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PRODUCTION OF HIGH-ENERGY CHEMICALS USING SOLAR ENERGY HEAT

IGT Project 8999 Final Report
For the Period September 1, 1977, Through May 31, 1978

James R. Dafler With Martin Novil
John Sinnott Bernard D. Yudow
Melinda G. Rackoff

Date Published — December 1978

Prepared by: Institute of Gas Technology
3424 S. State Street
Chicago, Illinois 60616
Under Subcontract No. 7390

For: Oak Ridge National Laboratory
P.O. Box X
Oak Ridge, Tennessee 37830

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Solar Energy

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UNITED STATES DEPARTMENT OF ENERGY
SOLAR ENERGY

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EXECUTIVE SUMMARY

Solar energy research has emphasized heating and cooling applications, and the generation of power by photovoltaic devices or by using a thermal intermediate in electricity generation cycles. Another application for the thermal or electrical energy generated from solar sources is the production of energy-intensive products such as chemicals, fuels, or possibly metals whose manufacture would otherwise consume significant quantities of conventional fossil energy. In this way an alternative use for the developing high-temperature solar technologies will emerge and will significantly reduce our dependence on fossil energy resources.

This report details work done in the first phase of a study intended to identify candidate processes and products suitable for future exploitation using high-temperature solar energy. The work was principally analytical, consisting of techno-economic studies, thermodynamic assessments of chemical reactions and processes, and the determination of market potentials for major chemical commodities that use significant amounts of fossil resources today.

The objective of this work has been to identify energy-intensive processes that are suitable for the production of chemicals and fuels using solar energy process heat — processes that could form the basis of future research and development. These processes and the products produced by them have been evaluated on a technical and economic basis. Of particular importance were the relative costs and energy requirements for the selected solar product versus those costs for the product derived from conventional processing.

The methodology uses a systems-analytical approach to identify processes and products offering the greatest potential for solar energy-thermal processing. This approach has been used to establish a basis for the work to be carried out in subsequent phases of the study. Specifically, it has been our intent to divide the analysis and identification into three distinct areas — process selection, process evaluation, and ranking of processes.

The following four conventional processes were selected for assessment.

Production Process	Annual Production, 10^9 lb
Vinyl Chloride Monomer	5.6
Methanol	6.5
Styrene	6.7
Terephthalic Acid	7.2

In addition, two processes of a futuristic character were selected: 1) methanol synthesis using by-product hydrogen from styrene production, and 2) ammonia production using hydrogen feedstock from a solar-driven high-temperature thermochemical hydrogen production plant.

All the processes show positive, strong projections for market growth and for future feedstock availability, indicating that the potential for this future use of solar energy process heat is considerable. The future costs of solar energy process heat will determine when such applications will be economically feasible. The cost trend for fossil energy and national energy policies will also have a strong impact on the development of an economically attractive solar chemicals facility.

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ABSTRACT

This program was the first phase of a study intended to identify candidate processes and products suitable for future exploitation using high-temperature solar energy. This phase has been principally analytical, consisting of techno-economic studies, thermodynamic assessments of chemical reactions and processes, and the determination of market potentials for major chemical commodities that use significant amounts of fossil resources today.

The objective of this work was to identify energy-intensive processes that would be suitable for the production of chemicals and fuels using solar energy process heat. Of particular importance was the comparison of relative costs and energy requirements for the selected solar product versus costs for the product derived from conventional processing.

The assessment methodology used a systems analytical approach to identify processes and products having the greatest potential for solar energy-thermal processing. This approach was used to establish the basis for work to be carried out in subsequent phases of development. It has been the intent of the program to divide the analysis and process identification into the following three distinct areas: 1) process selection, 2) process evaluation, and 3) ranking of processes.

In this study, four conventional processes were selected for assessment — namely, methanol synthesis, styrene monomer production, vinyl chloride monomer production, and terephthalic acid production.

1. INTRODUCTION

Solar-energy research has emphasized heating and cooling applications, and the generation of power by photovoltaic devices or by using a thermal intermediate in electricity-generation cycles. Under the U.S. Department of Energy (DOE) sponsorship, there are a number of continuing programs that are defining and enriching the state-of-the-art of solar power generation. The program of the National Aeronautics and Space Administration to define engine state-of-the-art is linked to a-c generating cycles,[1] and the large demonstration programs funded by DOE are for thermal-electric steam cycle generators.[2,3]

Another application for energy generated from solar sources is the production of energy-intensive products such as chemicals, fuels, or possibly metals, whose manufacture otherwise would consume large quantities of conventional fossil energy. In this way, an alternative use for high-temperature solar technologies will emerge that will significantly reduce our dependence on fossil-energy resources.

1.1. Background

The chemical manufacturing industry is one of the nation's largest consumers of process heat, usually supplied as fossil fuel energy. When electricity also supplies a large part of the consumed energy, the source use of fossil fuels is further increased. It is imperative, therefore, to develop an alternative source of process heat that does not depend on our dwindling reserves of oil and natural gas. Considerable research aimed at using nuclear process heat for synthesis gas production, coal gasification and liquefaction, and energy intensive manufacture of chemicals (e.g., methanol and ammonia) is already in progress.[4,5,6] Since the major portion of the chemicals industry does not require heat at the temperatures available from high-temperature gas-cooled nuclear reactors (HTR's), the use of solar heat provides an attractive, nonfossil, nonnuclear alternative to the current large-scale use of fossil fuel-produced heat. Solar heat use is considerably less controversial than that from an HTR, bypassing environmental controversies or problems associated with close coupling of plants to radioactive material sites.

Solar-based process heat also can be seen as having the potential to supply moderate- to high-quality heat for a very broad spectrum of consumers in the chemical industry. Restrictions on the siting of solar process heat plants will depend on insolation intensity and product distribution costs rather than on public safety or potential damage to the environment.

1.2. Perspective/The Solar Fuels and Chemicals Program

The rationale for this program is the eventual need for clean, transmittable supplements to (and eventual substitutes for) natural gas, petroleum fuels, and chemical process feedstocks. The use of solar energy to manufacture fuels and chemicals is based on the expectation that solar energy systems will provide a source of high-quality thermal energy that is inexhaustible. The benefits include satisfying a significant part of the growing need for new energy sources as well as providing support for a national economy that has been heavily influenced by energy resource imports and sensitive to fuel price increases and curtailments.

The program goal is the achievement of significant industrial use of solar-thermal process heat for the manufacture of transmittable fuels and essential energy-rich chemicals. Specific objectives include confirmation of the existence of technically and economically feasible manufacturing processes that can use solar energy process heat, initiation of commercial-scale demonstrations, and achievement of significant market penetration. Major objectives for the program include selection of the best candidates from a large number of industrial manufacturing processes, establishment of realistic cost and performance objectives (while considering changes and growth in markets), and defining strategies for process commercialization.

In certain energy and fuel sectors, the conservation opportunities are quite large. Currently, natural gas supplies about 36% of the energy used in the United States while supplying more than 50% of the U.S. industrial heating and feedstock requirement.[7] Natural gas is the preferred feedstock in several large-scale chemical processes and is frequently the fuel of choice for industrial chemical processes not sited near more desirable fuels.[8,9] For these reasons, the use of solar energy process heat in the chemical industry appears to offer especially strong natural gas conservation opportunities.

1.3. The DOE Advanced Solar Technology Programs

The DOE is currently funding several programs dedicated to this alternative application for solar energy. At the Energy Foundation of Texas,[10] an exploratory program to develop chemical cycles for energy storage is in progress. This effort aims to use the decomposition of ammonium bisulfate (NH_4HSO_4) for solar thermal energy storage, according to the reactions —

$$NH_4HSO_4(s) \rightarrow NH_3(g) + H_2O(g) + SO_3(g) \qquad (1)$$

$$NH_3(g) + H_2O(g) + SO_3(g) \rightarrow NH_4HSO_4(s) \qquad (2)$$

Other programs of a chemical nature at the Energy Foundation of Texas include —

- Thermal regenerative SO_2/O_2 fuel cell
- Computer analysis of solar synthetic fuels
- Cyclic catalytic solar energy storage and transmission.

The Aerospace Corporation, Los Angeles, currently does program definition work for solar thermal industrial processes.[11] It also is developing a series of CO_2- and CO-based chemical cycles designed to manufacture energy-intensive chemicals and fuels; its aim is to split carbon dioxide and combine it with hydrogen to produce synthesis gas, methane, or Fisher-Tropsch gasoline. Its program is oriented toward production of chemical feedstocks, rather than fuel. One of the more interesting reaction sequences it is currently studying is a new synthesis for sulfuric acid, according to the reactions —

$$\tfrac{1}{2}CO_2(g) + \tfrac{1}{2}C(s) \rightleftarrows CO(g) \qquad (3)$$

$$CO(g) + SO_2(g) + H_2O(g) \rightleftarrows H_2SO_4(g) + C(s) \qquad (4)$$

The Westinghouse (Corp.) Advanced Energy Systems Division (WAESD) is developing a solar-driven thermochemical water-splitting cycle to produce hydrogen feedstock.[12] WAESD will, purportedly, use product hydrogen in an advanced fuel cell to drive the electrolyzer, which is integral to their process.

