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Introduction

The purpose of this work was to assess methods for hydrogen production using concentrated solar energy. The results of this work can be used to guide future work in the application of concentrated solar energy to hydrogen production. Specifically, the objectives were to: 1. determine the cost of hydrogen produced from methods that use concentrated solar thermal energy, 2. compare these costs to those of hydrogen produced by electrolysis using photovoltaics and wind energy as the electricity source.

Four methods were considered in this analysis. The first was ambient temperature electrolysis of water. In this method, concentrated solar energy is used to generate alternating current (ac) electricity which is supplied to the electrolyzer. Production of hydrogen is limited to the times when electricity is available from the solar power plant. The second method is high temperature electrolysis of steam. This method operates at about 1273 K and, thermodynamically, requires less energy than ambient temperature electrolysis. In this method, a portion of the required energy can be supplied as thermal energy such that the solar plant may provide energy as both ac electricity and thermal. The third method is high temperature thermal dissociation of steam. This method operates above 2000 K and requires only thermal energy. The last method consists of a set of thermochemical cycles in which hydrogen is generated from steam via a number of intermediate chemical steps. These methods include cycles that utilize: 1. iron oxides, 2. iron and calcium oxides and bromides (UT-3 process), 3. sodium iodide and ammonium iodide (Hitachi). All of the thermochemical cycles require only thermal energy at temperatures up to 2500 K. The last two methods were analyzed only as process concepts and will require additional analysis before a quantitative assessment can be performed.

This project had the following scope of work:

1. perform cost analysis on ambient temperature electrolysis using the 10 MWe dish-Stirling and 200 MWe power tower technologies; for each technology, use two cases for projected costs, years 2010 and 2020 the dish-Stirling system, years 2010 and 2020 for the power tower,
2. perform cost analysis on high temperature electrolysis using the 200 MWe power tower technology and projected costs for the year 2020,
3. identify and describe the key technical issues for high temperature thermal dissociation and the thermochemical cycles.

Systems Analysis

For each case, fixed capital and operating & maintenance (O&M) costs were determined. Solar fixed capital and O&M costs for the dish-Stirling cases were obtained from reference

[1]. Solar fixed capital and O&M costs for the power tower cases were obtained from reference [2]. Fixed capital and O&M costs for the ambient temperature electrolyzer were obtained from commercial manufacturers: Electrolyzer Corporation (Canada) and Teledyne Brown (Baltimore). Fixed capital cost estimates for the high temperature electrolyzer were obtained from the Westinghouse Solid Oxide Fuel Cell Group (Pittsburgh). O&M costs for the high temperature electrolyzer were assumed to be the same as those of the ambient temperature electrolyzer.

After fixed capital and O&M costs for each case were determined, cash flow analysis was performed to determine the required selling price for hydrogen. The cash flow analysis had the following assumptions:

1. project lifetime: 21 years
2. construction period: 1 year
3. working capital: 10% of total capital
4. 100% of capital depreciated, 10% per year
5. tax rate: 28%
6. internal rate of return: 15%

Cash flow analysis determined the required selling price of hydrogen to achieve a net present value of zero at the end of the lifetime of the process. This approach is consistent with the method used by the Hydrogen Program to assess the economics of hydrogen production processes [3].

For all cases, the hydrogen that was produced was assumed to have an energy content of 39.4 kWhr/kg or 0.1345 MBtu/kg which corresponds to the higher heating value (HHV). The hydrogen was produced at ambient temperature and pressure.

Ambient Temperature Electrolysis

A schematic of ambient temperature electrolysis is shown in Figure 1.

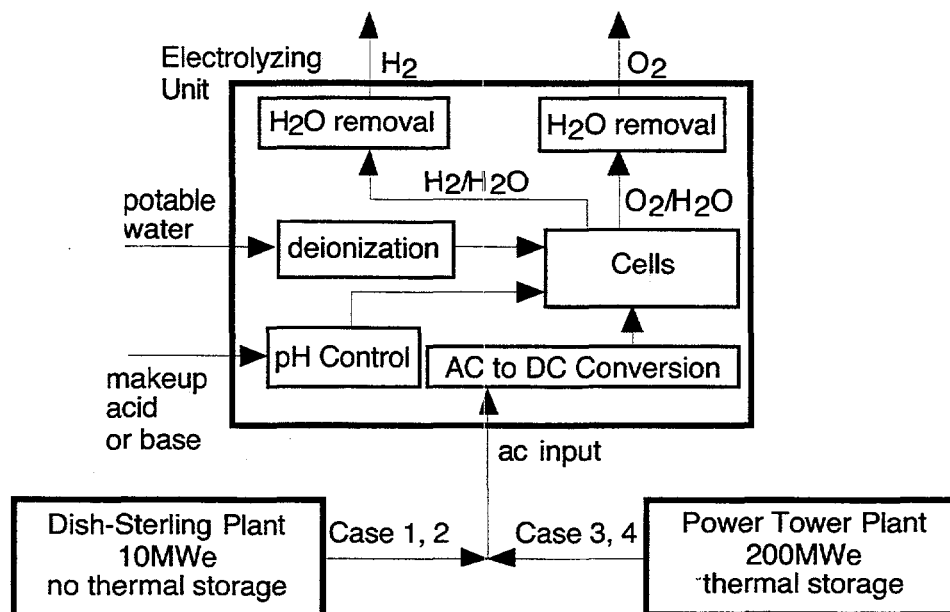


Figure 1. Schematic of ambient temperature electrolysis

The electrolyzer consists of a packaged unit with several components [4]. The electrolyzer accepts ac power and converts it to dc power which is provided to the electrolytic cells. Commercially available electrolyzers operate with basic electrolyte and require makeup base to maintain the pH of the electrolyte [5]. Water, which is provided to the cells, is first passed through a deionization step which removes ions that may interfere with the electrolysis reactions or cause degradation of the electrodes. The hydrogen product is saturated with water vapor which is removed using either a chiller or desiccant.

Power is provided to the electrolyzer from either a solar dish-Stirling or power tower system [6, 7a, 7b]. Specifications for these systems are listed in Table 1.

Table 1

<u>Case</u>	<u>System</u>	<u>Power</u>	<u>Capacity Factor</u>	<u>Projected Cost Year</u>
1	dish-Stirling	10 MWac	0.28	2010
2	dish-Stirling	10 MWac	0.28	2020
3	power tower	200 MWac	0.65	2010
4	power tower	200 MWac	0.77	2020

The dish-Stirling system provides power only when direct solar energy is available. The power tower has built in thermal storage allowing it to provide power at a higher fraction of time.

The electrolyzer has the following efficiencies:

1. ac to dc conversion efficiency: 0.97
2. dc to H₂ conversion efficiency: 0.82
3. overall conversion efficiency: 0.795

The following capital costs and factors were used for ambient temperature electrolysis:

1. electrolyzer cost: \$500/kWac
2. building (10MWac): \$500K
3. building (200 MWac): \$3000K
4. 10 MWac dish-Stirling (2010): \$1,660/kWac
5. 10 MWac dish-Stirling (2020): \$1,495/kWac
6. 200 MWac power tower (2010): \$2,605/kWac
7. 200 MWac power tower (2020): \$2,523/kWac

The following O&M costs were used for ambient temperature electrolysis:

1. electrolyzer: \$0.55/kg H₂/year
2. 10 MWac dish-Stirling (2010): \$27/kW/yr
3. 10 MWac dish-Stirling (2020): \$26/kW/yr
4. 200 MWac power tower (2010): \$30/kW/yr
5. 200 MWac power tower (2020): \$25/kW/yr

Cash flow analysis was performed on the cases described above. For each case, the required selling price of hydrogen was determined to provide a 15% internal rate of return. Figure 2 shows the cash flow spreadsheet for the 10 MWac dish-Stirling (2010) case. The required hydrogen selling price was \$78/MBtu.

Year		Sales Revenue (K\$)	Operating Expenses (K\$)	Depreciation (K\$)	Net Income (K\$)	Taxes (K\$)	After Tax Income (K\$)	Cash Flow (K\$)	Cummulative Cash Flow (K\$)	Discount Cash Flow (K\$)	Cummulative Discount Cash Flow (K\$)
1	(24,556)			-		-		(24,556)	(24,556)	(24,556)	(24,556)
2	-	5,173	542	2,456	2,176	609	1,566	4,022	(20,534)	3,497	(21,058)
3	-	5,173	542	2,456	2,176	609	1,566	4,022	(16,512)	3,041	(18,017)
4	-	5,173	542	2,456	2,176	609	1,566	4,022	(12,490)	2,644	(15,373)
5	-	5,173	542	2,456	2,176	609	1,566	4,022	(8,468)	2,300	(13,073)
6	-	5,173	542	2,456	2,176	609	1,566	4,022	(4,446)	2,000	(11,073)
7	-	5,173	542	2,456	2,176	609	1,566	4,022	(424)	1,739	(9,335)
8	-	5,173	542	2,456	2,176	609	1,566	4,022	3,598	1,512	(7,823)
9	-	5,173	542	2,456	2,176	609	1,566	4,022	7,620	1,315	(6,508)
10	-	5,173	542	2,456	2,176	609	1,566	4,022	11,642	1,143	(5,364)
11	-	5,173	542	2,456	2,176	609	1,566	4,022	15,664	994	(4,370)
12	-	5,173	542	-	4,631	1,297	3,334	3,334	18,998	717	(3,654)
13	-	5,173	542	-	4,631	1,297	3,334	3,334	22,333	623	(3,030)
14	-	5,173	542	-	4,631	1,297	3,334	3,334	25,667	542	(2,488)
15	-	5,173	542	-	4,631	1,297	3,334	3,334	29,001	471	(2,017)
16	-	5,173	542	-	4,631	1,297	3,334	3,334	32,336	410	(1,607)
17	-	5,173	542	-	4,631	1,297	3,334	3,334	35,670	356	(1,251)
18	-	5,173	542	-	4,631	1,297	3,334	3,334	39,005	310	(941)
19	-	5,173	542	-	4,631	1,297	3,334	3,334	42,339	269	(672)
20	-	5,173	542	-	4,631	1,297	3,334	3,334	45,673	234	(438)
21	2,456	5,173	542	-	7,087	1,984	5,102	7,558	53,231	462	24

Figure 2. Cash flow spreadsheet for case 1 of ambient temperature electrolysis

The annual and cumulative discount cash flow for this case is shown graphically in Figure 3.

