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A COMPARISON OF CAPITAL COST ESTIMATES AND PROCESS EFFICIENCIES FOR HYDROGEN PRODUCTION BY THERMOCHEMICAL CYCLES AND WATER ELECTROLYSIS

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Abstract

A survey of capital cost estimates and process efficiencies for two different technologies for producing hydrogen from water has been completed. Thermochemical cycles show costs ranging from \$600-1100/kW H₂ while advanced methods of water electrolysis were estimated in the range of \$700 - 1100/kW H₂. In general, efficiencies for thermochemical cycles were higher at 40 - 55%, than for water electrolysis systems at 30 - 40%

In all evaluations of new technology, careful attention must be paid to the assumptions underlying the derived cost and efficiency to ensure that design conditions conform to achievable results.

Introduction

The prospects of generating hydrogen from water are daily becoming brighter with the decline in fossil fuel supplies and their increasing price. Hydrogen can be used for a variety of our energy needs, e.g., an energy carrier, a chemical intermediate or reagent, a fuel supplement for existing gas supplies, and an energy storage medium for the regeneration of electricity produced during "off-peak" periods. Today, hydrogen is used mainly as a chemical intermediate in a "captive" sense, i.e., it is used internally within refineries for the upgrading of petroleum stocks, or in chemical plants for synthesis of substances such as ammonia and methanol. These uses are expected to broaden the use of hydrogen as a general fuel for applications such as aircraft and automobiles in the transportation sector where the attributes of hydrogen such as its nonpollution characteristic and its low-mass energy density (contrasted though with its high-volume energy density) are expected to play a major role in its implementation.

The major barrier to hydrogen's use is its cost and this must be taken into account in all aspects of its present and future use.¹ The conventional method of producing hydrogen is to react a light hydrocarbon such as methane (natural gas) or naphtha with steam. This method produces hydrogen at lowest price as result of the relatively inexpensive cost of natural gas (\$2.00 - 3.00/10⁶ Btu) and also because of the low capital cost of steam-reforming which is less than that of competing systems.¹ Another method of producing hydrogen from hydrocarbon sources includes the partial oxidation of heavy oil and coal with steam. This process will be used in the interim period when natural gas supplies become short and before the implementation of hydrogen production schemes based on renewable energy sources (solar, fission, and fusion) and water-splitting.

This paper addresses the cost of two water-splitting schemes. In the first scheme, water is split electrochemically in an electrolyzer to produce hydrogen and oxygen. This technique employs electricity which must first be generated from some primary energy source at an efficiency subject to

the Carnot limitation. The second and potentially more promising scheme involves the process of thermochemical water-splitting. Thermal energy is the primary energy input and water is reacted with intermediate chemicals in a complex chemical cycle to yield hydrogen and oxygen. The intermediate chemicals in the "thermochemical cycle" are completely circulated, reacted and regenerated with no losses in an ideal cycle.

In this paper, we have not attempted to answer the direct question of addressing the cost of hydrogen, rather, by displaying capital costs and efficiencies we will indicate the advantages and disadvantages as well as areas of improvement for several proposed hydrogen production processes.

Process Description

Water Electrolysis

In the electrolysis process, a voltage is applied between two metallic electrodes separated by an electrolyte, a conductor of ions, but not of electrons. The electrolysis reaction in water proceeds by electron transfer between the two electrodes and the mobile ions in the electrolyte, gaseous hydrogen (H₂) appearing at the cathode and gaseous oxygen (O₂) at the anode. In practice, alternating current from an electrical generating plant is rectified to direct current which in turn is fed to a series (battery) of electrolyzer cells. The hydrogen and oxygen gases are released separately and manifolded in liquid/gas separators where water vapor and excess electrolyte are removed. The overall system included feedwater treatment facilities as well as hydrogen compressors to a nominal (30 atm) outlet pressure.