Other new projects (at the Solar Energy Research Institute [SERI]) are developing computer simulation and analysis programs for solar energy process heat use.[13] There appears to be considerable development of computer program software to catalog process plant variables. These are to be used for the prediction of possible success of collector/site/chemical process combinations.

At the Naval Research Laboratory, T. A. Chubb and his associates are working on chemical means to convert solar heat to process heat. The Chubb et al. "Solchem" concept has been discussed in the literature; it uses high-temperature decomposition reactions to store energy for round-the-clock plant use. The most recently reported design employs methanation/reforming or $SO_3(g)$ decomposition as the storage-regeneration scheme.[14]

1.4. IGT Solar Fuels and Chemicals Project

This study is the first phase of a project intended to identify candidate processes and products suitable for future exploitation using high-temperature solar energy. This phase is principally analytical, consisting of techno-economic studies, thermodynamic assessments of chemical reactions and processes, and the determination of market potentials for major chemical commodities that use significant amounts of fossil resources today.

The objective of this work is to identify energy-intensive processes that are suitable for the production of chemicals and fuels using solar energy process heat. These selected processes would then form the basis of future research and development. These processes and the resultant products are being evaluated on a technical and economic basis. Of particular importance are the relative costs and energy requirements for the selected solar product versus costs for the product derived from conventional processing.

The assessment methodology used a systems analytical approach to identify processes and products having the greatest potential for solar thermal energy processing. This approach was used to establish the basis for work to be carried out in subsequent phases of development. Specifically, it was the intent of the contract to divide the analysis and process identification into the following three distinct areas:

1. Process Selection
2. Process Evaluation
3. Ranking of Processes.

The constraints used for process selection in relation to the 1977 marketplace were —

- Principal heat use at 400°F (205°C, 480 K) or higher
- Annual energy consumption of 10^{12} Btu (~10^6 GJ) for the total process market
- Peripheral electricity consumption only (rotating equipment, etc.)
- Chemicals and fuel-like chemicals only
- Production of 5×10^5 tons/year for a given process market.

The process operating guidelines being used to assess conventional processes were —

1. Feedstocks used according to current practice
2. Round-the-clock plant operations with fossil-fuel displacement
3. Direct use of feedstock materials as primary coolants if feasible
4. Electricity to be obtained by utility purchases.

After the processes for evaluation were selected, a techno-economic and market assessment for each of the processes and products was conducted. These analyses focused on —

- Projected costs for solar process heat
- Source and temperature heat requirements
- Power or electrical requirements
- Plant capital requirements
- Present bulk selling price of product
- Size of U.S. market for the product
- Current energy inputs in conventional manufacture and type of fuel consumed
- Status of technology for each step
- Costs of solar product compared with the conventional market price.

2. TASK 1 — PROCESS SELECTION

The processes selected should show positive, strong projections for market growth and for future feedstock availability, so that the potential for this future use of solar energy process heat will remain high. The future costs of solar energy process heat will determine when such applications will be economically feasible. The trend in costs for fossil energy and national energy policies will also have a strong influence on the development of an economically attractive solar chemicals process.

Process selection was limited to mature processes that require no development of the process steps themselves. This factor, coupled to the requirement that annual U.S. production be more than 500,000 tons (10^9 lb), limits the freedom of selection. The most likely candidates are in the petrochemicals industry — specifically the plastics or the chemical feedstock industry.

2.1. Organic Chemicals — Thermoplastics

An extended look at national production figures for aromatic and aliphatic organic chemicals is illuminating. A citation in the Chemical Marketing Reporter lists 21 aromatic chemicals, 11 of which had annual production levels of over 500,000 tons in 1976.[15] For 1977, only 10 of the listed chemicals reached production levels of at least 500,000 tons.[16] The 10 aromatic organic chemicals and their annual production in 1977 are shown in Table 1.

Of the 10 listed chemicals, 4 had decreased in production from 1976 to 1977, and most were feedstocks, linked intimately to other products and processes. According to Childs,[17] the thermoplastics industry is very healthy, and despite the downward trend indicated for terephthalic acid[15,16] (polyester fabrics, films, etc.), the industry should grow in a healthy manner.

From this listing, styrene monomer and terephthalic acid (TPA) appear very good candidates — they meet the production (500,000 tons/year) criterion easily. Styrene is made by dehydrogenating ethylbenzene at temperatures in excess of 875 K over SiO_2-Al_2O_3, ZnO, or phosphoric acid catalysts.[10] Terephthalic acid is made by catalytic oxidation of solvent-carried p-xylene at elevated pressure (861 to 1378 kPa) at temperatures of approximately 575 to 675 K.[18] Clearly, these two processes also satisfy the temperature criterion (480 K or higher).

Table 1. AROMATIC ORGANIC CHEMICALS PRODUCTION, 1977

Aromatic Chemical	Production, 1000 tons	Increase, %
Benzene	6530	6.2
Toluene	4489	−6.4
Ethylbenzene	3638	15.8
Styrene Monomer	3412	7.65
Terephthalic Acid	2430	−3.9
p-Xylene	1508	−6.0
Cumene	1320	−1.9
Phenol	1193	8.6
Cyclohexane	1120	2.9
Nylon 6	912	11.4

Of 32 aliphatic chemicals surveyed each year by the Chemical Marketing Reporter, 16 were produced during 1977 in quantities exceeding 500,000 tons.[19] This list is summarized, below, in Table 2.

Table 2. ALIPHATIC ORGANIC CHEMICALS PRODUCTION, 1977

Chemical	Production, 1000 tons
Ethylene	12,245
Propylene	5,317
Methanol	3,161
Formaldehyde	3,044
Vinyl Chloride Monomer	2,784
Ethylene Oxide	2,184
Ethylene Glycol (Mono)	1,701
Butadiene (Rubber Grade)	1,576
Acetic Acid	1,274
Acetone	1,005
Propylene Oxide	955
i-Propanol	931
Adipic Acid	924
Propylene (Crude)	904
Acrylonitrile	815
Vinyl Acetate Monomer	792

2.2. Other Thermoplastics Processes

Childs indicates that polyvinyl chloride (PVC) and copolymers are produced at the highest aggregate rate of all U.S. thermoplastics, and has grown at the rate of 8.3% per year since 1970 — only low-density polyethylene has exceeded PVC in resin sales in the United States.[17] The basic material for PVC polymer or copolymer synthesis is vinyl chloride monomer (VCM), and this material was produced in quantities of approximately 6 billion pounds in 1977.

The principal synthesis step for VCM manufacture is high-pressure pyrolysis of ethylene dichloride at 755 K over a pumice or charcoal catalyst,[20] so that it is clear VCM production meets the temperature and production criteria.

2.3. Other Processes — Methanol

Methanol is produced in the United States in larger amounts than any non-hydrocarbon, pure organic chemical.[21] It can be made by natural or synthetic processes. The bulk of methanol made in the United States is synthetic, made by one or two processes — the ICI or the Lurgi low-pressure process.[22,23] Both syntheses are conducted at temperatures in excess of 575 K. The ICI process operates at 7.60 MPa, and the Lurgi process at 6.59 MPa. Methanol synthesis also meets the production and temperature criteria for process selection.

2.4. Other Processes — Ammonia

Half of the world's capacity of ammonia is produced in Kellogg-designed syntheses.[24] These plants are modifications of the Haber-Bosch process. In such syntheses, temperatures of the order of 675 K and pressures of the order of 13.8-30.0 MPa are used. For the normal use of clean synthesis gas, carbon monoxide is scrubbed at high pressure by absorption in cuproammonium salt solutions. If either liquid hydrogen or liquid nitrogen are feedstocks, the mechanical compression requirement is reduced. Promoted iron catalysts are used to realize ~8-10 percent conversion.[25] A staged intercooler produces some liquid ammonia at the synthesis pressure, while the ammonia-rich gas phase is compressed and recycled to the converter.

An ammonia plant based on natural gas (yielding a less expensive product than does naphtha) requires 35,000 SCF of natural gas per ton of ammonia, 44% of which is burned for heat and nitrogen recovery. The cost of hydrogen is significant in ammonia production,[26] and the uncertainty in natural gas supply is having a profound effect on ammonia ventures.[27] The current price of anhydrous ammonia is $120/ton[27] or $.06/lb, nearly twice the price of a decade ago. Because of the relative long-term availability of coal, a considerable effort is being made to develop cost-effective ammonia synthesis processes that use coal as a feedstock.[8,9]

2.5. Selection of Candidates

The guidelines for process selection included a condition that the aggregate industry energy use must exceed 10^6 GJ ($\sim10^{12}$ Btu). Coupled with the production requirements (500,000 tons or more), this indicates a heat requirement of 2.11 GJ/ton of material (2.32 GJ/metric ton, 0.504 Gcal/ton, 0.555 Gcal/metric ton, 2×10^6 Btu/ton, or 2.2×10^6 Btu/metric ton).