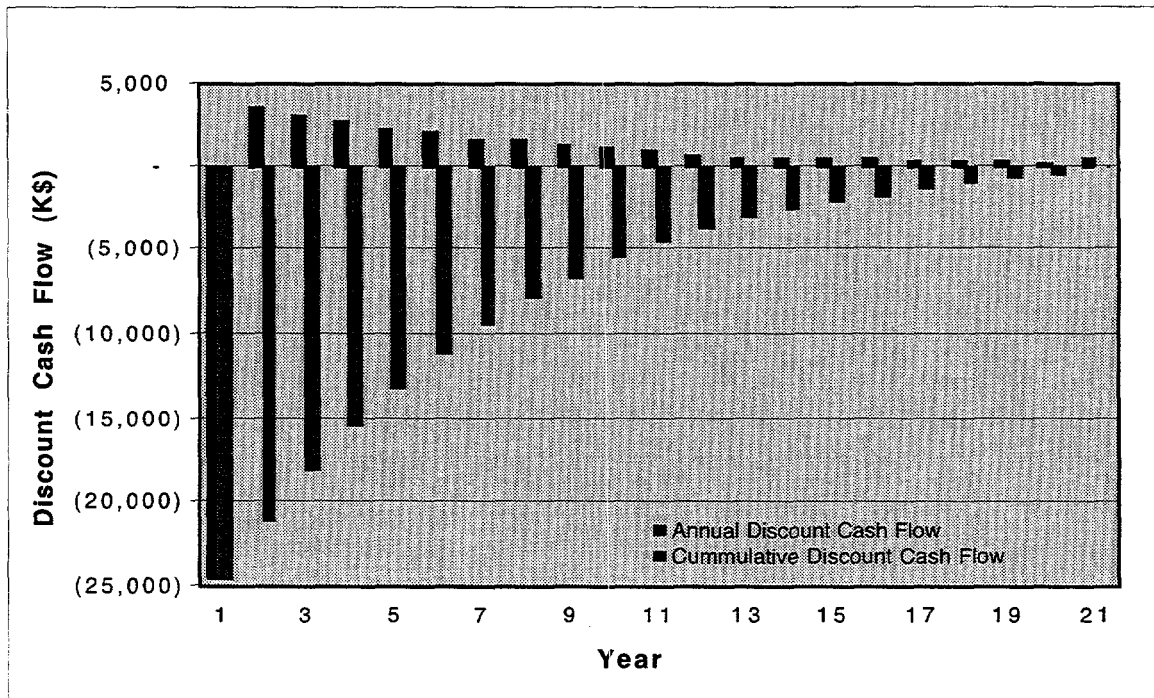


Figure 3. Annual and cumulative discount cash flow for case 1 of ambient temperature electrolysis

The price of hydrogen produced from solar thermal technologies was compared to the price of hydrogen produced from electrolysis using photovoltaics and wind as the electricity sources (Figure 4). Three photovoltaics cases were analyzed with the following assumptions:

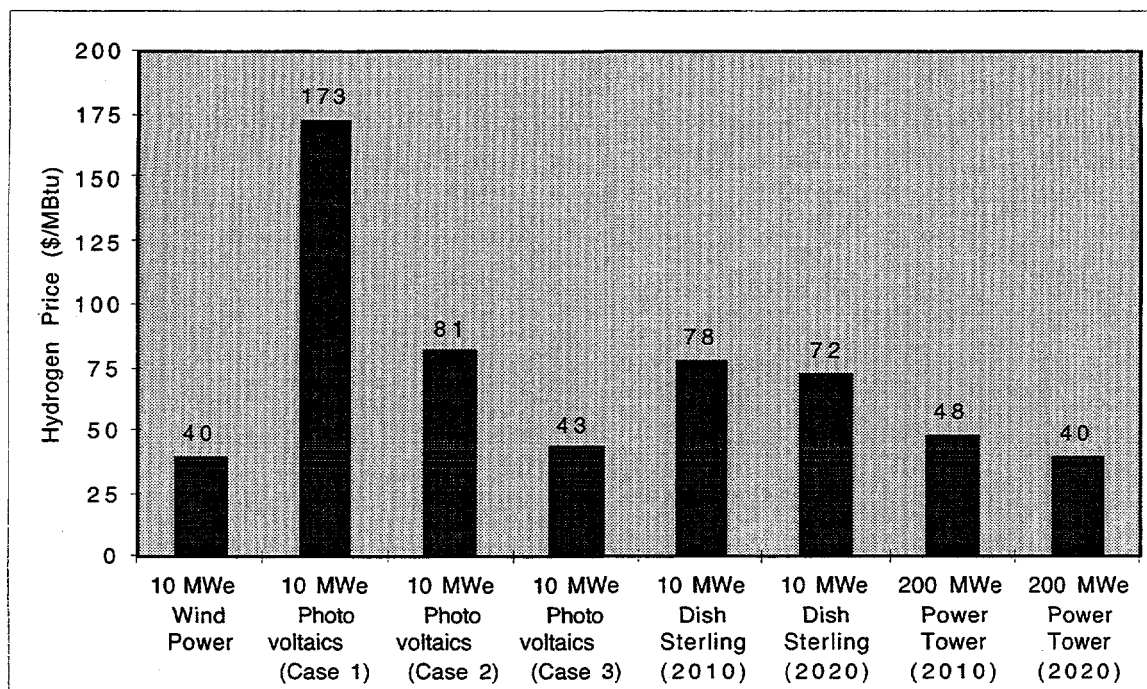


Figure 4. Hydrogen price for renewable technologies

For all cases, the capacity was 10 MW with these factors:

- | | |
|-------------------------------|-------------------------------|
| 1. electrolyzer capital cost: | \$450/kWdc |
| 2. electrolyzer O&M: | \$0.55/kgH ₂ /year |
| 3. photovoltaics O&M: | \$4.96/kWdc/year |
| 4. solar capacity factor: | 0.28 |
| 5. electrolyzer efficiency: | 0.82 |

The capital cost of the electrolyzer for the photovoltaics cases (\$450/kWdc) was less than that of the solar thermal cases (\$500/kWac) because the electrolyzer for the solar thermal cases includes an ac to dc converter that is not required for the photovoltaics system.

The capital costs for the photovoltaic systems were assumed to be [8]:

<u>Case</u>	<u>Cost</u>
1	\$5000/kWdc
2	\$2000/kWdc
3	\$750/kWdc

Results show that hydrogen produced from electrolysis using solar thermal technologies is in the same price range as that produced from electrolysis using photovoltaics technology when the capital cost of the photovoltaics system is in the range of \$2000-\$750/kWdc. The cost of hydrogen from the year 2020 case for the power tower system is comparable to the cost of hydrogen from wind energy.

A factor to consider is that, in general, electrolysis for hydrogen production is used to meet small, isolated markets. There may be locations where there is a demand for hydrogen but the location has a poor wind resource. In those cases, electrolysis using solar thermal or photovoltaics will be the most competitive renewable method for production.

High Temperature Electrolysis

A schematic of high temperature electrolysis is shown in Figure 5. The cells are made of high temperature materials capable of operating at 1273 K. The most likely design is that of the solid oxide fuel cell (SOFC) which can operate in this temperature range [9]. The SOFC can be used to generate hydrogen when it is operating in reverse compared to the electricity generation mode. The SOFC has a solid electrolyte, typically, yttria stabilized zirconia which has ionic conductivity at 1273 K due to the mobility of oxide ions. The cells do not require acid or base to maintain their conductivity as in the ambient temperature electrolyzer. The enthalpy contained in the product gases at 1273 K is sufficient to heat steam at 373 K to 1273 K, the operating temperature [10]. The thermal energy required to produce steam at 373 K is supplied as solar thermal energy. Again, this electrolyzer receives ac power and converts it to dc to be fed to the cells.

The source of solar energy for this method is a 200 MWe power tower. Capital and O&M costs along with the capacity factor were taken from the year 2020 case. In high temperature electrolysis, a portion of the energy required to generate hydrogen may be supplied as thermal energy. This option has the potential for lower overall energy costs because that portion of the energy supplied as thermal does not incur the losses associated with converting thermal energy to electricity.