Traditionally, electrolyzers such as that described above use caustic electrolyte solutions and operate at temperatures below 100 C. Alkaline electrolyzers, however, require substantial cell voltages to sustain modest current densities (e. g., 2.1 V at 4000 Am⁻²).² Some improvement in operating conditions may occur with a 28 wt% sulfuric acid electrolyzer in which calculations indicate 1.73 V at 4000 Am⁻² current density. In an advanced water electrolysis system, a solid polymer is used as the electrolyte, hence the term "solid polymer electrolysis" or SPE. This technology is being developed by the General Electric Company (GE) and was derived from their successful fuel cell work of the 1960s for the Space Program. In a recent study conducted by GE for the Electrical Power Research Institute (EPRI), an electrolyzer voltage of 1.655 V was attained at a current density of 10,000 Am⁻².

SPE technology is still under development at GE with the design and construction of a 500 kW unit in 1979 that is scheduled for testing through 1981. Future plans call for a 5 MW electrolysis plant to commence operation in 1983.

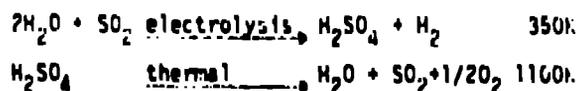
The voltage efficiency of a water electrolysis cell is equal to 1.484 V divided by the actual cell voltage. The value of 1.484 V represents 100 thermal efficiency, based on the higher value of hydrogen (286 kJ/mol) and 1.484 V is termed the thermoneutral voltage. For conventional water electrolysis, the overall efficiency (power-to-hydrogen) is often taken as 75%. The goal of the SPE program is to achieve 90% efficiency.

Thermochemical Cycle:

If hydrogen is to be used as a carrier of energy produced from nuclear reactors such as the High-Temperature Gas Cooled Reactor (HTGR) or solar furnaces, there is an incentive to develop processes for the thermal dissociation of water. The problem of splitting water using thermal energy along within the temperature constraints of practical nuclear and solar heat sources has been addressed by the concept of thermochemical cycles. This concept envisions a series of chemical reactions involving intermediate chemical species. These compounds are recycled internally within the process or "cycle" so that water and thermal energy are the only inputs and hydrogen and oxygen are the only outputs. The maximum temperature proposed for most of the cycles is in the range 700 - 1000 C (1000 - 1300 F) eliminating many lower temperature heat sources (e. g., geothermal energy).

To date, this technology has received wide attention, however it is still in its infancy and therefore sound economic projections have been difficult to make. Many (over 200) cycles have been proposed, but only a few have survived a preliminary efficiency and "ease of operation" analysis. Cycles that involve both thermal as well as electrochemical steps are termed "hybrid cycles." In these cycles, some of the input heat is used to produce electricity which in turn powers an electrochemical step that requires a lower voltage than water electrolysis. Bench-scale demonstrations have been carried out on three thermochemical cycles: The Westinghouse Sulfur Cycle,³ the General Atomic (GA) Sulfur-Iodine Cycle,⁴ and the Joint Research Center (JRC), Ispra, Italy, Mark 13 Cycle.⁵ The Westinghouse and JRC cycles are hybrid cycles and the GA cycle is a "pure" thermochemical cycle even though it requires a considerable amount of work to accomplish separations.

In the techno-economic evaluation of thermochemical cycle technology, the hybrid sulfur cycle, known commonly as the "Westinghouse Sulfur Cycle" and the "JRC Mark 11 Cycle," has received the most attention. This cycle is characterized by the following reaction sequence:



In both the Westinghouse and the JRC versions the process operates off nuclear heat delivered as a high-temperature helium gas stream from a HTGR or a Very-High Temperature Reactor (VHTR). If instead solar heat is considered for a thermochemical cycle, an additional factor must be considered. This is the cost of solar heat at the temperature required for the process. Solar heat is intermittent both on a daily basis (night and day) as well as during cloudy periods during the day. The lower capacity factor for solar plants (as contrasted to

nuclear plants) will have a larger effect on capital cost as compared to a nuclear plant. Solar-thermochemical schemes are just now receiving attention and this potentially promising technology has in its favor the capability of delivering heat at a practically isothermal temperature to a thermochemical cycle allowing consideration of cycles involving solid oxide or sulfide decompositions.

