only. This cost seems too low based on the published cost of pellets; representative would not give the price they pay for their pellets.
SRI International - Chemical Economics Handbook	11.50 - 11.80	3.50 - 3.60	Price of general use raw pellets in 1996 was **$0.89 - $0.94/lb**. The cost of making ready-to-use pellets is approx. $0.5/lb.

Table 7: Prices Obtained for 4" PET/PETG Tubes with 1/8" Wall Thickness

Source	Price ($/m)	Price ($/ft)	Notes
Genplex, Inc.	8.20	**2.50**	Ready-to-use pellet material costs approximately **$1/lb**; there is approximately 1 lb of material per foot of tube.
Eastman Chemical Company	7.40 - 9.00	2.25 - 2.75	Ready-to-use pellet cost is **$0.90/lb** for PET and **$1.10/lb** for PETG.
Preferred Plastics	5.80	**1.76**	This is a large manufacturer of extruded PET components, and so can give better prices.

Modern Plastics, January 1999	8.50 - 8.90	2.60 - 2.70	Raw pellet material (without stabilizers, etc.) cost is **\$0.54 - \$0.58/lb.** The cost to produce ready-to-use pellets is approximately \$0.5/lb. Resin cost in Indonesia and Malaysia is approx. **25%** less.
SRI International - Chemical Economics Handbook	7.60	2.30	Raw pellet material (see cell directly above) cost is **\$0.43/lb.**

The finished price of the housing assembly will be higher than the cost of the tubes. Perhaps to attach the end-caps and piping would require another 20-50%. Therefore, the cost of the housing unit will be approximately \$4.20 - \$5.25/ft (\$13.80 - \$17.20/m) for acrylic (assuming the cost of the tubing is \$3.50/ft) and \$3.00 - \$3.75/ft (\$9.80 - \$12.30/m) for PET or PETG (assuming the cost of the tubing is \$2.50/ft). If the number of units being built is very large, the price obtained from Preferred Plastics may be applicable, and the cost of a PET housing assembly could potentially be as low as \$2.10 - \$2.60/ft (\$6.90 - \$8.70/m). The values for the PET and PETG closely match the values used in the near- and mid-term analyses, but are higher than those used in the long-term analysis. It's important to recognize that prices for these materials vary depending on supply and demand characteristics of the commodity plastics markets (see Modern Plastics, January 1999, for example). PET is currently the world's fastest growing-demand polymer, but over-supply and slowing demand have led to a slide in its price in the last two years. Future PET (and PETG) prices may rise as new applications are found and new world-wide markets are developed. Therefore, the price used in the long-term analysis (\$7/m) is probably optimistic. Because the cost of acrylic is 40% higher than PET, it was not considered to be a suitable choice for this application.

Although PET and PETG are similar in cost, the higher crystallinity of PET is likely to allow less hydrogen to permeate (Kelley, 1999). Additionally, PET is more durable than PETG, but is slightly less UV stable. An additive to the PET pellet melt can likely impart better UV stability and should be explored with the manufacturer once the decision to build units for outdoor testing is made.

Summary of Economic Results

The economics of the long-term PEC case were re-run with the range of prices obtained for PET. Results for both a 37% and 28% tax rate, with a 15% after-tax IRR and a 0% pre-tax IRR are shown in Table 8.

Table 8: Hydrogen Selling Price or Production Cost from PEC

	Housing assembly cost			
	$7.00/m ($2.13/ft) (from 1998 analysis)	$9.80/m ($3.00/ft)	$12.30/m ($3.75/ft)	$6.90/m ($2.10/ft) (assumes very large PEC installations)
15% after-tax IRR, 37% tax rate	$36.2/GJ $5.1/kg	$39.7/GJ $5.6/kg	$42.9/GJ $6.1/kg	$36.0/GJ $5.1/kg
15% after-tax IRR, 28% tax rate	$33.1/GJ $4.7/kg	$36.3/GJ $5.2/kg	$39.2/GJ $5.6/kg	$33.0/GJ $4.70/kg
0% pre-tax IRR	$8.5/GJ $1.2/kg	$9.2/GJ $1.3/kg	$9.8/GJ $1.4/kg	$8.5/GJ $1.2/GJ
% of total capital cost	23%	29%	33%	22%

If a large number of PEC housing units are required, the cost of the housing unit may be close to that predicted in the 1997 analysis. However, a more likely scenario is that either a smaller number of units will be built or the price of PET resin will increase between now and 2020. Therefore, the percentage of the total capital cost due to the housing will remain significant. Future work on these housing units will include the examination of flexible plastic sheeting and alternative designs that reduce the amount of polymeric material required.

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