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COST ANALYSIS OF A CONCENTRATOR PHOTOVOLTAIC HYDROGEN PRODUCTION SYSTEM

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1. Abstract

The development of efficient, renewable methods of producing hydrogen are essential for the success of the hydrogen economy. Since the feedstock for electrolysis is water, there are no harmful pollutants emitted during the use of the fuel. Furthermore, it has become evident that concentrator photovoltaic (CPV) systems have a number of unique attributes that could shortcut the development process, and increase the efficiency of hydrogen production to a point where economics will then drive the commercial development to mass scale.

Concentrating solar energy to produce electricity can occur at quite high solar conversion efficiencies. The highest efficiency for solar concentrator cells, as measured at NREL, is now above 37%. Solar Systems P/L of Australia has exhibited a 40% boost in hydrogen production by separating the solar infrared radiation incident on concentrator solar cells and using it as the heat source for a solid oxide electrolyzer cell operating above 1000 Celsius [9]. With today's solar cell technologies, it is therefore possible to achieve a 50% conversion efficiency of the solar energy to hydrogen through high temperature electrolysis.

With gasoline prices constantly increasing, the cost associated with producing hydrogen is becoming more and more favorable. At approximately $3.10/kg, the cost of producing hydrogen through wind electrolysis is becoming competitive with that of gasoline [10]. It is expected that hydrogen production through thermal-CPV electrolysis has the potential to be equally as attractive, if not more so. Details of a cost analysis for such a hydrogen generation system will be presented.

2. Introduction

The development of a hydrogen economy can have many benefits for the environment. It could play a role in reducing global warming and air quality problems in and around major cities. A large percentage of the pollution that contributes to these issues is easily traced to the power demands of buildings and the emissions of vehicles. Provided hydrogen can be produced from renewable resources at reasonable costs, the use of hydrogen fuel cell technology in buildings and vehicles would effectively eliminate a major contribution to air pollution problems and global warming. Additionally, the United States dependence on foreign oil would be curtailed, and providing buildings with their own power generation capability would reduce the demand on the electric grid. These are only a few of the many beneficial possibilities of a hydrogen economy.

For the hydrogen economy to come to fruition, there are many obstacles that need to be overcome. The most prevalent roadblock is the current lack of an infrastructure to support a hydrogen economy. Hydrogen production facilities need to be constructed and methods for transporting hydrogen need to be developed.

Another issue is the cost of producing hydrogen. For hydrogen to be considered as an alternative to fossil fuels, production costs from renewable resources need to be substantially reduced. This paper examines the costs associated with a system that uses solar energy to produce hydrogen from water.

3. System Description

To address the cost issues associated with hydrogen production from renewable resources, methods of performance enhancement should be explored. The use of spectrum splitting of solar energy to harness the thermal portion of the solar spectrum offers a potential for higher efficiency and increased hydrogen production capability. In this section, we will outline a method of producing hydrogen that combines solar concentration and spectrum splitting to increase system efficiency and production capability.

The CPV hydrogen production system (developed and patented by Solar Systems P/L of Australia) consists of four major components: a concentrator dish (including PV panel), optical filter, fiber optic light guide, and solid oxide electrolyzer cell (SOEC) stack. The following is a

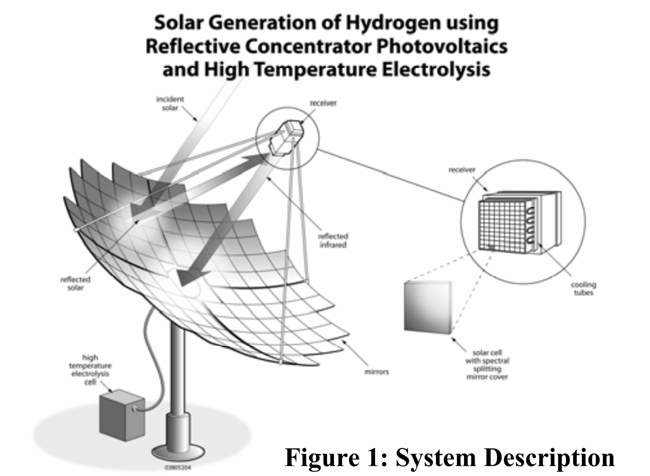

Figure 1: System Description

description of the hydrogen production process (See Fig. 1 for visual reference):