Pinto and Rogerson,[28] analyzing energy conservation in methanol and ammonia plants, report the energy requirement for ammonia is about 26.2 million Btu/ton and for methanol is about 29.4 million Btu/ton. The ICI low-pressure synthesis process[22] claims it requires ~2.7 GJ/metric ton. The Lurgi process is listed at ~2.1 GJ/metric ton.[23] Styrene (Monsanto) is listed[29] as requiring 2780 Btu/lb of monomer (5.56×10^6 Btu/ton). Terephthalic acid (by the Toray Industries, Inc., process) requires 4.68×10^6 Btu of process heat/ton TPA.[30] Vinyl chloride monomer requires[31] 3.1×10^6 Btu process heat/ton monomer.

These five processes and at least one additional feedstock process — cyclohexane — meet all the process selection and assessment guidelines. Of the six strong candidates, cyclohexane was not investigated in great detail, but the final selection was made from the other five. The U.S. capacity for cyclohexane[32] is far above demand, though demand is expected to grow at an aggregate rate of ~7% per year. Demand for cyclohexane is generated in the plastic fiber processing business, which is expected to grow aggressively.[17]

The final choice of processes was made to represent a compromise with end product use and process complexity. From the pool of acceptable processes, it was decided that we do the Task 2 assessment and evaluation work on the following processes:

- Synthetic Methanol Production — a fuel or chemical with very large growth potential.
- Styrene Monomer Production — a very large process industry that is linked to two of the largest feedstock sources — ethylene and ethylbenzene — in the United States.
- Vinyl Chloride Monomer Production — VCM is the feedstock for the second largest, single-thermosetting resin market, using ethylene and a large fraction of the U.S. chlorine production.
- Terephthalic Acid Production — the principal intermediate in the rapidly growing synthetic film and fiber market, TPA is synthesized from p-xylene or toluene and methanol feedstocks.

3. TASK 2 — PROCESS EVALUATION

For the multiple effort of Task 2, a simple network chart of projected work was constructed. The subtask assignments yielded, using the program constraints, a comparison between the conventional processes and the same processes integrated to use solar energy process heat. The network task chart is shown in Figure 1, where ovals represent regular milestones or decision points and small circles, the subtasks in their appropriate order.

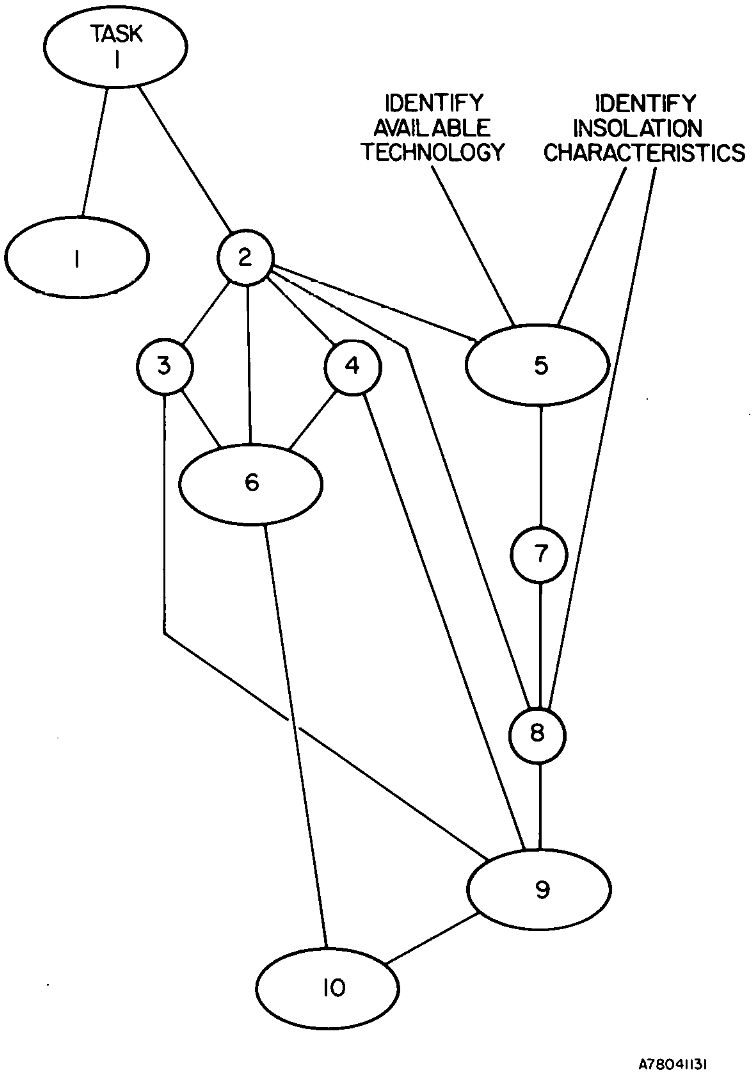
In this task, the Institute of Gas Technology (IGT) has analyzed four selected processes to provide a techno-economic analysis and market characterization for each. The intent was to provide a long-term description of each process and predict the long-term ability of solar energy process heat to displace conventional thermal energy sources in each of the processes.

The relative uncertainty with regard to the economics of using solar energy process heat is large because of the following factors:

- Cost of conventional process energy in the 1985-90 period is difficult to predict.
- Technologies for making the different chemicals may change, particularly as the processes are revised to be more energy efficient.
- Types, costs, and performance of solar collectors should improve.
- Design, performance, and cost of high-temperature interfaces between the solar collectors and the chemical plants have not yet been studied thoroughly enough to provide reliable technical and economic estimates.

In short, it would be hazardous to make definitive comments on solar energy process heat substitution for the period around 1990 based on the technology and economics information available in 1978. A preferable course uses today's information to determine on an aggregate basis whether solar energy process heat is close to being economically feasible. The next step would be to use sensitivity analyses to identify areas and set goals that could be reached through intensified technical and economic research and development.

IGT's techno-economic and market analysis, therefore, has been directed toward the aggregate basis of feasibility determination for each of the four chemicals. The principal criteria for long-term success of the processes and products were the U.S. market demand for the products, the availability



NETWORK KEY

1. MARKET RESEARCH — PRODUCTS
2. CHARACTERIZE CHEMICAL PRODUCTS
3. MARKET RESEARCH — FEEDSTOCKS
4. MARKET RESEARCH — ENERGY SOURCES
5. CHOOSE SOLAR TECHNOLOGIES
6. DEVELOP ECONOMICS OF CONVENTIONAL PROCESSES
7. CHARACTERIZE SOLAR TECHNOLOGIES
8. INTEGRATE SOLAR TECHNOLOGY WITH CHEMICAL PROCESSES
9. DEVELOP ECONOMICS FOR INTEGRATED PROCESSES
10. COMPARE ECONOMICS FOR CONVENTIONAL AND INTEGRATED PROCESSES

Figure 1. NETWORK PLANNING DIAGRAM — TASK 2

of process feedstocks, and any safety or health implications that might change the economics greatly or cause the products to be taken from the market. To determine the ability of using solar energy process heat to displace conventional fuels, IGT addressed the economics of substituting direct solar thermal energy for conventional fossil energy and the ability of a direct solar thermal energy system to meet a process thermal energy requirement.

The assumptions for process evaluation can be divided into three categories — concerning chemical processes, economics, and direct solar thermal energy. Chemical process assumptions are described on a general basis here, with more specific information in a later section. The economics and solar energy assumptions are described in following sections.

The chemical processes were approached on an as-is basis. It was assumed that any solar energy process heat system would be attached to, rather than integrated with, an existing process technology. The solar energy process heat would be provided through specific interfaces to heat exchangers associated with process hardware. The thermal energy requirements were divided into steam and direct heat. For the purpose of this study, it was assumed that different requirements in one of these would be met through progressively lower temperature cascades. This assumption is reasonable in view of the level of precision used in the economics. No attempt was made to design or engineer the necessary interfaces; instead, the costs of these interfaces were included in the cost estimates for the heat transfer hardware (not heat exchangers). These estimates are described in another section.

3.1. Collectors and System Performance

Collectors with the capability of producing high-temperature process heat at reasonable efficiencies are required for fuels and chemicals production using solar energy. Flat plate and nonfocusing concentrators are unsuitable for this application.[33,34] Single-axis parabolic trough collectors are suitable for the production of relatively low-temperature process steam,[35,36] with an upper temperature limitation of about 645 K. Above 645 K, when parabolic trough efficiencies drop off, central receivers must be considered. Central receivers utilize a large field of two axis tracking mirrors (heliostats) focusing on a centrally positioned, tower-mounted receiver to produce high solar flux and high temperatures.[37,38]

Temperature limitations with a central receiver are size dependent. Large systems can produce temperatures far in excess of 1100 K. In the capacities required for solar chemicals production (less than 100 megawatts thermal), the upper limitation of central receiver temperature is assumed to be about 925 K. Of course, central receivers can be used for process steam requirements as an alternative to parabolic troughs. Such a decision requires comparison of system performance in terms of solar energy supplied to the process, and detailed examination of total installed costs of parabolic troughs, including piping versus the installed costs of central receivers. Central receivers do not require the extensive pipe field associated with parabolic trough collectors. For temperatures above 925 K, a two-axis tracking parabolic dish is most appropriate.[14] Parabolic dish collectors require extensive high-temperature piping systems.