The efficiencies for thermochemical cycles have been computed for many cycles based on conceptual flowsheets. These efficiency values are highly dependent on the assumptions made during flowsheet preparation, especially in the case of a hybrid cycle where the electrolyzer operating characteristics (voltage, current density, and acid concentration) play the leading role. Initially values of 50 - 60% were estimated as the efficiencies for these cycles. Recently the estimated efficiencies have decreased to 40 - 50% as laboratory data has altered flowsheet conditions.

Methodology

Data on water electrolysis and on the hybrid sulfur cycle have occurred most often in the literature and this study is mainly based on their comparison. In many instances, data were estimated simultaneously as water electrolysis forms a "baseline" against which the competitiveness of thermochemical processes can be judged.

All data were placed on a common basis. The assumptions were:

A plant capacity of 100,000 Nm³/hr of hydrogen. (This was the basis chosen by JRC.)

All data were converted to mid-1974 \$ using the Chemical Engineering Plant Cost Index.⁶

The total investment cost was broken down into its components and expressed as \$ specific investment /kW H₂.

The following breakdown was employed to categorize the individual components of water electrolysis and thermochemical plants:

- **Nuclear (N).** This included the cost of the nuclear reactor and its auxiliaries. Also included in (N) are the costs of the primary and secondary helium loops required for heat transfer.
- **Power Generation and Conditioning (P).** This included the costs of the electrical generators plus the costs of the transformers, rectifiers, etc. required to condition the electricity.
- **Electrolyzer (E).** The electrolyzer system required to produce a 99.9% pure hydrogen product at 30 atm pressure is included in this category.
- **Chemical Plant and Heat Exchange Equipment (C).** For a hybrid or "pure" thermochemical cycle, we include the reactors, separators, and heat exchangers making up the plant in this category. Also included are the piping, pumps, and instrumentation. The hydrogen product is delivered to a pipeline at 30 atm. All capital costs are derived for

"grass roots" plant.

Results

Tables 1 and 2 present detailed summaries of the estimated investment costs and efficiencies derived for the different processes. The data are also presented in bar chart format in Figs. 1 and 2 on the basis of \$ Investment/kWh₂ (1979 \$) and (%) efficiency. The data were drawn from a number of original references in the literature. Explicit assumptions were made regarding cycle as well as heat source conditions and relevant information regarding these assumptions are given below.

Case I. Westinghouse Sulfur Cycle - NASA (1976)⁷ Cycle Efficiency: 45.2.

Assumptions:

A. Nuclear Heat Source

- ° Prestressed concrete reactor vessel.
- ° Reactor Outlet Helium Temperature = 1283 K.
- ° Turbogenerators in primary Helium loop.

B. Acid Electrolyzer

- ° Acid Concentration: 75 wt. %.
- ° Voltage: 0.45 V.
- ° Current Density: 2000 Am⁻².

Case II. Schulten Methanol Cycle - Funk/Lummus, EPP1 (1976)⁸

Cycle Efficiency: 37.5.

Assumptions:

A. Nuclear Heat Source

- ° As per Case I.

B. Thermochemical Cycle

- ° All reactions proceed to equilibrium.
- ° A key reaction ($\text{CH}_3\text{OH} + \text{SO}_2 + \text{H}_2\text{O} \rightleftharpoons \text{H}_2\text{SO}_4 + \text{CH}_4$) is not technically feasible.

Case III. Westinghouse Sulfur Cycle - ERDA (1977)⁹ Cycle Efficiency: 54.1.