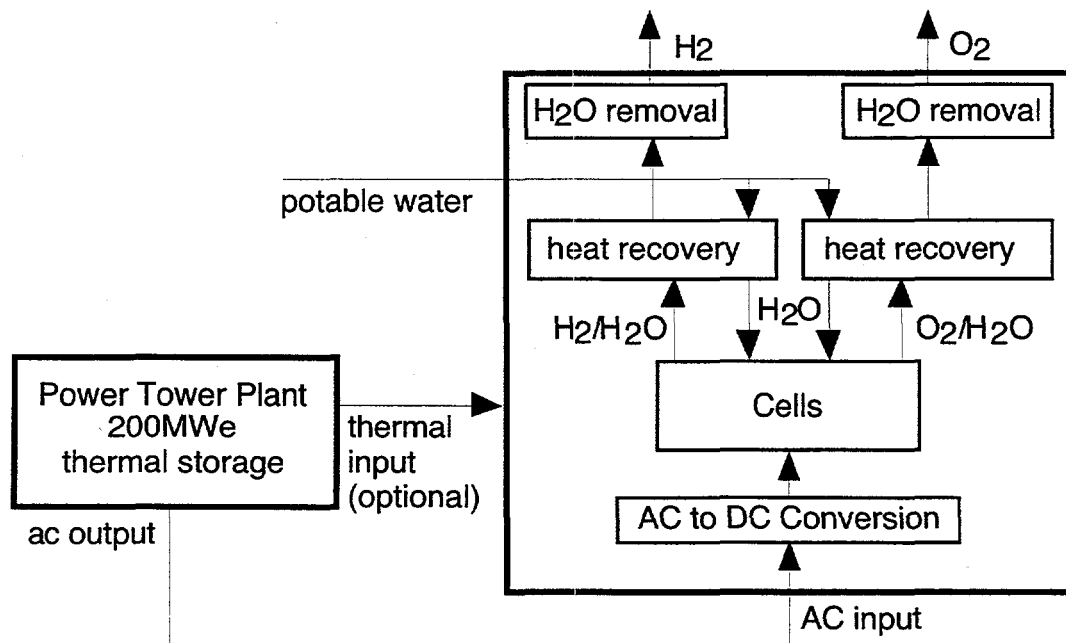


Figure 5. Schematic of high temperature electrolysis

Examination of the thermodynamic functions of this reaction as a function of temperature reveals the potential advantages of this method compare to ambient temperature electrolysis. The thermodynamic functions as a function of temperature are shown in Figure 6 [10]. Figure 6 shows that the enthalpy of the water splitting reaction at 1273 K (249 kJ/mole) is less than that at ambient temperature (286 kJ/mole). The entropy term at any temperature represents the amount of total energy that can be supplied as thermal energy [11]. At 1273 K, this makes up about 30% of the total energy requirement. This indicates that, in principle, 30% of the energy needed for the generation of hydrogen will not incur the losses associated with converting thermal energy to electricity resulting in further energy savings.

Practical implementation of a process that takes advantage of the energy savings, however, has difficulties which will be described next. Figure 7 shows a plot of applied voltage to the electrolyzer vs electrode current density for a SOFC [12].

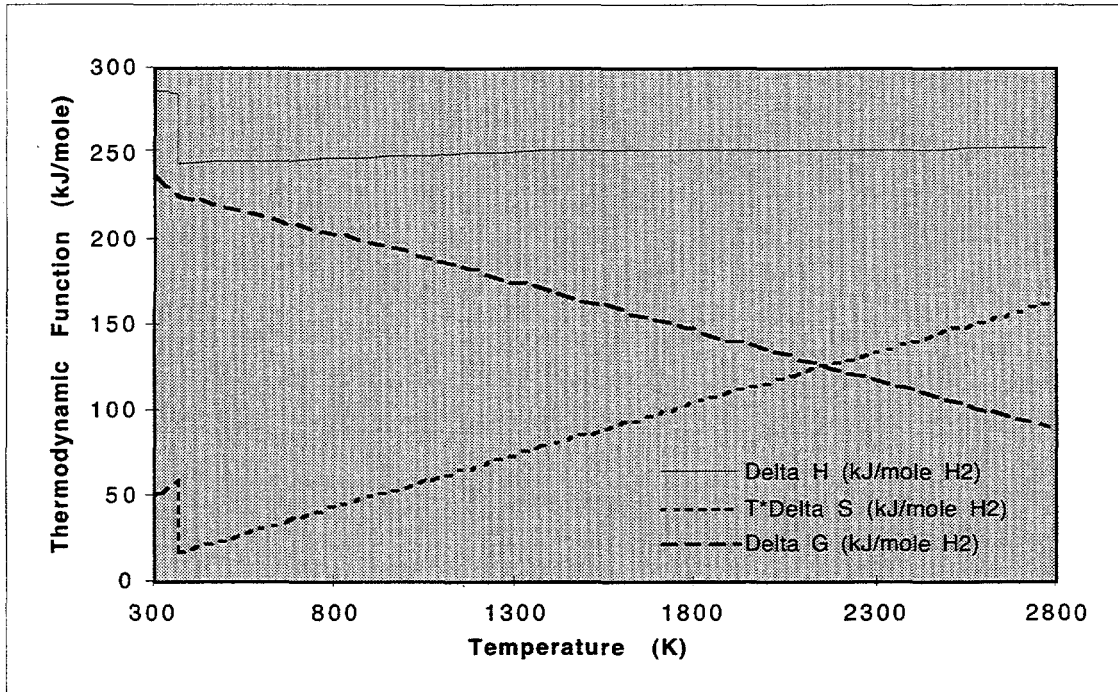


Figure 6. Thermodynamic functions versus temperature for the water splitting reaction

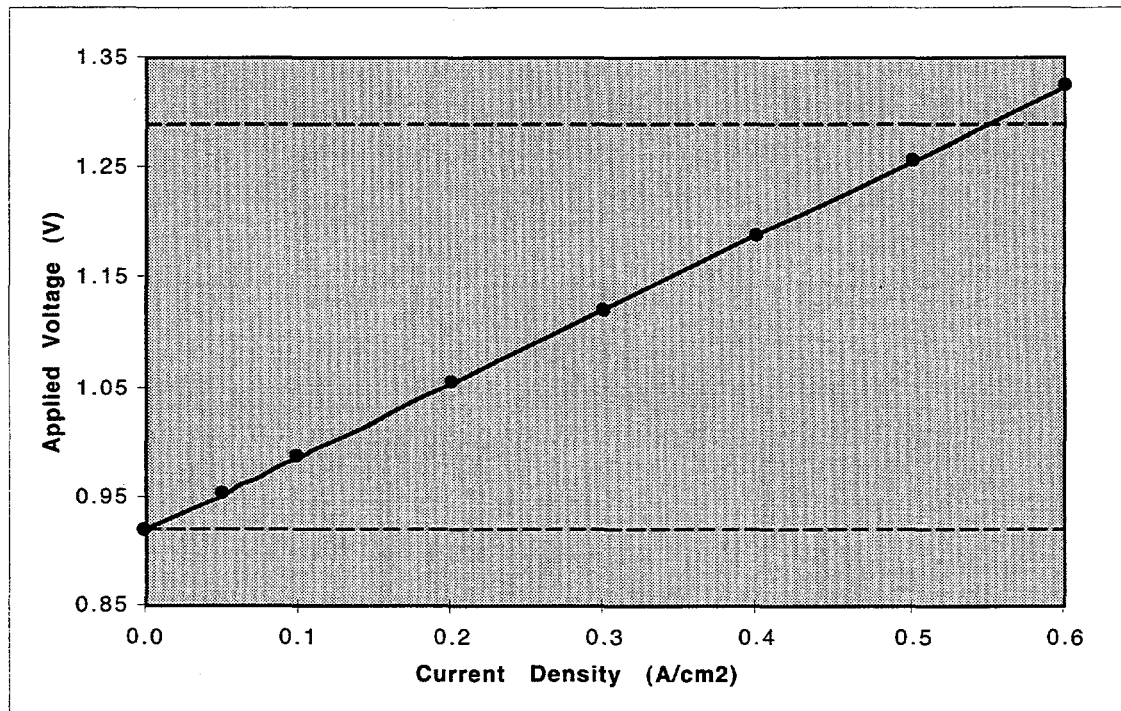


Figure 7. Applied voltage versus electrode current density for SOFC

The reversible voltage for a SOFC [13] is 0.92 volts at 1273 K. This voltage equals the potential generated by the reverse reaction. As indicated by the graph, a voltage greater than the reversible potential must be applied to generate electrode current and hydrogen. The additional voltage supplied above the reversible is proportional to the energy that is dissipated in the cells as ohmic or resistive losses. This thermal energy can be used to supply the thermal energy requirements of the reaction that are represented by the entropy term in Figure 6. At an applied voltage of 1.29 volts, referred to as the thermoneutral voltage, the thermal energy that is generated by resistive losses is equal to the thermal energy required for the reaction at 1273 K. If the electrolyzer is operated at this voltage, no additional thermal energy, supplied directly as solar, is required.