For the purposes of this study and with the process selection guidelines used (Section 1.4), it was necessary to assume a standard insolation characteristic, in order to calculate energy (fossil fuel) displacement. A Phoenix, Arizona, location was arbitrarily chosen as a standard for insolation intensity, and this in turn related to previously evaluated parameters for solar collectors.

The efficiency of parabolic trough collectors in a polar-mount orientation (axis of collector tilted up from horizontal at an angle equal to local latitude) has been established for Albuquerque and was assumed to have comparable efficiency in a Phoenix location. In this case, efficiency is defined as the percentage of normal direct radiation (radiation available to a collector that perfectly tracks the sun) which becomes useful heat at the collector outlet. Parabolic trough efficiencies vary linearly from 57% at a 425 K outlet temperature to 46% at a 620 K outlet temperature. Such performance is available from state-of-the-art collectors of this type.

Central receivers do not show an extended range of efficiency over their outlet temperature range. Data from several sources on annual efficiency of central receivers are in substantial agreement. Furthermore, central receiver efficiencies are not very dependent upon the latitude of their location or the pattern of available insolation. (Parabolic trough efficiency is more latitude and insolation pattern dependent.) A central receiver efficiency of 46.6% was used in this analysis.

Because of their high concentration ratios and small receivers, heat losses from parabolic dish collectors are very low, resulting in high efficiencies. Because they track the sun perfectly in any location and heat loss is minimal, efficiency shows very little regional dependence. An efficiency of 70% was used in the analysis for parabolic dish collectors.

The capital and operating and maintenance (O&M) costs for the solar collectors/receivers are predicted to be considerably less expensive (in 1978 dollars) in 1990 than in 1985. Table 3 shows the cost assumptions for capital and O&M costs used for the economics analysis.

Table 3. SOLAR COLLECTOR/RECEIVER COST ASSUMPTIONS (1978 Dollars)[39]

	1985		1990		2000	
Type	Capital, $/ft^2	O&M, $/ft^2-yr	Capital, $/ft^2	O&M, $/ft^2-yr	Capital, $/ft^2	O&M, $/ft^2-yr
Parabolic Trough*	22.10	0.50	15.00	0.34	14.00	0.32
Central Receiver**	19.50	0.44	9.00	0.20	7.00	0.16
Parabolic Dish**	35.50	1.00	13.00	1.00	13.00	1.00

* Polar-mount single-axis tracking.

** Double-axis tracking.

To bring the thermal energy from the collector/receiver system to the point of use, a transfer and interface system is needed. This element in the system will eventually become the subject of considerable research for high-temperature solar energy applications.[38,40] For the purposes of this study, IGT has had to estimate the cost of these systems relative to the type of collector/receiver technology used. Both the parabolic trough and the parabolic dish will require extensive pipe fields to bring the thermal energy from the collector fields to the process plant. The parabolic dish, operating at high temperatures, requires extensive and special equipment and materials, whereas the central receiver system needs a much smaller transfer system between the receiver tower and the process plant. For the purposes of this research, then, it was estimated that the transfer system would add the following percentages to the capital and O&M costs[39]:

Collector/Receiver Type	Additive for Transfer and Interface, %
Parabolic Trough	50
Central Receiver	10
Parabolic Dish	100

To prevent shading of adjacent collectors, the collectors must be appropriately spaced. This constraint leads to the necessity for a substantial amount of land for siting the collector fields and is an important element in the economics of solar chemicals production. The amount of land needed by the collector field is measured by the ground cover ratio (GCR), which is the fraction of land that is represented by collector areas. (For example, a GCR of 0.4 means one can display 4 square feet of collector area for 10 square feet of land.) Parabolic troughs operate at a GCR of 0.4; central receivers, 0.35; and parabolic dishes, 0.35.

The amount of insolation reaching a collector at a Phoenix location was determined by data from a Sandia publication giving up-to-date average direct insolation data.

3.1.1. Economics Assumptions

The economics assumptions used are based on the economics methodology developed by the Jet Propulsion Laboratory for the Energy Research and Development Administration/Electric Power Research Institute study done in 1976.[41] This methodology was described in an April 1977 report, SAN/1132-2/3, by McDonnell Douglas Astronautics Co.[42] As part of this study, this methodology was modified and put into model form by the staff at Oak Ridge National Laboratory.[43] IGT added to this model a sensitivity analysis capability for certain variables, such as cost of capital, conventional energy costs, and direct solar thermal energy capital costs.

The model analyzes the economics of substitution using a current dollars, normalized-cost basis. The current dollar basis means that all costs are adjusted by escalation factors that include both inflation and price increase in excess of inflation. The normalized-cost basis means that the costs are escalated for each year over the life of the system and then normalized to an annual cost using a capital recovery factor. Because a constant escalation rate is assumed for the costs, a single formula is used in the model, which does the annual escalation and normalization in a single step. These costs are then used to determine a rate of return and a return on investment. The normalized rate of return is the annual savings of the direct solar thermal energy costs over the normalized conventional energy costs as a percentage of the capital investment. The normalized return on investment is the normalized rate of return that has been adjusted to reflect the life of the direct solar thermal energy system; the longer the life of the direct solar thermal energy system, the less the difference between the normalized rate of return and the normalized return on investment. The principal economic assumptions used in the model are shown in Table 4.

Table 4. ECONOMIC ASSUMPTIONS

Escalators	%/yr
General	6.0
Conventional Energy	10.0
Capital Costs	8.0
Land Costs	10.0
Operating and Maintenance Costs	6.0
Timing Factors	
System Life, yr	15
Depreciation Period, yr	15
Price Year	1978
Base Year	1990
Start of Operations Year	1990
Income Factors	
Tax Rate, % of income	50
Investment Tax Credit, % of capital cost	10
Other Taxes, % of capital and land cost	1.2
Insurance, % of capital and land cost	1.2
Cost of Capital, % of capital and land cost	8

3.1.2. Process Characterization — Economics

The objective of this study is to determine the economics of supplying process heat using solar energy. A constraint is that the solar energy should be used as available, rather than providing some means to store the solar heat. The strategy in sizing the system is to provide sufficient collector area to satisfy the process requirements at conditions of peak insolation (i.e., 1 $\text{kW}_{\text{th}}/\text{m}^2$ or 317 Btu/hr-ft^2) and at all other times to use the available insolation supplemented by conventional fuel. Collector area is thus —

$$\text{Collector Area, ft}^2 = \frac{\text{Process Energy Required, Btu/hr}}{(\text{Fractional Collector Efficiency})(317\ \text{Btu/hr-ft}^2\ \text{Insolation})}$$

The energy supplied to the process is then —

$$\text{Daily Total Solar Process Heat, Btu/day} = (\text{Collector Area, ft}^2)(\text{Fractional Collector Efficiency}) \times (\text{Average Annual Direct Normal Insolation, Btu/ft}^2\text{-day})$$

The percentage of process heat supplied by solar energy is a function only of the average insolation availability and the peak insolation. For Phoenix, the maximum obtainable fraction of the process heat required is 31.4%.[39]

The characteristics of the four chemical processes in which process steam and high-temperature process heat are to be supplied, in part, by solar energy are summarized in Table 5. Note that process steam is not required for methanol production. Steam produced in the process of methanol synthesis is used elsewhere in that process plant.

Several assumptions were made to establish process energy requirements. For process steam, the inlet to the steam boiler was assumed to be saturated water at the desired steam temperature. All heat addition was heat of vaporization. Outlet steam quality was assumed to be saturated steam. For both process steam and high-temperature process heat, a collector outlet temperature approximately 28 K above the process steam or process heat temperature was assumed, to provide an adequate driving force for heat exchange. A reduction in this temperature difference would benefit overall energy efficiency, but would demand larger, more expensive heat exchangers.