1. The dish of the CPV focuses sunlight on the PV panel providing it with the energy equivalent of 250 – 300 Suns. This increase in energy boosts the electrical output of the PV panel by the same factor.
2. The optical filter is placed in front of the PV panel and reflects the infrared energy. The remaining visible light is transmitted through to the PV panel where it is transformed into electric energy and supplied to the SOEC.
3. Meanwhile, the reflected infrared energy is focused into the light guide and transmitted to the SOEC.
4. The SOEC combines this heat energy with the electricity to separate water into hydrogen and oxygen. An electrical charge is supplied to the electrolyzer creating a potential that draws the hydrogen and oxygen molecules to the cathode and anode, respectively. Supplying heat to this process reduces the amount of electricity needed to separate the molecules and increases the efficiency of the process.
5. From the SOEC, the hydrogen and oxygen are released at atmospheric pressure and can be stored in tanks for usage by fuel cells or other hydrogen powered devices.

For this system to be effective, these components need to be implemented into a system that achieves high efficiency. Two components that can be the cause of significant losses are the optical filter and the fiber optic light guide. These components will be discussed further in Section 4.

Table 1: System Cost Analysis

Component Cost (per kW)	Current Cost for a 1kW System	1GW Purchase Est. Cost per kW (Yr. 2020++)
CPV	$10,000	$800.00
Dichroic Filter	$500	$5.50
Light Pipe*	$990	$14.75
SOEC**	$2,000	$400.00
Unknown Costs	$5,000	$5.00
Total	**$18,490**	**$1,221**

*Prices quoted by CeramOptec

**Manufacturing costs quoted by Ceramatec, Inc.

4. Cost Analysis

The cost of solar hydrogen production needs to be competitive with similar hydrogen production processes for it to be successful in the hydrogen market. As a prototype, constructing a system today is relatively expensive. However, efficient and cost effective design and mass production can significantly reduce future production costs. In this section, the projected cost for such a system will be evaluated and compared to similar hydrogen production systems.

4.1 Projected System Cost

Table 1 provides component cost information for a one kilowatt system at current cost as well as a projected per kilowatt cost based on the future purchase of 1GW of CPV Electrolysis systems. All numbers provided in the projected costs column are based on the purchase of 1GW worth of electrolysis systems (consists of fifty thousand 20kW CPV Electrolysis dish systems). As seen in the table, CPV currently costs $10,000 per kilowatt. This cost includes the dish, sun tracking capability, and the PV panel. The PV panel is only 10% of the system cost, allowing for room to reduce cost through package and structure design. The projected cost for CPV is $800 per kilowatt [11].

The rugate and dichroic filters are the types of spectral splitters being considered for implementation into this system. As shown in Figure 2b, the rugate filter uses a graded index film to bend the energy rays where as the dichroic filter utilizes layers of thin film with different indices to achieve the same results (Figure 2a) [1-2]. When compared to the step-indexed filter, the rugate filter presents a slightly more efficient design, as it requires fewer internal reflections to achieve the same result. These two technologies will need to be tested and compared to determine what benefits the rugate filter has over the dichroic filter. For the cost of the spectral splitter, information is provided for the dichroic filter. Costs for rugate filters were not available for this study. Costs for dichroic filters ranged anywhere from $70 to $500, with the more efficient filters generally being the most expensive. Determining which filter is best designed for this system will require some testing. Assuming that the solar hydrogen system will demand the most efficient filter, cost for the most expensive filter is factored into the system cost. For a 1GW system the cost of the dichroic filter is estimated to be $5.50 per kilowatt.

Like the optical filter, there are two types of fiber optics that will be considered for use in this system. The first is the step-indexed light guide, which transmits energy through reflections as the dichroic filter does. The second is the graded-index fiber, which bends energy in the same manner as the rugate filter. The response is best described as sinusoidal in nature. The graded index fiber reduces the effects of many of the losses associated with attenuation and dispersion in the fiber [3]. The performance of graded indexed fibers needs to be evaluated and compared to that of step-indexed fibers to determine what benefits the