Assumptions:

A. Nuclear Heat Source

- ° As per Case I.

B. Acid Electrolyzer

- ° Acid Concentration: 83 wt. %.
- ° Voltage: 0.48 V.
- ° Current Density: 2000 Am⁻².

Case IV. EXXON Study - Cornell, ERDA (1977)¹⁰

Assumptions:

A. Heat Source

- ° Unspecified, electricity cost assumed at 2.7 ¢/kWh.

B. Electrolyzer

- ° Conventional type (alkaline), efficiency: 75.7%.
- ° Advanced type (SPE), efficiency: 77.6%.
- ° Advanced type (SPE), efficiency goal: 90%.

Case V. Westinghouse Sulfur Cycle - EPP1 (1978)¹¹ Cycle Efficiency: 46.8%.

Assumptions:

A. Nuclear Heat Source

- ° As per Case I.

B. Acid Electrolyzer

- ° Acid Concentration: 80 wt. %.
- ° Voltage: 0.6 V (Case 2).
- ° Current Density: 2000 Am⁻².

Water Electrolysis (sulfuric acid electrolyte)

Efficiency: 40.8%.

Assumptions:

C. Water Electrolyzer

- ° Acid Concentration: 42 wt. %.
- ° Voltage: 1.64 V.
- ° Current Density: 2000 Am⁻².

Case VI. Masada - at present sulfur cycle - Masada, Ispra (1978)¹²

Cycle Efficiency: 41.7%.

Assumptions:

A. Nuclear Heat Source

- ° No electricity generation in primary helium loop.
- ° Use of bottoming cycle for additional electricity generation.

B. Acid Electrolyzer

- ° Acid Concentration: 75 wt. %.
- ° Voltage: 0.62 V.
- ° Current Density: 4000 Am⁻².

Advanced Water Electrolysis

Efficiency: 32.7%.

Assumptions:

C. Electrolyzer

- ° Voltage: 1.64 V.
- ° Current Density: 2000 Am⁻².

Table 1 Estimated Capital Costs and Efficiencies for Thermochemical Cycles

(All data are in \$/kW H₂, 1979 \$. Conversion from other years made by use of the Chemical Engineering Plant Cost Index.⁶)

Case	I	III	V	VI(Mk 11)	VI(Mk 13)	VII	II
N	262	227	258	629 (+P)	711 (+P)	274	326
P	58	66	95	-	-	113	-
E	144	142	192	236	236	172	-
C	165	154	164	133	143	186	612
Total	632	589	729	998	1089	745	938
Efficiency (%)	45.1	44.1	46.8	41.7	37.2	42.5	37.5

(N - Primary Energy Source, P - Power Generation & Conditioning, E - Electrolyzer,

C - Chemical Plant & Heat Exchangers.)

Table 2 Estimated Capital Costs and Efficiencies for Water Electrolysis

(All data are in \$/kW H₂, 1979 \$. Conversion from other years made by use of the Chemical Engineering Plant Cost Index.⁶)

Case	IV(Adv.)	IV(Adv.)	V	VII	VI
N	NA	NA	374	454	462
E	62	167	161	365	251
Total	68	167	161	749	692
Efficiency (%)	75.7	77.0	90.0*	40.8	40.2

(*) Electrolyzer Efficiency Only;

(N - Primary Energy Source, P - Power Generation & Conditioning, E - Electrolyzer)

* - 90 Efficiency, is the goal for SPE Water Electrolysis.

Case 13 - V₂ Cycle. Hybrid cycle based on sulfuric acid and bromine.

Efficiency: 37.2.

Assumptions:

D. Acid (Hydrogen Bromide) Electrolyzer

" Acid Concentration: 80 wt. %

" Voltage: 0.8 V.

" Current Density: 4000 Am⁻².

Case VII. General Electric Study - EPRI (1979)²

Hybrid Sulfur Cycle. Cycle Efficiency: 42.5%.