Table 5. SOLAR SYSTEM REQUIREMENTS AND ASSUMPTIONS[39] (Phoenix Site, 1978 Dollars)

	Methanol	Vinyl Chloride Monomer	Styrene Monomer	Terephthalic Acid
Steam Requirements				
Quantity, lb/lb of product	--	2.1	1.4	10
Pressure, kPa (psia)	--	1034(150)	517(75)	2757(400)
Temperature, K	--	455	426	504
Energy Required, 10^6 Btu/yr	--	1.32	0.71	2.82
Collector/Receiver Requirements (Alternative 1)				
System		Parabolic Trough	Parabolic Trough	Parabolic Trough
Collector Area, 10^6 ft^2	--	0.93	0.44	1.73
Land Area, acres	--	53.6	25.2	99.2
Energy Displaced, 10^{12} Btu/yr	--	0.42	0.20	0.72
Capital Cost in 1990, \$$10^6$	--	21.0	9.89	39.0
O&M Cost in 1990, \$$10^6$	--	0.48	0.22	0.88
Land Cost in 1990, \$1000/acre	--	12.	12.	12.
Collector/Receiver Requirements (Alternative 2)				
System		Central Receiver	Central Receiver	Central Receiver
Collector Area, 10^6 ft^2	--	1.02	0.50	1.76
Land Area, acres	--	67.1	32.7	115.3
Energy Displaced, 10^{12} Btu/yr	--	0.42	0.20	0.72
Capital Cost in 1990, \$$10^6$	--	10.14	4.95	17.42
O&M Cost in 1990, \$$10^6$	--	0.23	0.11	0.39
Land Cost in 1990, \$1000/acre	--	12.	12.	12.
Direct Heat Requirements				
Temperature, K	725	765	925	625
Energy Required, 10^{12} Btu/yr	2.63	0.79	0.98	1.35
Collector/Receiver	Central Receiver	Central Receiver	Parabolic Dish	Central Receiver
Collector Area, 10^6	2.03	0.61	0.51	1.04
Land Area, acres	133.1	40.0	33.2	68.4
Energy Displaced, 10^{12} Btu/yr	0.83	0.25	0.31	0.42
Capital Cost in 1990, \$$10^6$	20.1	6.04	13.16	10.30
O&M Cost in 1990, \$$10^6$	0.45	0.13	1.01	0.23
Land Cost in 1990, \$1000/acre	12.	12.	12.	12.

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3.2. The Processes Assessed

3.2.1. Methanol

Methanol production is the most complex of the four processes selected. It can be made from either a natural or a synthetic feedstock,[44] and is commonly used both as a fuel and a chemical.[45] Extensive research to determine whether methanol can be effectively used as a gasoline additive or substitute is being done.[46] If methanol has promise as a fuel additive, the technology for producing it will have to change from being dominated by natural gas feedstocks to domination by coal feedstocks. For the purpose of this study, however, IGT has assumed that the current technology for synthetic methanol — steam-reforming natural gas plus catalytic conversion — will be the principal technology through 1990.

3.2.1.1. Methanol Market

In 1977, synthetic methanol use in the United States was divided into three major markets: chemical feedstocks, 75%; fuels, 15%; and exports, 10%. As a major chemical feedstock, the major use was in the production of formaldehyde, approximately 45% of total use.[47] Other significant chemical feedstock uses were in the production of dimethylterephthalate, methyl halides, methyl methacrylate, acetic acid, and other methyl-based solvents. The fuel uses for methanol were as gasoline additives or substitutes.[46]

The market for formaldehyde is dominated by the housing industry because of its use in plywood bonding resins. Because of this, the demand for methanol for formaldehyde production is strongly seasonal. Environmental concerns over fumes from burning formaldehyde resins in structural fires may complicate the long-term picture for this methanol end use.

Use of methanol as a fuel could have a significant effect on its market. For methanol to become a competitive gasoline additive or substitute, the economics of making methanol as opposed to gasoline will have to change markedly. This change would result both from the introduction of new methanol manufacturing technology, based on coal, peat, and biomass gasification, and from increases in the costs of crude oil. Currently, however, cost estimates for synthetic gasoline from coal are less than those for methanol from coal.[48]

One result would be a less expensive methanol, relative to other chemicals, for which new chemical uses might be found. This likelihood is presently the subject of considerable speculation.

The production of methanol has varied considerably over the last 10 years. This is principally because of fluctuations in the housing market. U.S. production for 1977 has been estimated between 6.3 and 6.45 billion pounds. This is up slightly from the 1976 value, 6.25 billion pounds, and up significantly from the 1975 level, 5.2 billion pounds. During the 10-year period 1967-77, the average annual growth in methanol production was 8.8%, while during the recent 5-year period, 1972-77, the average annual growth was only 1.3%. Growth is expected to be relatively slow through 1980 with production growing to approximately 6.6 billion pounds.[22,44] During the following decade, the production of methanol is expected to grow to between 10 and 13 billion pounds per year. Prices in 1977 were in the 42¢-47¢/gallon range, rising from about 35¢/gallon in 1974.

3.2.1.2. Methanol Production Processes

There are several types of technology that can be used for methanol production, both natural and synthetic. In the principal natural commercial process, methanol is obtained through the destructive distillation of wood,[44] although it is also possible to design a synthesis for methanol manufacture using wood waste products.[49] The three established synthetic process technologies require the production of synthesis gas (carbon monoxide plus hydrogen) and the catalytic conversion of carbon dioxide-spiked synthesis gas into methanol. These synthesis gas production processes are 1) steam-reforming of natural gas; 2) partial oxidation of fuel oil; and 3) gasification of coal, peat, or biomass.

In 1977, there were 12 major methanol plants in the United States, ranging in size from 140,000 pounds/day to 3.9 million pounds/day, with an average plant size of 150 million gallons/year.[47] All these units use synthesis gas made by steam-reforming natural gas as the primary feedstock. The 1977 capacity was estimated at 9.3 billion pounds. By 1990, that capacity is expected to double. About 15 SCF of natural gas (1000 Btu/SCF) is required for each pound of methanol produced. Although eventual natural gas shortages are predicted, regulatory and allocation action will determine what parts of the economy experience them. Availability of natural gas as a methanol feedstock, therefore, cannot be predicted at this time. For the longer term, worldwide methanol markets appear headed for significant change. The predicted end of inexpensive natural gas in the United States will hold down domestic capacity expansion, and new projects based on other feeds such as high-grade coal, peat, or biomass will probably emerge. Projects in other areas of the world where natural gas is still inexpensive and plentiful will certainly increase. For example, Celanese Corporation is a partner in a project that plans to build a 2000 ton/day methanol plant in Saudi Arabia.[47] Borden Incorporated of Louisiana is also involved in Saudi Arabia methanol plans.

Within the methanol industry, there are several variations of the steam-reforming process for synthesis gas production. Considering a representative process, approximately 2570 Btu are required for every pound of methanol produced, yielding a reaction temperature in the range 723 to 728 K. Natural gas is the preferred fuel for providing this heat, and no steam input is required. The catalytic conversion of the synthesis gas is exothermic and yields a small quantity of steam for export to other parts of the plant. Depending on national energy perspectives and priorities, natural gas for feedstock may be more available than natural gas for fuel.

3.2.1.3. Methanol Solar Energy Process Heat System

For a 500,000 ton/year methanol synthesis plant, IGT has chosen a central receiver system to provide the reforming heat requirement. A process heat system has been scaled to meet the maximum energy needs during the periods of maximum sunlight in the Phoenix area. The details are shown in Table 5. The economics of substitution of a solar energy process heat system, using the assumptions detailed in Sections 3.1, 3.1.1, and 3.1.2, are summarized in Table 6.

3.2.2. Styrene Monomer Production

Styrene monomer is one of the more important plastic resin feedstocks. Its polymers are evident in both the consumer and industrial marketplaces. Its feedstocks, ethylene and benzene, are available in relative abundance in the United States. Some long-term pressure may be put on benzene supplies as the United States becomes more dependent on foreign and Alaskan crude oils,

Table 6. SUBSTITUTION ECONOMICS — METHANOL
(1990 Dollars)

Heat Requirements

Direct Solar Thermal System	Central receiver
Cost, $\$/10^6$ Btu	
Solar	6.80
Conventional*	9.90
Rate of Return,* %	5
Return on Investment,* %	—3.5

* Based on normalized costs.

which have a smaller fraction of the aromatic base from which benzene is derived. This is not expected to make a significant short- or mid-term impact on U.S. supplies for styrene. Another potential problem, which makes the benzene situation unclear, is its carcinogenic characteristics. Increased handling costs, brought on by stringent EPA regulations, may affect the competitiveness of styrene and other derivative chemicals.

3.2.2.1. Styrene Monomer Marketplace

Styrene is used almost exclusively for making polymers. Polystyrene and expanded polystyrene require between 50% and 55% of production. Polystyrene is a well-known insulating and packing material. Other major uses are for acrylonitrile-butadiene-styrene (ABS) plastics, styrene-acrylonitrile (SAN) resins, and styrene-butadiene-rubber (SBR) resins. Styrene is also mixed with polyester resins to increase flexibility and decrease hardness. Approximately 10% to 15% of styrene production is exported. The major areas for growth of styrene production are expected to be expanded polystyrene, ABS, and polyesters.

The production of styrene in 1977 has been estimated to be ~3.4 million tons (between 6.7 and 6.9 billion pounds). This is an increase from about 6.3 billion pounds in 1976, and 5 billion pounds in 1975. During the 10-year period 1967-77, the growth in average annual production was about 11%, which, during the most recent 5-year period, averaged only 3%. The recent decrease in growth rate is partially the result of the increased fuel and feedstock costs resulting from the rapid rise in domestic and imported crude oil prices.