Figure 8 shows the fraction of thermal energy supplied as solar and internal resistive losses vs current density. This relationship is true if the resistive losses due to the resistance of the electrolyte and the polarization of the electrode are linear with current density. This assumption is valid over the current density range in consideration. Figure 8 shows that in order for a significant portion of the thermal energy to be supplied directly from solar thermal, the electrolyzer must operate at low current densities. For a given

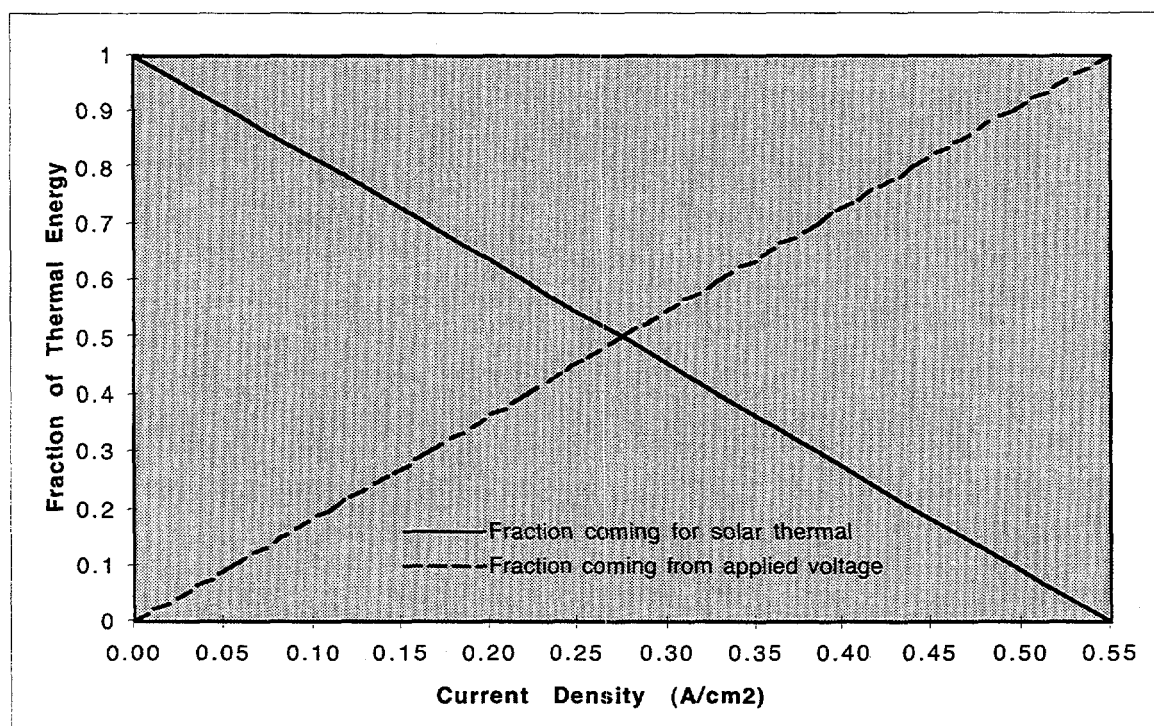


Figure 8. Thermal energy source as a function of electrode current density for SOFC

production capacity, lower current densities require greater electrode surface area. Figure 9 shows the relationship between electrode surface area and current density. Figure 9 shows that as current density decreases, the amount of relative electrode surface area increases dramatically. In order to supply 80% of the thermal energy with solar, the electrolyzer would need to be about six times as large compared to one that provides all the thermal energy as internal resistive losses. Since electrolyzer costs scale linearly with electrode surface area, the electrolyzer cost must be very inexpensive before it becomes cost effective to provide a significant amount of the thermal energy as solar.

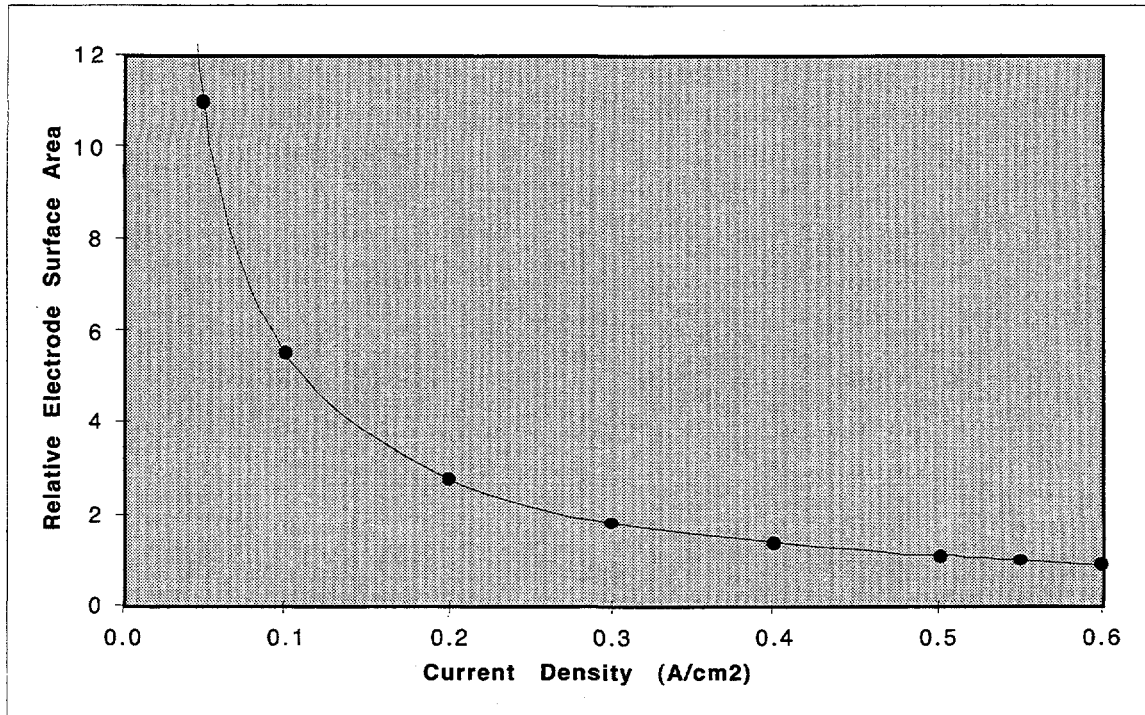


Figure 9. Relative electrode surface area versus current density

The cost of hydrogen produced by high temperature electrolysis was determined and compared to that produced by ambient temperature electrolysis. Since commercial high temperature electrolyzers are not available, the cost is uncertain. Westinghouse estimated the cost of a commercial electrolyzer including recovery of enthalpy from the products to be \$2000/kWdc. Cases were analyzed in which the capital cost of the electrolyzer was \$2000/kWdc and \$500/kWdc. The second corresponds to the cost of the ambient temperature electrolyzer. The O&M costs were assumed to be the same as those of the ambient temperature electrolyzer.

Since the solar plant may provide both electricity and solar thermal energy, the capital costs had to be determined by component. The following component fixed capital costs were used for the 200 MWe (year 2020) plant:

1. heliostats:	\$93/m ²
2. power tower/receiver:	\$63/kWth
3. thermal storage:	\$76/kWth
4. ac generator:	\$632/kWac
5. electrolyzer cost:	\$500-\$2000/kWdc (thermoneutral)
6. building (for electrolyzer) cost:	\$3,000,000
7. land cost:	\$600/acre

The following O&M cost factors were used:

1. power tower plant O&M:	\$5.00/kWth/yr
2. electrolyzer O&M:	\$0.55/kg H ₂

The following factors and efficiencies were used in this analysis:

1. solar resource:	1.1 kW/m ²
2. solar land use:	6.1 m ² /kWth
3. solar capacity factor:	0.28
4. electrolyzer capacity factor:	0.77
5. heliostat/receiver efficiency:	0.531
6. thermal to electric conversion efficiency (kWth to kWac):	0.377
7. overall conversion efficiency (kWth to kWac):	0.200

Figure 10 shows the hydrogen selling price as a function of current density for two electrolyzer capital costs: \$2000/kWdc and \$500/kWdc. This is the base cost assuming the electrolyzer operates at the thermoneutral voltage or highest current density. As the current density is decreased, the electrode surface area and, therefore, the cost increase proportionately. The results show that for a electrolyzer capital cost of \$2000/kWdc, the most cost effective mode in which to operate is at a current density of 0.55 A/cm². This corresponds to operating at the thermoneutral voltage with no direct solar thermal input to the electrolyzer. Even at an electrolyzer cost of \$500/kWdc, there is still no benefit to operating at a voltage below the thermoneutral voltage.

Results show that high temperature electrolysis is essentially the same (\$39/MBtu) as ambient temperature electrolysis (\$40/MBtu) when the electrolyzer costs are comparable. The enthalpy of the reaction at 1273 K is less than the enthalpy of the reaction at 293 K. Even though the process is more energy efficient at low current densities, the capital cost of the electrolyzer drives the operation of the process to be 100% electric with no direct solar thermal input to the electrolyzer.