A. Nuclear Heat Source

" As per Case V.

B. Acid Electrolyzer

" SPE Type.

" Acid Concentration: 80 wt. %

" Voltage: 0.73 V.

" Current Density: 4000 Am⁻².

C. Water Electrolysis, Efficiency: 40.2%

" SPE Type

" Voltage: 1.665 V.

" Current Density: 10,000 Am⁻².

Discussion

Data for the specific investment for thermochemical cycles is presented in Fig. 1. The investments range from a low of \$589/kW H₂ to a high of \$1089/kW H₂ for the cycles reviewed. Efficiencies were estimated between 37.2 (low) to 54.1 (high). Examination of these data show that optimistic assumptions were made to bring about the low investment/high efficiency values. In case III for the hybrid sulfur cycle, a voltage under 500 mV was assumed for the electrolyzer. In reality, the voltages achieved are closer to 800 mV at 50 wt. % acid, and the research goal is 600 mV. Raising the design voltage to this level would bring the capital investment closer to \$1000/kW H₂ and the efficiency to 40.2%.

Only one "pure" thermochemical cycle was included in this sample. The Schulten-Methanol cycle suffers in comparison with hybrid cycles. Its investment cost is high (\$938/kW H₂) and its efficiency is low (37.5%).

The total investment portions are broken into their component parts (Fig. 1). For the six hybrid cycle cases, the investment allotted to the electrolyzer and the chemical sections of the plant are found to be almost similar. The major deviation was found in the pricing of the nuclear portion of the plant. The nuclear plant costs in Case VI (Mk 11 and 13) may be too large as they were obtained from the annual charges assigned by the authors.¹² Fig. 2 shows results for the water electrolysis plants. Their efficiencies are lower than those for the thermochemical cycles shown in Fig. 1 and range from 32.7 (low) to 40.8 (high). The efficiency for water electrolysis is the product of the electricity generation efficiency and the electrolyzer efficiency. The investment costs for water electrolysis appear to be in the same range as those computed for hybrid thermochemical cycles ranging from \$692/kW H₂ to \$1089/kW H₂. The data on the extreme right-hand side of Fig. 2 for stand-alone electrolyzer plants where electricity is purchased directly.¹⁰

There is a large difference between the cost obtained for conventional electrolysis (\$691/kW H₂) and those estimated for advanced electrolyzers using SPE technology. Conventional electrolyzers have efficiencies in the 70 - 80% range and SPE has a

goal of 90% efficiency which will help lower the overall investment cost if it is achieved.

Not taken into account in this study is the technique of high-temperature water electrolysis. As experimental data on these systems are relatively scarce, economic projections are even more speculative than for SPE or thermochemical cycles. Data from studies in which competitive hydrogen production schemes were compared by the same authors is presented in Fig. 3. These data are grouped in pairs. In the first set of data, (Case V), Westinghouse compared their cost for the hybrid sulfur cycle against that for an advanced water electrolyzer utilizing sulfuric acid as the electrolyte. The costs were strikingly similar even though their efficiencies differed.

To understand the investment difference between water electrolysis and hybrid thermochemical cycles see Fig. 4, in which a water electrolysis process is powered by the same heat source as a hybrid cycle. For water electrolysis, heat is first converted into electricity. An investment must be made for the heat source, for the power generation and power conditioning, (transformers and rectifiers) equipment, and for the electrolyzers. In a hybrid cycle, the same investment is made for the heat source (the efficiencies are assumed equal in both cases). Only part of the heat is necessary for electrolytic step, thus the power generation and conditioning investment is significantly less than for water electrolysis. The electrolyzer cost for a hybrid cycle however remains the same as for water electrolysis as the same amount of current must be used to produce the same quantity of hydrogen.