Production is expected to grow to 7.5 billion pounds by 1980, and to over 9 billion pounds by 1985. After 1985, styrene production is expected to continue to grow at a 5% to 6% average annual rate. Prices in 1977 ranged from $.18 to $.21/pound. This is a substantial increase from the pre-oil embargo prices of about $.06/pound in 1972 to $.09/pound in early 1974.

3.2.2.2. Styrene Monomer Production Processes

The production of styrene is generally a two-step process. The first step is the Friedel-Krafts alkylation of benzene to form ethylbenzene. The second step is the dehydrogenation of ethylbenzene to styrene. At least five processes are available: Monsanto Lummus, Alkar (UOP Inc.), Mobil-Badger Union Carbide-Kosden-Badger, and CDF Chimie. As of 1976, the U.S. capacity was approximately 8 billion pounds. This capacity is expected to exceed 4.5 million tons (9 billion pounds) by the end of 1978.

The feedstocks for styrene are ethylene and benzene. Both are common chemicals for which there are major production industries. Ethylene is produced in larger amounts than any other petrochemical-based material made in the United States.[50] The benzene supply situation is expected to be very strong over the short to middle term.[51] Feedstock requirements for styrene make up approximately 50% of overall benzene demand. In 1977, more than 5.5 million tons were produced, up from 5.25 and 3.75 million tons in 1976 and 1975, respectively. Demand for benzene is expected to reach 6.5 to 6.8 million tons in 1980, and 8.8 to 9.0 million tons in 1985. Benzene capacity is estimated to achieve 9.0 to 9.3 million tons by 1980, and about 9.5 million tons by 1985. This appears to indicate that some market tightening might be expected in the 1985-90 interval.

Raw materials for benzene production may become limited because increased U.S. crude oil consumption will depend on the paraffinic Middle Eastern and Alaskan crude oils. These crude oils are low in the aromatic components essential to benzene production. Because of the mutagenic and carcinogenic properties of benzene, its commerce will probably require new and more expensive handling procedures and equipment. This would be reflected in increases in its total costs, affecting the competitiveness of various derivatives and lessening its demand. This may also make shortages less likely to occur.

For this analysis, IGT chose the Monsanto-Lummus styrene process as representative of current technology.[29] In this process, approximately 2780 Btu's are needed for every pound of styrene produced. The benzene alkylation step requires a reaction temperature in the range 560 to 575 K. The ethylbenzene dehydrogenation step requires a reaction temperature from 870 to 980 K. Steam, at 517 kPa (75 psi, 430 K), is required in quantities of 1.4 pounds per pound of styrene. The preferred fuel for the alkylation and dehydrogenation processes is natural gas. The steam system can be fired by natural gas or any miscellaneous hydrocarbons.

3.2.2.3. Styrene Solar Energy Process Heat System

Assuming a process plant size of 200 tons/day, the solar energy process heat system was scaled to meet the maximum energy needs during periods of maximum insolation in Phoenix. To supply the high temperatures for the direct heat, a parabolic dish collector system was needed. To supply the heat for steam generation, both a parabolic trough and a central receiver system were considered.

Using the assumptions described in Sections 3.1, 3.1.1, and 3.1.2 in the calculation model previously discussed, the economics for solar energy process heat substitution in styrene production are shown in Table 7 below.

Table 7. SUBSTITUTION ECONOMICS — STYRENE[39]
(1990 Dollars)

Heat Requirements		Steam	
	Direct Heat	Alternative No. 1	Alternative No. 2
System	Parabolic dish	Parabolic trough	Central receiver
Cost, ¢/10^6 Btu			
Solar	14.40	12.70	6.80
Conventional*	9.90	8.70	8.70
Rate of Return,* %	−5	−3	3
Return on Investment,* %	ND	ND	−8

* Based on normalized costs.

ND = Not determined, fails to cover cost of capital.

3.2.3. Vinyl Chloride Monomer

Vinyl chloride monomer (VCM) is the feedstock for the second-largest aggregate thermoplastic resin business in the United States.[17] Homopolymers of VCM (polyvinyl chloride) and copolymers play an important role in the everyday lives of most Americans. The feedstocks for VCM production, ethylene and chlorine, are available in relative abundance. In recent years, there appeared to be an obstacle that could have had a significant effect on the long-term prominence of VCM in the petrochemical industry. Because of the carcinogenic character of VCM, Occupational Safety and Health Administration (OSHA) regulations prohibiting contact with it were issued, resulting in somewhat increased handling costs for both VCM and the polymer resins. OSHA regulations have also caused some limitations in the end use for PVC materials; however, the industry has overcome the residual VCM problem in a remarkably short time. New reactors of increased size (larger than 35,000 gallons in the United States) have resulted in economies of scale, and shortened polymerization cycles have increased both productivity and profitability.[17]

3.2.3.1. Vinyl Chloride Monomer Marketplace

VCM is primarily used in making homo- and copolymer resins such as PVC. These polymer resins, in turn, are made into a very wide assortment of plastic products. The single largest use is in PVC pipe, with approximately one-third of the total PVC resin production being used for this product. Other significant uses are films, coatings, and moldings. Approximately 10% of production is exported. The industry is aggressively looking for new markets to maintain the growth rates it has had in the past. Recent development of foamed PVC pipes for low-pressure use has opened up new markets. Another area with some potential for growth is the siding market for residential and commercial buildings.

The production of VCM in 1977 is estimated at about 3 million tons (6 billion pounds), up from about 5.7 billion pounds in 1976. Production in 1975 was only 4.2 billion pounds. During the decade 1967-77, the average annual production growth rate was 14%, while during the latter 5 years of that period, the average annual growth was only about 3%. Production is expected to grow to 7 billion pounds by 1980, and 9 billion pounds by 1985.

Projected growth after 1985 is uncertain, although Childs[17] has projected a very aggressive growth pattern to the year 2000 (from 3.8 million metric tons in 1980 to 11 million metric tons in 2000).

Prices for VCM in 1977 ranged from 14¢ to 15¢ per pound. Rising feedstock and manufacturing costs should push VCM prices up at a rate in excess of inflation. Prices in 1970 were about 4¢ per pound.

3.2.3.2. Vinyl Chloride Monomer Production Processes

The production of VCM usually consists of the direct oxyhydrogenation or oxychlorination of ethylene to produce ethylene dichloride, followed by pyrolysis of the ethylene dichloride to form VCM and hydrochloric acid. At least five companies, Stauffer Chemical, Monsanto, Rhone-Poulenc, PPG, and B.F. Goodrich, sell process technology for VCM production. As of 1977, U.S. capacity was about 7 billion pounds, with additions coming on-stream in 1978 estimated at 1.5 billion pounds. The principal feedstocks for VCM are ethylene and chlorine, though acetylene has been used as an ethylene substitute. Both ethylene and chlorine are common feedstocks for which there are major production industries. In 1977, 24 to 25 billion pounds of ethylene and 20 to 22 billion pounds of chlorine were produced. VCM demand required about 10% of ethylene and 8.5% of chlorine production in 1977. Production capacity for chlorine is expected to grow to 32 billion pounds by 1980, and capacity for ethylene is expected to grow to 45 billion pounds by 1985. As a result, no VCM feedstock shortages are expected, unless shortages occur in ethylene feedstocks such as naphtha, methane, gas oils, or liquid petroleum gases. The likelihood of shortages occurring in ethylene feedstocks is uncertain. Although there are ambiguous indications of both shortage and abundance, price increases in excess of inflation are a certainty nonetheless.

From the number of available processes for VCM, IGT has chosen the Stauffer process, believing it to be representative of current technology.[28] In this process, approximately 1550 Btu's are needed as direct heat for every pound of VCM produced. The larger portion of this heat is for the pyrolysis of ethylene dichloride in the range 760 to 770 K. Steam at 1035 kPa (150 psi, 455 K) is also required in quantities of 2.1 pounds per pound of VCM. The preferred fuel for the cracking furnace has been natural gas. Steam generation is usually fueled by miscellaneous waste hydrocarbons and either natural gas, fuel oil, or distillate oil. For the purpose of this study, fuel oil is assumed.

3.2.3.3. VCM Solar Energy Process Heat System

The plant size was assumed to be commercial size at 1000 tons/day. To supply the direct heat to the plant, a central receiver system was chosen. To supply the heat for steam generation, both a parabolic trough and a central receiver system were considered. Each solar energy process heat system was scaled to meet the maximum energy needs during periods of maximum sunlight in the Phoenix area. Using assumptions already described in an economics model described earlier, the economics of solar energy process heat substitution in vinyl chloride monomer production yield the results shown in Table 8.

Table 8. SUBSTITUTION ECONOMICS — VINYL CHLORIDE MONOMER[39]
(1990 Dollars)

Heat Requirements		Steam	
	Direct Heat	Alternative No. 1	Alternative No. 2
Solar Energy Process Heat System	Central receiver	Parabolic trough	Central receiver
Cost, $\$/10^6$ Btu			
Solar	6.80	13.20	6.80
Conventional*	9.90	8.70	8.70
Rate of Return,* %	5	—3	3
Return on Investment,* %	—3	ND	—8

* Based on normalized costs.