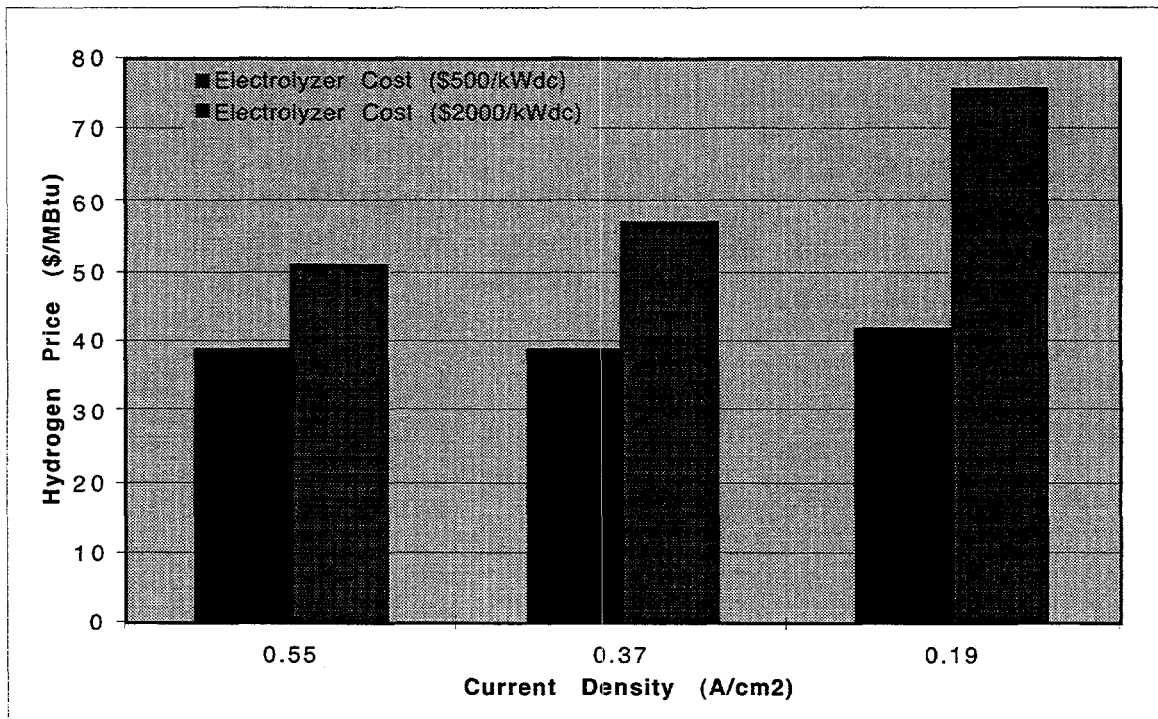


Figure 10. Hydrogen price as a function of current density

High Temperature Dissociation

High temperature thermal dissociation is based on the thermodynamic equilibrium of the water splitting reaction at temperatures above 2000 K [10]. The equilibrium mole fractions of atomic and molecular hydrogen at these temperatures and at 0.5 atm pressure are shown in Figure 11. As the temperature increases, an increasing mole fraction of all the components exists in the reaction mixture. Figure 12 shows the equilibrium mole fractions of atomic and molecular hydrogen at these temperatures and at pressures of 0.2, 0.5, and 1.0 atmospheres. As pressure decreases, the equilibrium mole fractions of atomic and molecular hydrogen increase. These graphs indicate that with no limits on the operating conditions due to materials or other constraints, the process should be operated at high temperature and low pressure.

Figure 13 shows a schematic of the steps required in this process. The steps consist of recovering the enthalpy from the products, both atomic and molecular hydrogen and oxygen, and using this enthalpy to preheat the incoming steam to the reaction temperature, allowing the reaction to occur at temperature, separating the hydrogen components and oxygen components at temperature, and compressing the product hydrogen at ambient temperature back to 1 atmosphere. An alternative approach is to rapidly cool the equilibrium mixture and then perform the separation of products at low temperature.

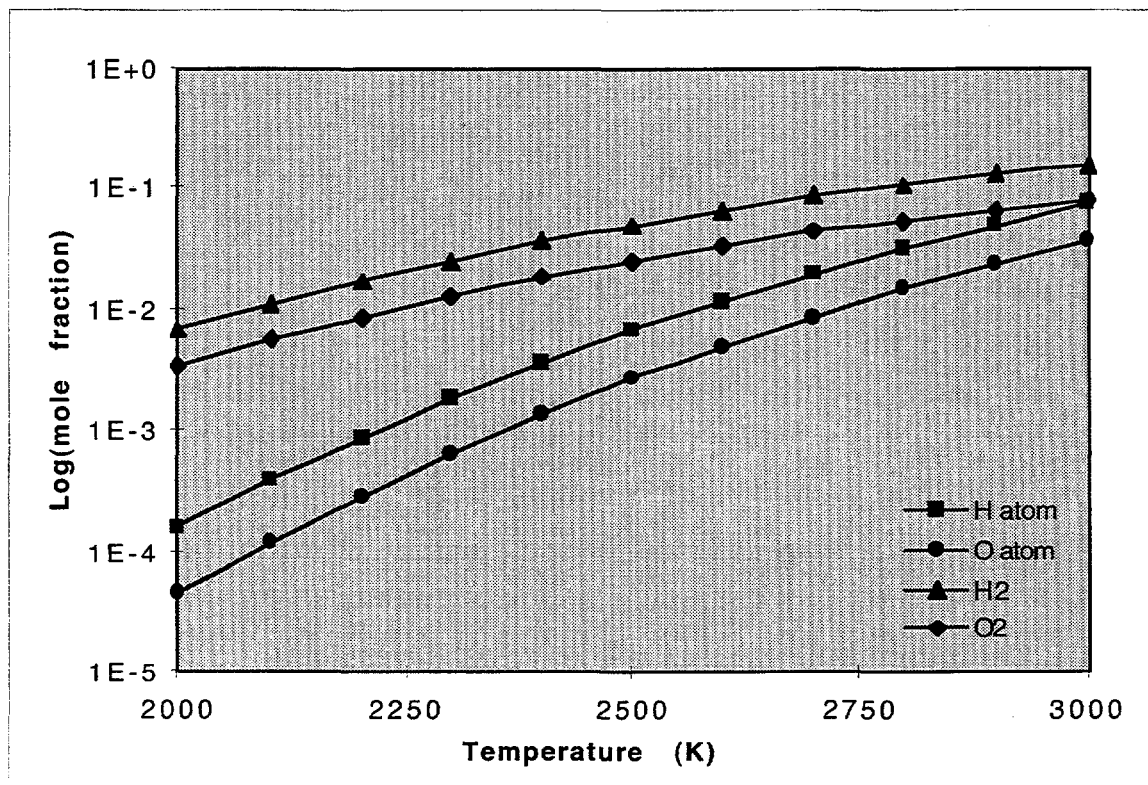


Figure 11. Mole fractions of products versus temperature at 0.5 atmospheres

The losses associated with the recovery of enthalpy from the entire reaction mixture, however, make this approach impractical [14].

Methods and materials for the high temperature reaction and separation have not been sufficiently identified at this time to allow a quantitative analysis of this process. An indication of the most favorable operating conditions can be obtained by calculating the thermal and mechanical power requirements of the steps as a function of temperature and pressure. To do this, the following equations were used:

Reactor volume

$$V_{\text{react}} = m_{\text{total}} * t_{\text{res}} * V_{\text{std}} * (T_{\text{react}}/T_{\text{std}}) * (P_{\text{std}}/P_{\text{react}})$$

Ideal separation power [15]

$$\text{Power}_{\text{sep}} = -R * T_{\text{react}} * m_{\text{total}} * \text{Sum}_i (x_i * \ln x_i)$$

Recovery of enthalpy in products

$$q = \text{Sum}_i (h_i^{(T_{\text{react}}-298)} * m_i)$$

Ideal compression power [16]

$$\text{Power}_{\text{comp}} = R * T_{298} * m_{\text{H}_2} * \ln(1/P_{\text{react}})$$

Total thermal requirements

$$q_{\text{thermal}} = \Delta H_{\text{react}} * m_{\text{H}_2} + h_{\text{H}_2\text{O}}^{(298-T_{\text{react}})} * m_{\text{H}_2\text{O}} - q$$

where:

Delta H	Heat of reaction
h_i	enthalpy of component i
m_i	molar flow rate of component i
P_{react}	reaction pressure
P_{std}	standard pressure (1 atm)
R	gas constant
T_{react}	reaction temperature
T_{std}	standard temperature (298 K)
t_{res}	residence time
V_{react}	reactor volume
V_{std}	standard molar volume (22.4 liters/mole)
x_i	mole fraction of component i

The thermal and mechanical power requirements for these steps were calculated as a function of temperature and pressure. The results are shown in Figures 14 and 15. The separation power was calculated assuming a separation efficiency of 0.8. The compression power was calculated assuming a compression efficiency of 0.6. The total thermal requirement was calculated assuming a solar concentration factor of 10,000 and a receiver thermal energy loss with a T^4 dependence.

Figure 14 shows the relative dependence of the thermal and mechanical power as a function of temperature at constant pressure. Both reactor volume and separation power decrease with increasing