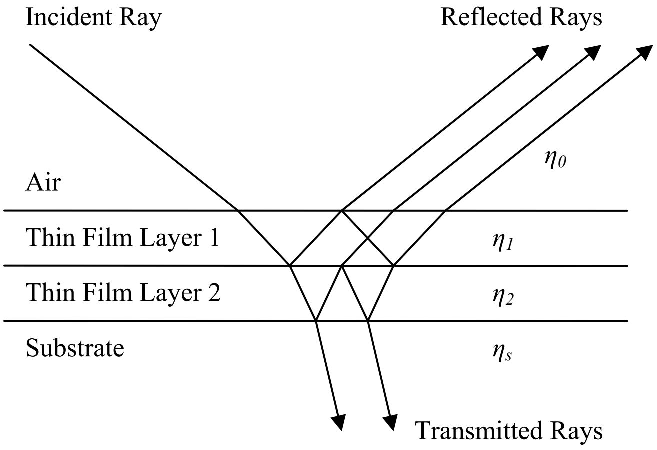

Figure 2a: Dichroic filter response

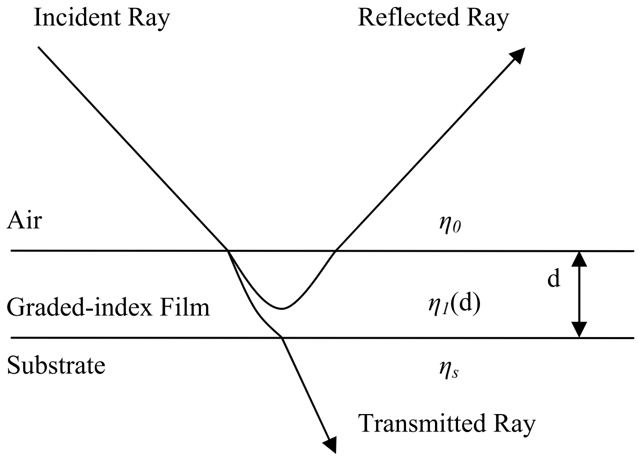

Figure 2b: Rugate filter response

technology may have. Estimates for this study are provided for the step-indexed fiber. The fiber optic light-guide is estimated by CeramOptec to cost $990/part for 1 to 2 parts and $24.75/part for 500 parts. These estimates are used to forecast the future cost of 50 thousand parts (See Table 1). This information is based on a fiber optic cable that is one meter in length and 25mm in diameter, constructed of boro-silica fibers, and encased in a stainless steel interlock jacketing.

The final piece of the system is the SOEC stack. As a custom made product, SOECs are fairly expensive. Their cost currently ranges from $1000 to $2000 per kilowatt depending upon the ceramic material used as the electrolyte. However, Ceramatec has projected costs for this component to be reduced to as low as $400 per kilowatt by year 2020.

In addition to the costs associated with the components mentioned above, there are miscellaneous costs that cannot be determined this early in the development of the system. Other areas of concern have to deal with the components required to connect the light pipe to the SOEC and to the CPV. Another system component that will affect system cost is an automatic control system to manage and maintain hydrogen production. Estimates of what these additional costs would add to the price of the system are factored into the miscellaneous costs provided in Table 1.

4.2 Plant Investment and H_2 Production Analysis

Provided that the projected cost for a CPV Electrolysis system is $1221/kW, a capital cost analysis for the construction of a 10MW CPV electrolysis farm is provided in Table 2. The information in this table is based on the cost analysis of a chemical plant provided in [8]. Some percentages, such as piping, service facilities, and buildings and structures, have been adjusted to better reflect the costs expected to be associated with a CPV hydrogen production plant. The Total Fixed Investment (TFI) is a summation of the Total Direct and Indirect Costs, and the Total Capital Investment (TCI) is a summation of the TFI and the Total Working Capital (TWC). The TCI calculation carries an error factor of ±30%.

For cost per kilogram of H_2 calculations, the production capability of the plant needs to be determined. With assistance from Ceramatec, Inc., we have determined that an electrolyzer, consisting of three 50 cell stacks, operating at 1000°C and consuming 20kW of electricity, would be capable of producing 5.719 kg of hydrogen over a time period of 7.7 hours. Using this calculation as the daily average production for one unit, we expect a 10MW system (consisting of 500 units) to be capable of producing approximately 1.04 million kg-H_2 during one year of production (See Table 3).