The major trade-off in investment cost is therefore quite simple to evaluate. It lies between the larger amount of power generation and conditioning equipment for water electrolysis which is balanced off by the cost of the chemical plant for a hybrid cycle. The first set of data in Fig. 3 indicate that this trade-off occurs.¹¹ The second set of data² assumed an advanced SPE water electrolyzer and a hybrid cycle using a similar SPE electrolyzer. The data indicate a higher cost for the hybrid cycle as compared to SPE electrolysis even though the efficiency of the former is higher than that of the latter. Another comparison was done by JRC, Ispra. They compared a hybrid cycle (Mk II) similar in nature to Westinghouse's to advanced water electrolysis. The investment costs for these two processes appears equivalent even though the hybrid cycle has a greater efficiency.

In the above results one must always take into account the assumptions. For hybrid cycles as for water electrolysis, key parameters are the electrolyzer voltage and current density. Doubling the current density leads to halving the cost for electrolyzers, roughly. GE used a current density of 10000 Am⁻² in their SPE water electrolysis design.² For the hybrid cycle, a 4000 Am⁻² current density was used. Although the specific cost of GE's SPE electrolyzer was greater than that of the hybrid cycle, their overall cost was estimated lower due to operation at higher current density.

Summary and Conclusions

The cost data show slight differences in investment between two methods of hydrogen generation.

All the costs were in the range, \$589 - 1089/kW H₂. Efficiencies are in general, higher for thermochemical cycles than for water electrolysis. These range from 37.2% to 54.1% for thermochemical cycles and from 32.7 to 40.8% for water electrolysis.

The values of investment cost or efficiency derived are only as good as the assumptions. Values of the sulfur dioxide electrolyzer voltage assumed in early studies on the hybrid sulfur cycle were below 0.5 V at acid concentrations of the 75 - 80 wt%. These voltages are impossible to attain under the assumed conditions. In these cases, investment costs and efficiencies must be revised to reflect conditions that are more realistic.

The major trade-off between hybrid thermochemical cycles and water electrolysis appears in the specific investment for the chemical portion of the plant, typically the sulfuric acid concentrator, acid decomposer and sulfur dioxide/oxygen separation unit. This cost must be balanced against the cost of the additional power generation and power conditioning facilities required in the case of water electrolysis. The chemical portion of the plant is fairly constant in cost at \$133 to \$186/kW H₂. Unfortunately few data are available for power equipment required in water electrolysis systems to quantify this trade-off. The specific investment for the electrolyzer portion for both processes is also alike ranging from \$142 to \$187/kW H₂ for advanced electrolyzers. Values of \$238/kW H₂ and \$365/kW H₂ were obtained for SPE and sulfuric acid electrolysis in later studies, however.

There does not appear to be any simplistic method to determine investment costs or efficiencies for new technologies such as thermochemical cycles or advanced water electrolysis. Computer codes will speed the process of cost estimation but a flowsheet reflecting reliable operating conditions is still the prime requirement in techno-economic evaluation.

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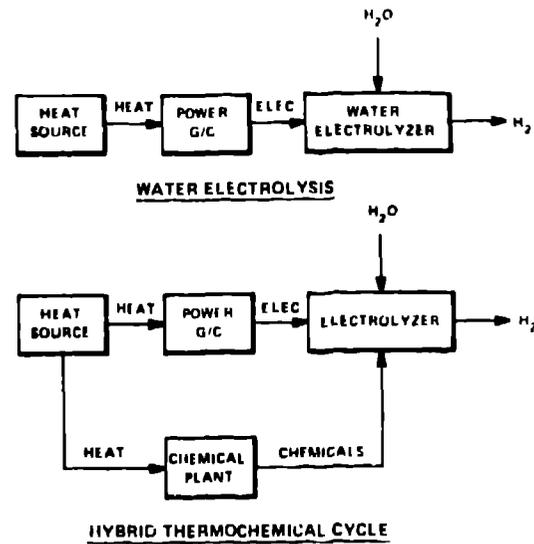


Fig. 4. Comparison of Water Electrolysis and Hybrid Thermochemical Cycle Processes.