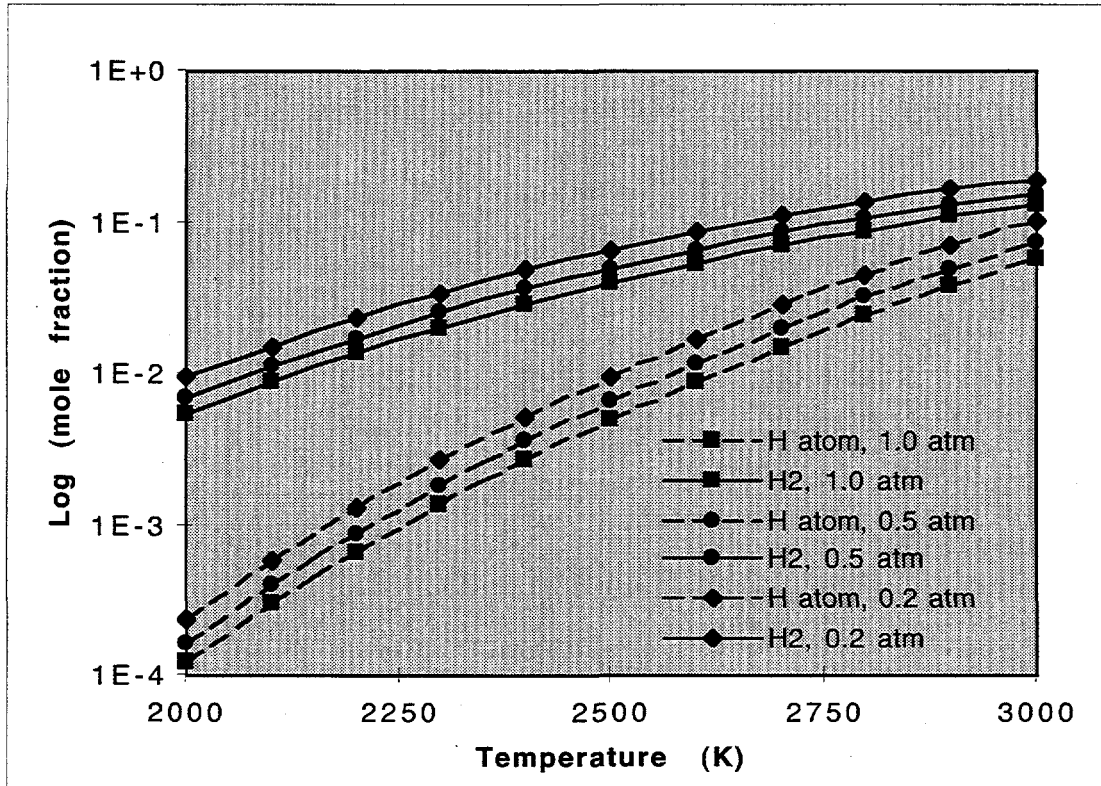


Figure 12. Mole fractions of atomic and molecular hydrogen vs temperature and pressure

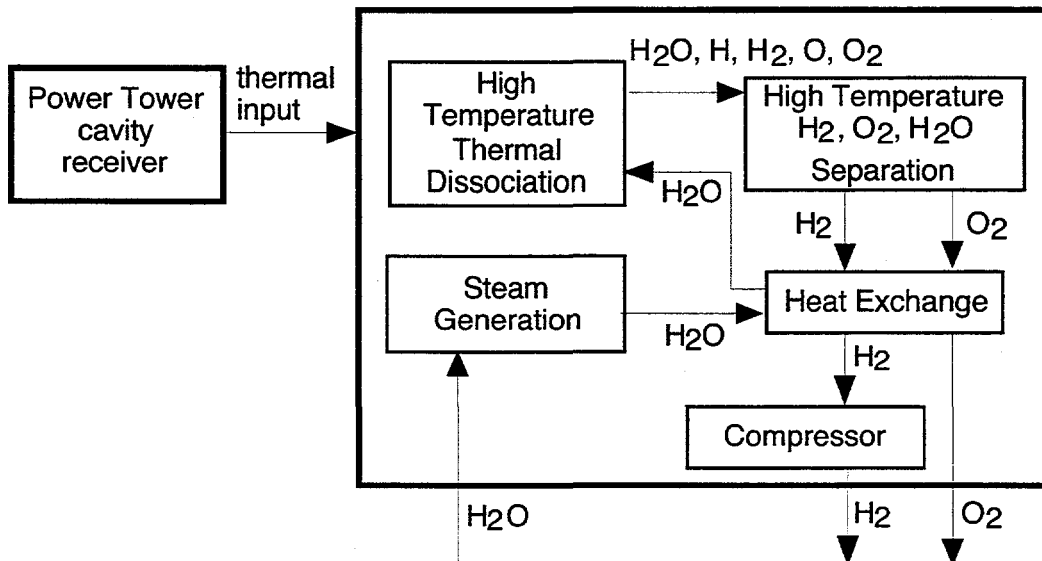
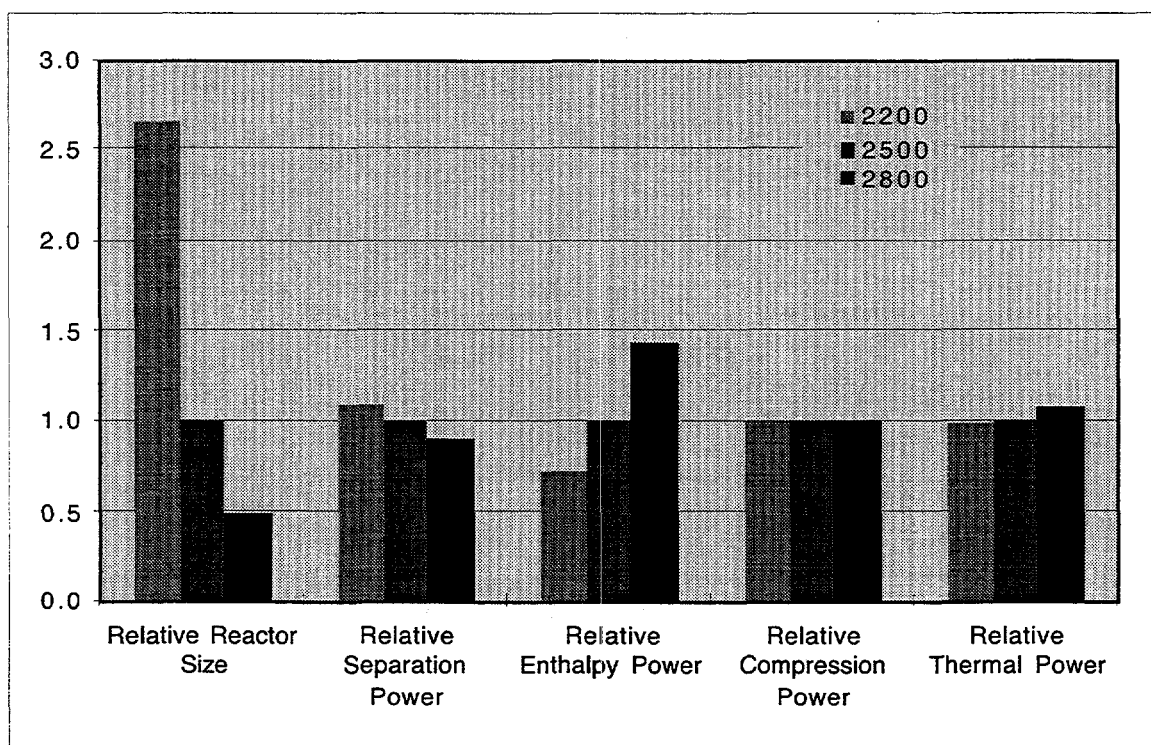


Figure 13. High temperature thermal dissociation

temperature even though these functions are proportional to temperature. This is because the product yield is increasing with temperature. The enthalpy requirement increases with temperature because of the increase in product enthalpy at higher temperatures. The compression power is constant with temperature. The total thermal power requirement is essentially constant with temperature even though thermal losses has a T^4 dependence. This is because the product yield at higher temperature compensates for the increase in thermal losses.

The thermal and mechanical power requirements are shown as a function of pressure at constant temperature in Figure 15. Reactor volume increases with decreasing pressure because the higher volume is required to maintain a constant residence time at the lower gas density. Compression power also increases with decreasing pressure as one would expect. All the other power requirements are relatively constant with pressure.

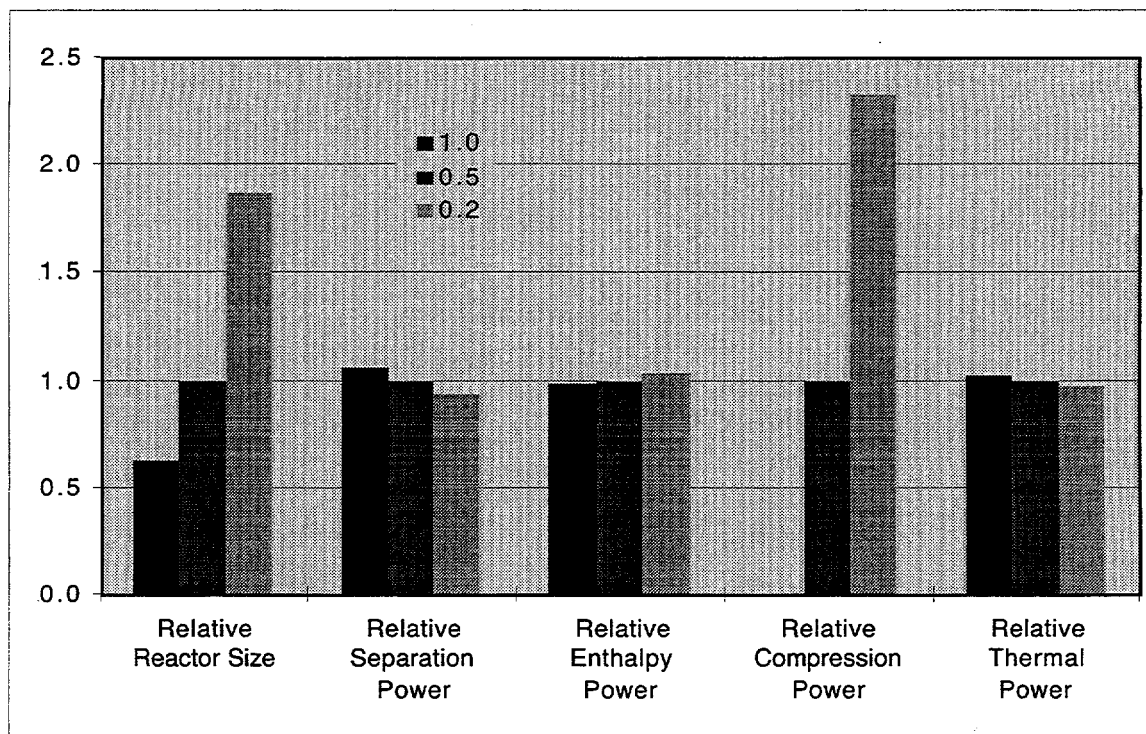


Figures 14. Thermal and mechanical energy requirements as a function of temperature

The relative costs of these steps as a function of temperature and pressure cannot be determined until all of the steps have been fully characterized in terms of method and materials. The most critical issues are the identification of materials of construction for the reactor and separator and the identification of a method for the separation of the product components from steam at the reaction temperature.