Now that the capital cost associated with the construction of a plant and the production capability of said plant are known, the price at which H2 will be provided to the consumer can be determined. To do so, a payback period on the capital investment is set at 20 years. Assuming the plant produces hydrogen at the rates provided in Table 3, hydrogen can be sold to the consumer at $3.18/kg ±30%. Furthermore, investors can expect to see an 11% return on their investment with hydrogen sold at this price. The error associated with this calculation accounts for the uncertainties in investment analysis. This cost estimate shows that hydrogen production from CPV electrolysis can be cost competitive with other methods of production.

Table 2: Investment Analysis

Major Equipment Cost (per kW)	$1,221
Total Major Equipment Cost (TMEC)	$12,210,000.00
Installation (47% of TMEC)	$5,738,700.00
Piping (50% of TMEC)	$6,105,000.00
Instrumentation (25% of TMEC)	$3,052,500.00
Buildings and Structures (12% of TMEC)	$1,465,200.00
Electrical Systems Installed (11% of TMEC)	$1,343,100.00
Yard Improvements (10% of TMEC)	$1,221,000.00
Service Facilities (35% TMEC)	$4,273,500.00
Total Direct Costs (TDC)	*$35,409,000.00*
Engineering & Construction (E&C) (33% of TMEC)	$4,029,300.00
Contingencies (35% of TMEC)	$4,273,500.00
Construction Expenses (41% of TMEC)	$5,006,100.00
Legal Expenses (4% of TMEC)	$488,400.00
Contractor's Fee (5% of TDC)	$1,770,450.00
Total Indirect Cost (TIC)	*$15,567,750.00*
Total Fixed Investment (TFI)	***$50,976,750.00***
Total Working Capital (TWC) (15% Total Capital Investment)	***$8,995,897.06***
Total Capital Investment (TCI)	**$59,972,647.06**

Table 3: Hydrogen Production Cost Analysis

Plant Size	10MW
System Cost	$1,221/kW
Hydrogen Produced in 1 day*	2,865 kg
Hydrogen Produced in 1 year	1,043,765 kg
TCI	$60.0 million
Hydrogen Cost (Break Even)	**$2.87/kg ±30%**
Hydrogen Cost (11% ROI)	**$3.18/kg ±30%**

*Assumes each electrolyzer is capable of producing 5.719 kg-H_2 in a 7.7-hour day.

Table 4: Cost Comparison

Process	**Hydrogen Production Cost (per kg)**
Gas Reformation [4]	$1.15
Wind Electrolysis [10]	$3.10
Nuclear Electrolysis [5]	$1.48
PV Plate Electrolysis [6]	$7.40
CPV Electrolysis	**$3.18**

4.3 Cost Comparison

Other methods of producing hydrogen include gas reformation and wind, nuclear, and PV plate electrolysis. As shown in Table 4, consumer costs for these technologies range from as little as $1.15/kg for gas reformation to $7.40/kg for PV plate electrolysis. While gas reformation is inexpensive and nuclear electrolysis is projected to be cheap, neither of these technologies utilizes renewable resources. Furthermore, a byproduct of gas reformation is CO_2, which is the very pollutant a hydrogen economy seeks to eliminate. While production from renewable resources is more expensive, the environmental benefits out weigh the cost.

While hydrogen production from CPV electrolysis would greatly benefit the hydrogen economy, it is important to note that production from other renewable methods is necessary to supply the nation's energy demands. In 2004 automobiles in the US consumed 9 million bbl/d (378 million gal/day) of gasoline [7]. Considering that 1kg of hydrogen is about the energy equivalent of one gallon of gasoline, it is easy to conclude that no one renewable technology is capable of supplying this demand on its own. However, solar radiation is one of the most abundant renewable resources available.

5. Conclusion

From a cost standpoint, we have projected CPV electrolysis to be a feasible method of producing hydrogen. Component cost projections suggest that in the future, CPV hydrogen production will be competitive with other hydrogen production methods. Development of a system needs to be completed to verify production capabilities. Initial steps toward the development of a CPV electrolysis system will include the testing of optical filters and fiber optic light guides and the development of methods of exchanging the heat to the water for the electrolysis process.

With oil prices constantly rising, the development of a hydrogen economy presents a reasonable method of slowly reducing the dependency of the United States on foreign oil. With further development, CPV electrolysis systems could be a major contributor to the support structure of such an economy.

6. Acknowledgements

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