ND = Not determined, fails to cover cost of capital.

3.2.4. Terephthalic Acid

Terephthalic acid (TPA) and its ester, dimethyl terephthalate (DMT), are major feedstocks for the production of polyester fibers, films, and molded items such as soft drink bottles and other liquid containers. The fiber market, the largest consumer of TPA and DMT, is tied closely to the apparel market and is, therefore, subject to substantial swings in demand as different styles and fabrics gain or lose popularity. TPA and DMT are so closely intertwined that their production figures are not commonly separated. The primary feedstock for

TPA is paraxylene, although there are two processes that utilize toluene as a feedstock for this synthesis.[52] DMT is made by the methanol-based methylesterification of crude TPA.

3.2.4.1. TPA Marketplace

TPA is used principally for polyester fibers, films, and molded items, with additional applications in herbicides, adhesives, inks, coatings, paints, and animal feeds. The marketplace statistics do not differentiate between TPA and DMT, as they are used almost interchangeably. The two principal polyester fiber markets are for apparel fibers, such as dacron, and for tire cord. The apparel fiber market is subject to strong fluctuations as styles and fabrics become more or less fashionable. Currently, interest in the natural look, comfort, and competitive costs of cotton have reduced the TPA/DMT growth in demand. New uses for TPA/DMT derivatives — polybutylene terephthalate (PBT) resins and polyethylene terephthalate (PET) resins — have to some extent buffered lags in demand. PBT resins appear headed for rapid growth in the near future.[53] The producers of this material see a potential role for their products in a variety of engineering resin applications, with one large potential growth market in automobiles, where PBT resins are bidding for a larger part of the market.[54] PET resins appear to have taken over a large part of the PVC soft drink bottle market. PET is now the almost uncontested plastic of choice for replacing glass in large-size soft drink bottles, and forecasts call for growth of 15% per year or more.[55] Specific details of TPA and DMT demand by end use were not available in the literature surveyed. In 1977, approximately 3% of production was exported, as compared with almost 10% in earlier years.

TPA capacity is realized in a relatively few very large plants: Amoco Chemicals will add 18% to U.S. capacity when its newest plant comes on-stream in South Carolina at the end of 1978.[53] This huge new unit, with a 1 billion pound/year capacity, is expected to increase the overcapacity problem that already exists. Amoco also has a 2 billion pound/year unit in Decatur, Alabama. It is expected that pressure from revitalized cotton markets will be lessened because of Federal regulations concerning inhalation of cotton dust. Over the long term, it is anticipated that population pressures will require the use of more acreage for food production, driving up the price of cotton.

The production of TPA and DMT in 1977 was about 5 billion pounds. According to capacity and capacity utilization figures, production of resins for TPA end uses was about 1.8 billion pounds and production for DMT-based end uses was about 2.8 billion pounds, totaling approximately 4.6 billion pounds. The major products from TPA synthesis, fiber grade TPA, medium grade TPA, and DMT, have markedly different transfer costs. Crude TPA has a transfer price per pound of approximately 18.6¢, whereas fiber grade DMT costs about 28.8¢/pound. Purified, or fiber grade TPA sells at about 28.1¢/pound, so that interest in a medium TPA process using less expensive feedstocks is very high.

During the 10-year period 1967-77, average annual growth was 36%, whereas during the recent 5-year period the growth rate averaged only 14%. These are both in contrast to the 1976-7 and 1975-6 growth rates of about 1% and 10%, respectively. Production of TPA is expected to grow annually at a 5% to 7% rate through 1985, gradually decreasing to the 2% and 4% level between 1985 and 1995.

3.2.4.2. Terephthalic Acid Production Processes

TPA synthesis usually consists of the oxidation of paraxylene to technical grade TPA, followed by purification to fiber grade product. The purification of crude TPA is an expensive process requiring some catalytic conversion, which adds almost 10¢/pound to the transfer price of this material.[52] The oxidation reaction can be either liquid-phase oxidation with nitric acid or catalytic air oxidation using a solvent medium such as methylethylketone (MEK) or acetic acid and catalysts such as the salts of cobalt, manganese, or other heavy metals. At least four processes have been available: Mobil, UOP-Chemische, Amoco, and Toray. Of these, Amoco Chemicals Corporation dominates the technology and production of TPA in the United States. (In two plants, Amoco possesses approximately 40% of the U.S. capacity for terephthalates.) Because of its commanding position, Amoco has been reluctant to release process information. Capacity for TPA and DMT is estimated to exceed 7.5 billion pounds in 1978. Of this, about 3 billion pounds is for TPA and 4.5 is for DMT. Capacity utilization in 1978 is expected to be approximately 70% for TPA and under 80% for DMT.

The principal feedstock for TPA is p-xylene. If a liquid-phase reaction is used, nitric acid is required. If the catalytic air-oxidation synthesis is used, a solvent such as acetic acid or MEK is needed. Paraxylene, with o- and m-xylene, are primarily used as gasoline octane improvers and high-boiling paint solvents. The xylenes are found principally as a distillate product from catalytic reforming. In 1977, approximately 6 billion pounds of xylenes of all grades were produced, from which approximately 3 billion pounds of p-xylene were separated, principally by a differential crystallization process. As with benzene, p-xylene production depends on the availability of reformates from crude oil refining. Unlike benzene, however, p-xylene does not seem to require special handling. Over the long term, as crude oil requirements are increasingly met by paraffin-based crude oils, p-xylene availability may be reduced. Of the three other chemicals needed, nitric acid and acetic acid are very common, widely available chemicals. MEK is widely used as a solvent and has many substitutes. Shortages of MEK are unlikely; however if they do occur, acetic acid could be used with some minor process changes.[52,53]

Due to the unavailability of TPA process information from Amoco, IGT used the Mobil Corp. process as representative of the technology. In this process, approximately 5500 Btu's are required for every pound of TPA produced. The oxidation takes place in a reaction at 575 to 675 K. Steam at 2700 kPa (400 psi, 500 K) is needed in quantities of about 10 pounds per pound of product. The preferred fuel for the oxidation reactor is natural gas. The steam system can be fired with miscellaneous hydrocarbons.

3.2.4.3. TPA Solar Energy Process Heat System

A TPA synthesis plant with the capacity of about 500 tons/day was chosen for this analysis. To supply direct heat to the plant, a central receiver system was chosen. To supply heat for steam generation, both a parabolic trough and a central receiver system were considered. Each solar energy process heat system was scaled to meet the maximum energy requirements during periods of maximum insolation in the Phoenix region. Using previously described assumptions and models, the economics for solar energy process heat substitution in TPA synthesis are shown below in Table 9.

Table 9. SUBSTITUTION ECONOMICS — TEREPHTHALIC ACID[39]
(1990 Dollars)

Heat Requirements	Direct Heat	Steam Alternative No. 1	Steam Alternative No. 2
Solar Energy Process Heat System	Central receiver	Parabolic trough	Central receiver
Cost, \$/10^6 Btu			
Solar	6.80	20.30	6.80
Conventional*	9.90	8.70	8.70
Rate of Return,* %	5	—7	3
Return on Investment,* %	—3	ND	—8

* Based on normalized costs.

ND = Not determined, fails to cover cost of capital.

3.3. Conceptual Solar Process Plants/Sketch

In addition to four conventional chemical processes selected for analysis, two processes of a futuristic nature were also investigated. The investigation of these conceptual processes was to be at a lower level than for the conventional processes, and two such futuristic, conceptual process schemes are sketched below.

3.3.1. Styrene/Methanol Integrated Plan

Styrene is manufactured by making ethylbenzene from benzene and ethane or ethylene by typical Friedel-Krafts processing. The ethylbenzene is then dehydrogenated over silica alumina catalysts at high temperature (875 to 975 K). The hydrogen, currently burned as excess boiler fuel, could be converted to feedstock for producing synthesis gas for either methanol or ammonia production. It is recommended, therefore, to study a solar-driven styrene and methanol production facility, to ultimately provide techno-economic assessment of such a plant.

Heat demands for such a plant are primarily for steam, which could easily be the solar heat exchange medium. The reactor steam requirement for the styrene production system could be used directly as the solar coolant, in the same manner in which steam is generated for thermal electrical generating cycles.[2,3] Steam requirements for the various fractionation systems could be supplied by a primary steam coolant. (There is also the possibility of direct heat exchange with the distillation feedstock.) Although a portion of the process requires a very high temperature heat (above 780 K), large amounts of low- and medium-pressure steam are required. A lower temperature solar collection system in addition to a high-temperature solar system appears to be the logical arrangement. Electricity demands are a small portion of the total energy requirement and could be met with any type of conventional generation cycle, or through utility purchasing.