Thermochemical Cycles

Three thermochemical cycles were reviewed as part of this work. As with the high temperature thermal dissociation, these cycles have not been sufficiently characterized at this time to allow for cost analysis of solar processes based on these cycles. As a result, the scope of this work was limited to describing the cycles and identifying the relative



Figures 15. Thermal and mechanical energy requirements as a function of pressure

merits of each cycle and identifying the technical issues that need to be addressed in order to perform a quantitative analysis of the cycles.

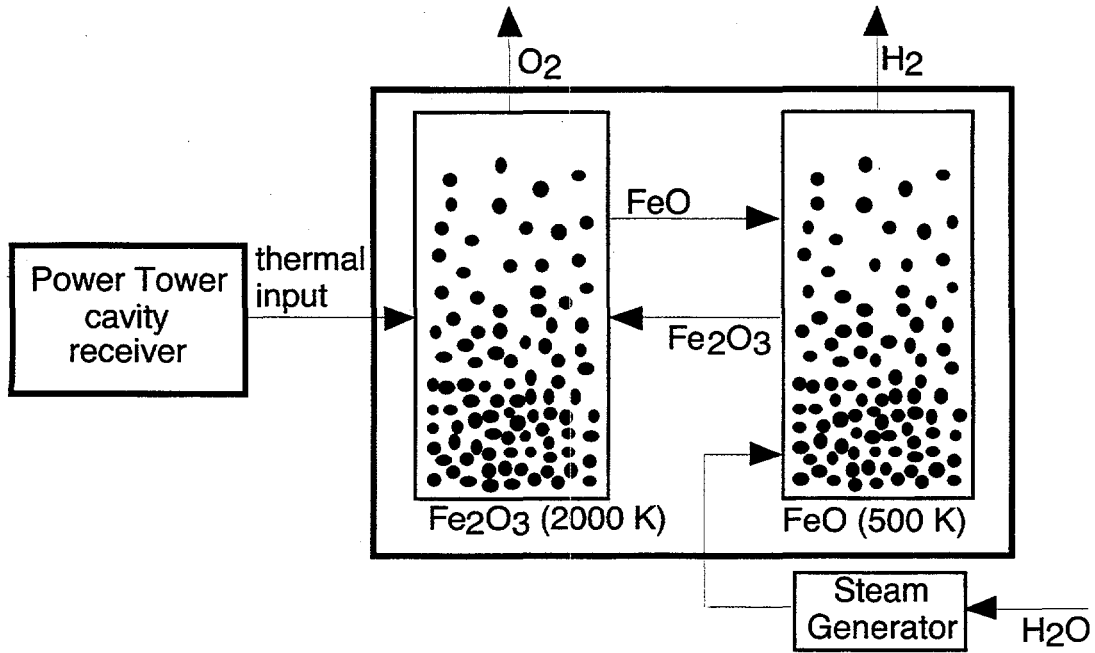
Iron oxide cycle

The iron oxide cycle is a specific case of a general thermochemical cycle in which some metal oxide alternates between two oxidation states to facilitate the water splitting reaction [17]. In this case, FeO is oxidized by H₂O to form Fe₂O₃ and H₂. The FeO is regenerated from Fe₂O₃ by heating to high temperature in a separate step. The two steps generally occur at significantly different temperatures requiring either the transfer of the oxide between two vessels (Figure 16) or the operating conditions of each vessel must be alternated as the respective reactions in each vessel approach completion (Figure 17). Detailed process analysis of these two approaches must be performed, taking into account the thermodynamics of the reaction, in order to determine the best approach for this cycle.

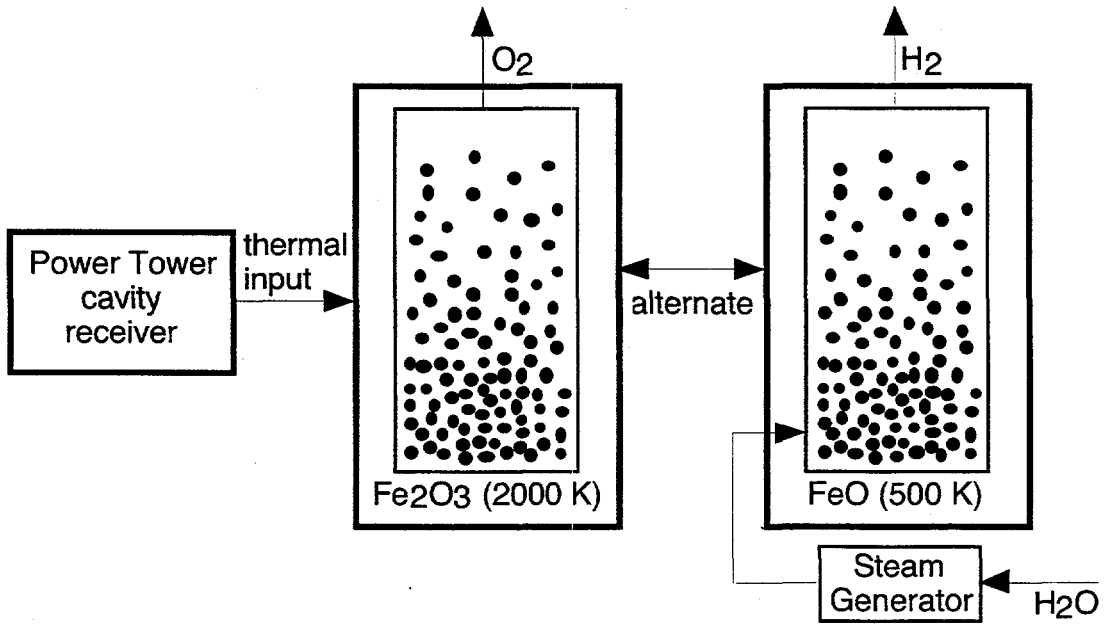
Iron/calcium oxide/bromide cycle (UT-3)

A schematic of this cycle is shown in Figure 18. Although, chemically, it is the most complex, it has promise in that the forward and reverse reactions between iron oxide to iron bromide occur at about the same temperature [18]. The same is true for the forward and reverse reactions between the oxide and bromide of calcium. This allows for the forward and reverse reactions to be performed by reversing the direction of the flow of reactants and products shown in Figure 18. The solid reactants and products can then remain in their respective beds eliminating the need for solids material transfer.

The maximum required temperature for reaction is 900 K which is achievable in thermal energy storage of molten salts, the heat transfer fluid in solar power towers. This means



Figures 16. Iron oxide process with material transfer between beds



Figures 17. Iron oxide process with alternating operating conditions between beds