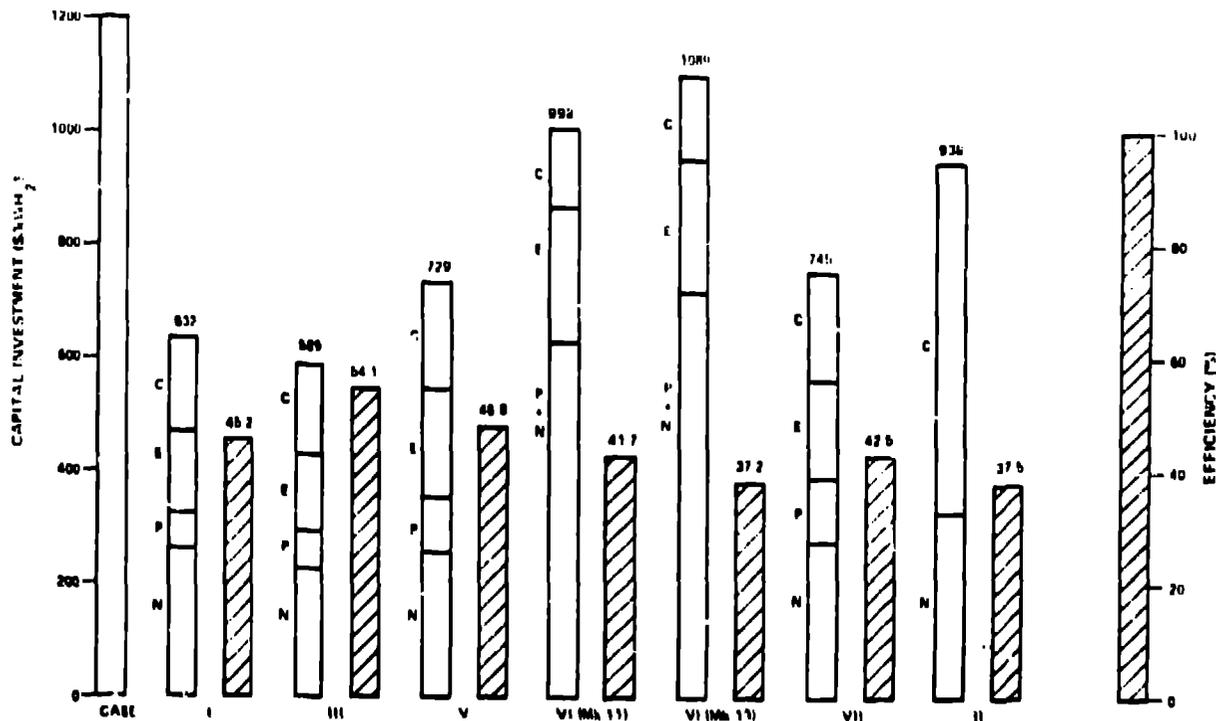


Fig. 1. Investment and Efficiency Estimates for Thermochemical Cycles.