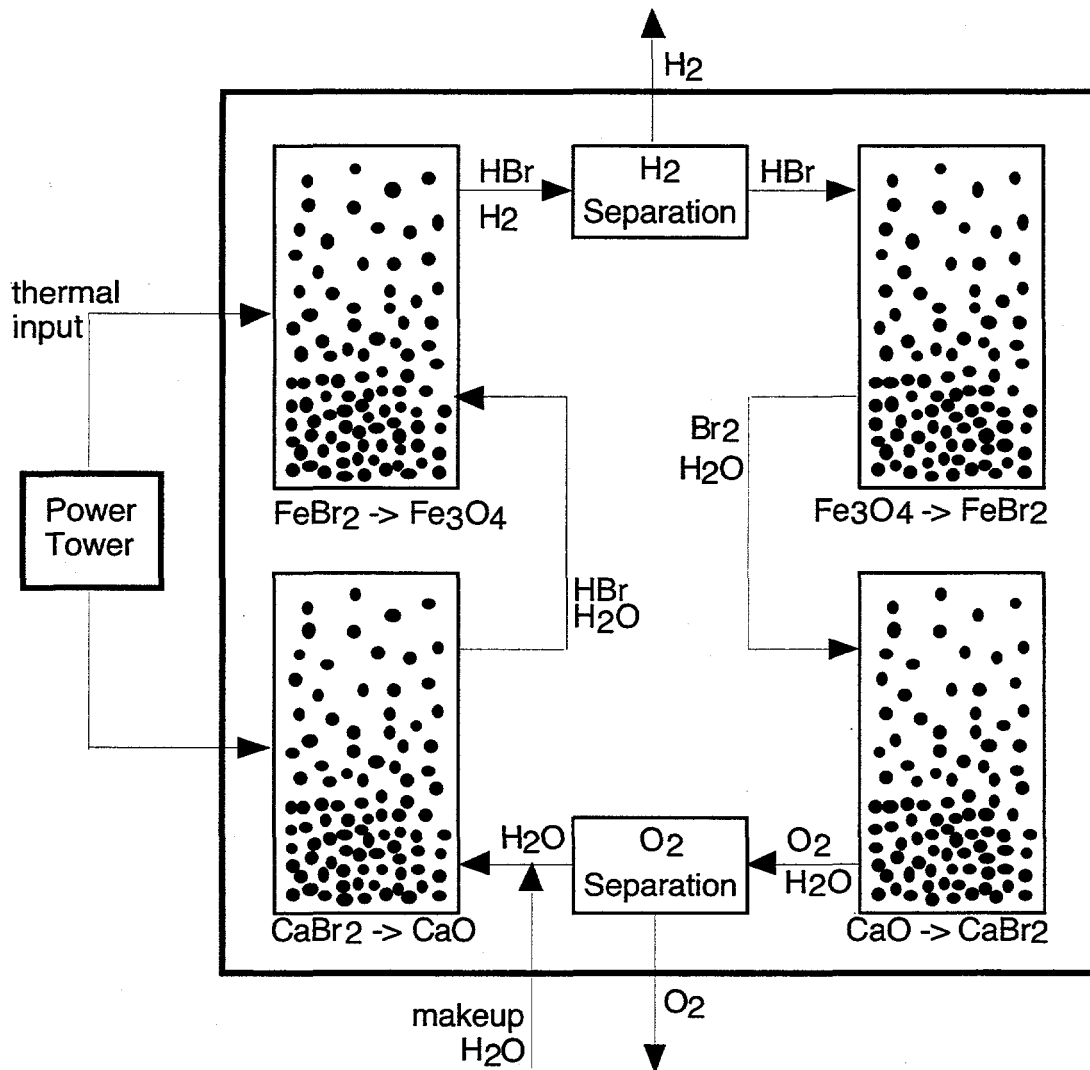


Figure 18. Iron/calcium oxide/bromide process

that the process could take advantage of the higher capacity factor that is allowed when thermal storage is used.

This process has been investigated and characterized to the point where solar-specific designs can now be examined. Several options exist for this process, one is to operate the two high temperature, endothermic reactions during on-sun conditions and operate the low temperature, exothermic reactions during off-sun conditions.

Sodium iodide/ammonium iodide cycle (Hitachi)

A schematic of the sodium iodide/ammonium iodide (Hitachi) cycle is shown in Figure 19 [19]. This cycle has not been developed past the point of characterizing the thermodynamics of the chemical reactions. The cycle has the advantage of having a low maximum operating temperature (600 K) and its reactants are relatively noncorrosive

compared to those of the UT-3 cycle. One non-solar limitation for this cycle is the conversion of HI to H_2 and I_2 . This conversion is limited by thermodynamics and does not improve with temperature. Equilibrium conversions around 10% can be expected at reasonable temperatures. Methods need to be determined for enhancing this conversion. HI can be reacted with a metal M to form MI and H_2 , the HI can be electrolyzed to H_2 and I_2 , or the H_2 and I_2 can be separated from the H_2 , HI, I_2 gas mixture as they form. This issue need to be addressed in order for this process to be considered feasible.

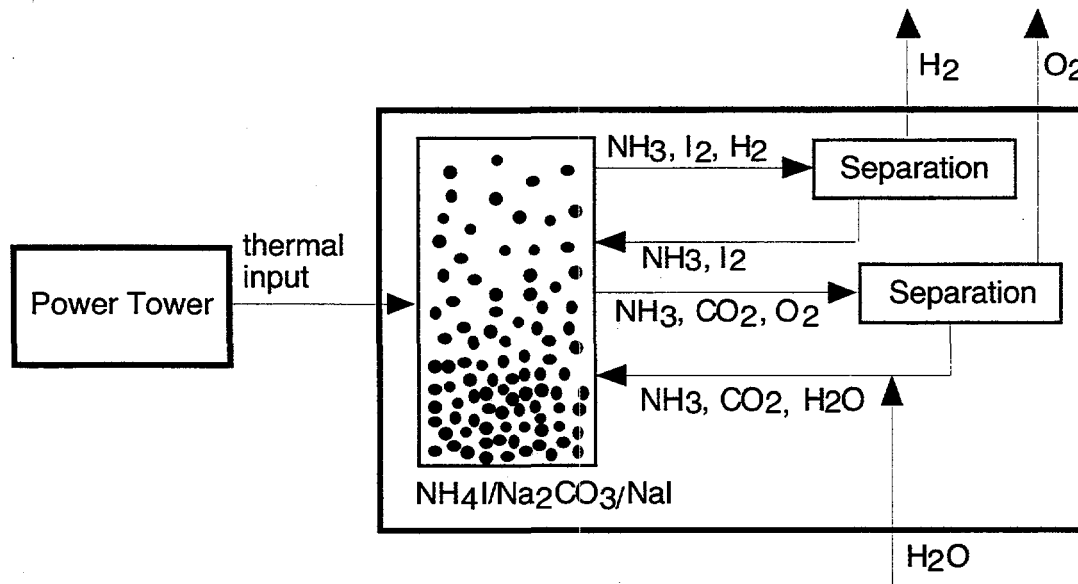


Figure 19. Hitachi NaI/NH₄I process

Conclusions

Cost and process analysis was performed on a number of methods for producing hydrogen from concentrated solar energy. Results of the cost analysis were compared to the results of cost analysis for producing hydrogen using electrolysis and other renewable electricity generation technologies, photovoltaics and wind energy.

Results showed that the price of hydrogen using solar concentrating technologies and ambient temperature electrolysis was comparable to the price of hydrogen using photovoltaics and electrolysis. Results also showed that it will be difficult for any solar technology, be it solar thermal or photovoltaics, to compete with the future price of hydrogen from wind unless storage is used. Storage of electricity in photovoltaic systems is expensive because of the need for batteries. Solar power towers are already designed with thermal storage because the heat transfer fluid has to be stored in any case. As the scale of an electrolysis process increases, a greater portion of both the capital and operating costs are incurred by the electrolyzer. This is because capital and O&M costs for electrolyzers tend to scale linearly with capacity. If economies of scale can be realized for electrolyzers at larger scales, then the cost of hydrogen from solar power towers will decrease and may be competitive with wind in the future.

A benefit of using solar power tower technology for electrolysis is the constant supply of ac power as a function of time. This due to the thermal storage capability of power towers. Conversations with electrolyzer manufacturers indicate that electrolyzing units prefer to

operate with constant ac power input. If power is not constant, the performance and longevity of the electrolyzer can be adversely affected.

Another factor to consider is that, in general, electrolysis for hydrogen production is used to meet small, isolated markets. There may be locations where there is a demand for hydrogen but the location has a poor wind resource. In those cases, electrolysis using solar thermal or photovoltaics will be the most competitive method for production.

Results show that high temperature electrolysis is the same (\$39/MBtu) as ambient temperature electrolysis (\$40/MBtu) when the electrolyzer costs are comparable. The enthalpy of the reaction at 1273 K is less than the enthalpy of the reaction at 293 K. Even though the process is more energy efficient at low current densities, the capital cost of the electrolyzer drives the operation of the process to be 100% electric with no direct solar thermal input to the electrolyzer.

A critical issue for high temperature thermal dissociation is the identification of materials of construction for the reactor and separator and the identification and characterization of a method for the separation of the product components from steam at the reaction temperature. The relative costs of these steps as a function of temperature and pressure cannot be determined until all of the steps have been fully characterized in terms of method and materials.

Detailed process analysis of the two approaches for the iron oxide cycle must be performed, taking into account the thermodynamics of the reaction, in order to determine the best approach for this cycle.

The iron/calcium oxide/bromide (UT-3) process has been investigated and characterized to the point where solar-specific designs can now be examined. Several options exist for this process, one is to operate the two high temperature, endothermic reactions during on-sun conditions and operate the low temperature, exothermic reactions during off-sun conditions.

Methods need to be determined for enhancing the conversion of HI to H₂ and I₂ in the sodium iodide/ammonium iodide cycle. HI can be reacted with a metal M to form MI and H₂, the HI can be electrolyzed to H₂ and I₂, or the H₂ and I₂ can be separated from the H₂, HI, I₂ gas mixture as they form. This issue needs to be addressed in order for this process to be considered feasible.

All of the thermochemical cycles have reactor/receivers that are either a fixed or fluidized bed type. These types of reactors generally scale less than linearly with capacity so that the capital costs of these processes will improve relative to those of electrolysis at larger scales. For that reason, the thermochemical cycles are, generally, a better match for the large scale solar power tower than electrolysis. A hydrogen production process based on a well-characterized thermochemical cycle will most likely be competitive with the future wind electrolysis technology.

Recommendations for Future Work

Ambient temperature electrolysis

1. determine effect of intermittent power supplied to electrolyzing units;
2. determine any economies of scale for larger scale electrolyzing units;

High temperature electrolysis

3. an electrolysis design needs to be developed that operates economically at low current density; this issue is most likely beyond the scope of the solar electric program;

High temperature thermal dissociation

4. identify materials of construction for the reactor and separator and identify and characterize a method for the separation of the product components from steam at the reaction temperature [20];

Thermochemical cycles

5. detailed process analysis of the two approaches for the iron oxide cycle must be performed, taking into account the thermodynamics of the reactions, in order to determine the best approach for this cycle;

6. the iron/calcium oxide/bromide (UT-3) process has been investigated and characterized to the point where solar-specific designs can now be examined; options for solar based processes should be examined;

7. methods need to be determined for enhancing the conversion of HI to H₂ and I₂ in the sodium iodide/ammonium iodide cycle;

8. perform detailed engineering and cost analysis on one or more of the thermochemical cycles and identify one or more configurations of a cycle incorporated with a solar power tower; compare the price of hydrogen from these processes to that produced from wind energy and electrolysis; at large scales, the solar power tower with a thermochemical cycle should have better economics than the wind electrolysis system.

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