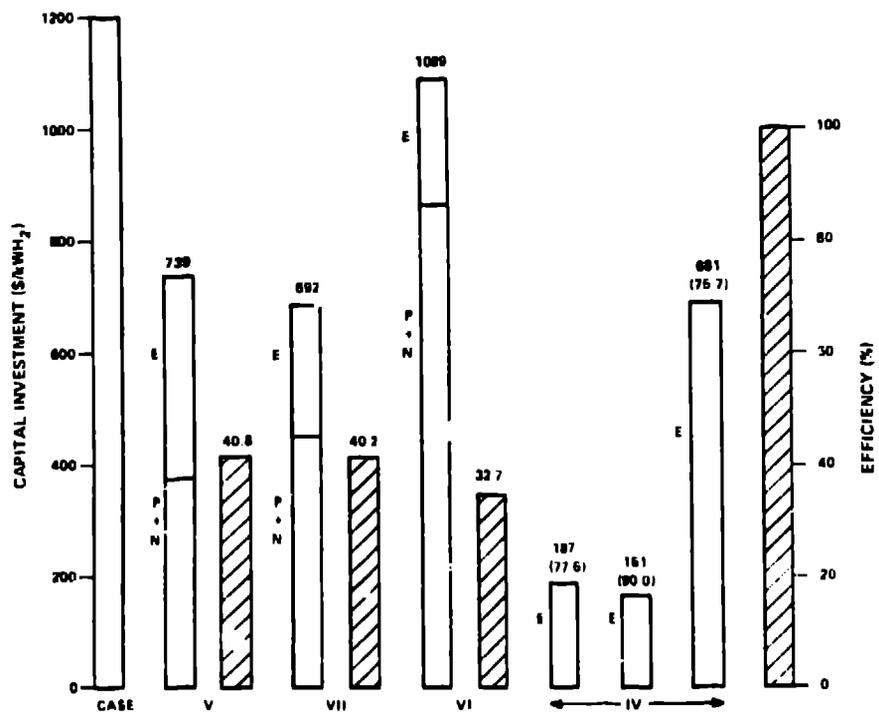


Fig. 2. Investment and Efficiency Estimates for Water Electrolysis.

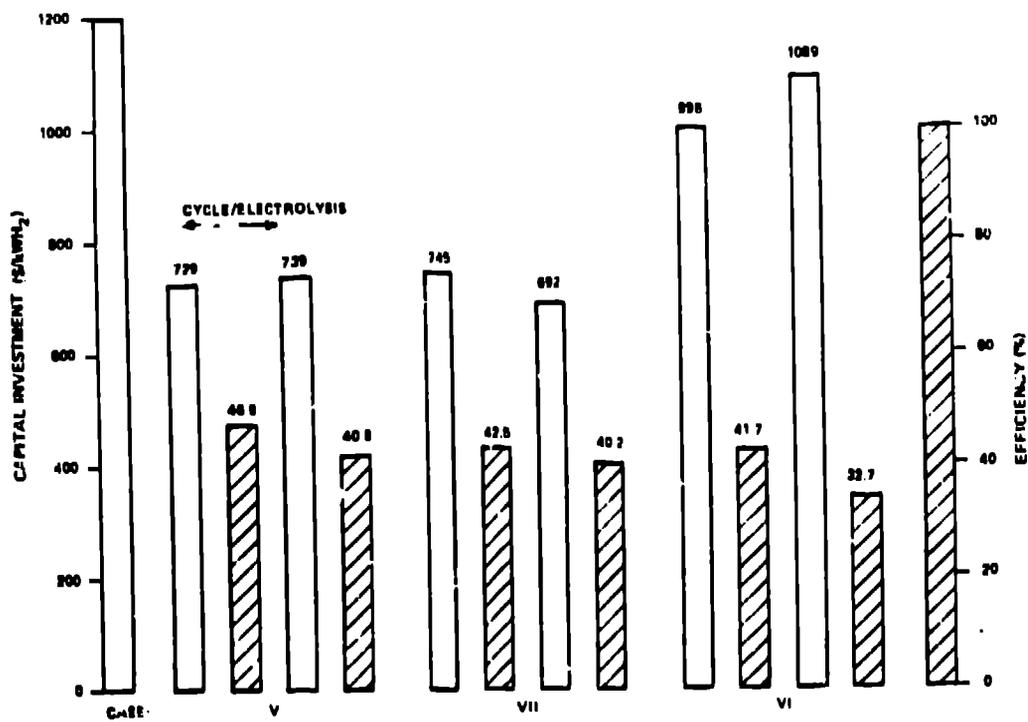


Fig. 3. Comparative Data for Investment and Efficiency, Thermochemical Cycles and Water Electrolysis. (Same Study)