Feedstock requirements for a styrene/methanol plant are the same as for a styrene plant, with the exception that feedstock carbon dioxide is required for methanol synthesis. For such a plant, in addition to regular styrene feedstocks per pound of styrene produced, 0.13 pound of carbon dioxide is required for make up the necessary syngas feedstock for the methanol subplant. The aggregate plant requires fuel amounting to 3037 Btu per combined pound of product. The electricity requirements per combined pound of product are approximately 0.05 kWh. A combined plant that produced 1.2 million pounds per day of styrene would also produce 120,000 pounds per day of methanol. The projected 1990 demand for combined products, styrene and methanol, is 30 billion pounds.

3.3.2. Very High Temperature Solar Thermochemical Hydrogen-Ammonia Facility

Hydrogen is one of the most widely used chemical feedstocks. It is produced by a wide variety of processes — naphtha and natural gas reforming, and electrolysis — and used in widely varying chemical and commodity manufacturing techniques. Research is currently being conducted to develop a hydrogen-from-coal process. In 1970, more than half of the hydrogen produced was used in ammonia manufacture (56%).[50] Hydrogen so produced, with the exception of high-purity electrolyzer hydrogen, was manufactured from fossil fuel resources. With the possibility of broadening the capabilities for hydrogen production using thermochemical cycles, solar-driven processes for hydrogen feedstock production should be investigated and developed.

This is a long-term commercialization possibility, but one that promises to use solar energy to supply a vitally needed feedstock for an essential, fast-growing industry — ammonia production. A high-efficiency thermochemical cycle derived and tested in the thermochemical hydrogen program at IGT, sponsored by the American Gas Association, is summarized below:

$$Cd(s) + 2H_2O(\ell) \rightarrow Cd(OH)_2(s) + H_2(g)^{*} \qquad 300\ K \qquad (5)$$

$$Cd(OH)_2(s) \rightarrow CdO(s) + H_2O(g) \qquad 600\ K \qquad (6)$$

$$\underline{CdO(s) \rightarrow Cd(s) + \tfrac{1}{2}O_2(g)} \qquad 1500\ K \qquad (7)$$

$$H_2O(\ell) \rightarrow H_2(g) + \tfrac{1}{2}O_2(g) \qquad (8)$$

At the listed temperatures, this cycle has a calculated maximum attainable energy efficiency of about 65% (based on the high heating value of hydrogen), and it has been operated stepwise with reagent grade chemicals at the listed temperatures. The compounds in this cycle are relatively noncorrosive, and this process can produce hydrogen at controlled pressures according to the operating conditions of the electrochemical step (successfully tested at potentials of 0.1 through 0.3 volt). Separations and gas cleanup are required to be very efficient for this cycle: Cadmium metal is an extremely toxic substance. Approximately 75% of the input energy for this cycle is heat between 1300 and 1475 K, and the cycle is not now being pursued in the IGT program because it cannot be interfaced with a high-temperature nuclear reactor (HTR). This cycle is protected by U.S. Patent No. 3,907,980, September 23, 1975, which is assigned to the American Gas Association. It is an ideal high-efficiency cycle with which to explore solar energy process heat interfacing.

For this thermochemical cycle, assumed to be operated at 50% energy efficiency and based on a 300-MWth solar facility, a plant capacity of 930,000 pounds per year of ammonia would result. Such a plant would require 1.59 pounds of water and 0.82 pound of nitrogen as feedstock for each pound of ammonia produced. The energy requirements for this production amount to 21,505 Btu's per pound of ammonia.

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[*] Electrochemical step requiring, theoretically, 0.02 volt. Satisfactory laboratory operation has been achieved with 0.2 volt.

Nonfossil-based synthesis gas drastically changes the character of ammonia plants, eliminating the required primary reformer and methanator subsystems, and also the customary CO_2 scrubbing and venting systems.

Promoted iron catalysts are used to realize about 8% to 10% conversion. A staged intercooler produces some liquid ammonia at the synthesis pressure, while the ammonia-rich gas phases are recompressed and recycled to the converter. An ammonia plant based on natural gas required approximately 35,000 SCF of natural gas per ton of ammonia, 44% of which is burned as fuel. Such an integrated thermochemical hydrogen/ammonia plant would possess a significantly simplified ammonia subsystem as compared to the ammonia synthesis system currently required for fossil-based synthesis gas feedstocks.

3.4. Cost Predictions for Major Feedstocks

In parallel with the market and process analysis of the four chemical synthesis processes, we calculated the approximate future costs of the major feedstocks for the selected processes. These feedstocks were —

Process	Feedstock
Methanol Synthesis	Natural gas
Vinyl Chloride Monomer	Ethylene Chlorine
Styrene Monomer	Ethylene Benzene
Terephthalic Acid	Paraxylene

Because there are extensive, and somewhat conflicting, opinions and because of the limited scope of this project, the costs for natural gas were not predicted.[21,57] (See page 48 for sensitivity analysis.) The other feedstocks were analyzed in some detail using available information. The intent is to develop approximations to the future market prices for these feedstocks. The methodology and the results of a first-order market forecast for all the feedstocks used in the processes being studied are summarized as follows.

- Data from existing forecasts as presented in Predicasts, a publication that surveys periodicals for forecast information based on SIC codes, were noted for each feedstock. Only 1977 data and the early supplements of 1978 were used. Data gathered included a) capacity, b) demand, and c) price, as available for each feedstock.

- The feedstock demand and capacity data were analyzed as a relationship of quantity versus time. Price data was abstracted from these constructions. One analysis was done for each feedstock.
- As a first-order approximation, a line was fitted to the tabulated data using the least-squares method.

The results of these analyses are presented in the two following tables. Table 10 is a summary of solar chemical feedstock predictions, and includes the important data on capacity, demand, and predicted wholesale price. Table 11 is a feedstock price summary based on Predicasts for 1985 and, in some cases, extrapolations of data from Predicasts. The price predictions in Table 11 are remarkably linear for the scale of this analysis. The linearity may be suspect because of the normal uncertainty in chemical and feedstock markets. Analysis of the predicted future costs for ethylene and chlorine resulted in the best linearization of the data, whereas the benzene and p-xylene predictions are somewhat more uncertain.

Table 10. SUMMARY OF SOLAR CHEMICAL FEEDSTOCK FORECAST
(First-Order Approximation — All Data From Respective Graphs Except Price Information)*

	1976			1978	1985			1990		
Feedstock	Capacity, 10^9 lb	Demand, 10^9 lb	Wholesale Price, \$/lb	Whol Price, \$/lb	Capacity, 10^9 lb	Demand, 10^9 lb	Whol Price, \$/lb	Capacity, 10^9 lb	Demand, 10^9 lb	Whol Price, \$/lb
Benzene Total	12.7	11.6	0.116	0.115	17.0	16.0	0.20	19.0	18.0	*
Used in Ethyl Benzene and Styrene	--	5.6	--	--	--	9.8	--	--	12.0	--
Chlorine	25.0	20.0	0.060	0.07	40.0	37.0	*	49.0	47.0	*
Ethylene	29.7	23.0	0.12	0.13	47.0	44.0	0.25	56.0	55.0	*
p-Xylene	3.7	2.9	0.17	0.175	7.5	6.3	*	9.5	8.0	*

* Indicates insufficient data.

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Table 11. FEEDSTOCK PRICE SUMMARY

	Prices*				Quality of Analysis	
Feedstock	1976	1978	1985	1990	Correlation Coeff	Std Error of Est
Benzene, \$/gal	0.80-0.87	0.85	1.50	2.20	0.9845	0.139
Chlorine, \$/ton	1.20	1.40	2.40	3.50	0.9922	0.162
Ethylene, \$/lb	0.12	0.13	0.25	0.30	0.9924	0.0134
p-Xylene, \$/lb	0.16	0.17	0.30	0.45	0.9852	0.0285

* Growth at 8%/year in current dollars, except for chlorine (1978) and p-xylene (1976 and 1978).

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4. TASK 3 — PROCESS RANKING

4.1. Ranking Criteria

Ranking a group of chemical processes, all of which fit the assessment guidelines and represent major users of process energy, is difficult and arbitrary. We have attempted to use a technique for ranking that addresses specific characteristics. These are 1) process complexity, 2) feedstock availability, 3) feedstock futures, 4) demand projections, and 5) conservation opportunities. The ranking process specifically excluded the economics developed in Section 3.

4.1.1. Process Complexity

Process complexity and conservation opportunities appear linked. What is meant here is the ability to increase plant efficiency. If a process is reasonably simple, then work and heat recovery schemes are more straightforward.[58-60] In this respect methanol is the least favored, and styrene or VCM the most favored. In terms of complexity, the processes are ranked 1) styrene production, 2) VCM production, 3) TPA synthesis, and 4) methanol production.

4.1.2. Feedstock Availability

Styrene monomer synthesis and VCM production use ethylene, chlorine, and benzene as feedstocks. Ethylene is the most important, most widely manufactured feedstock in the chemicals industry,[50] with chlorine also manufactured on an exceptionally large scale. Chlorine, moreover, is frequently manufactured with very little dependence on fossil fuel resources. Benzene is a petrochemicals product and is less certain of strong future availability.[51] Methanol feedstock currently is synthesis gas from natural gas, and p-xylene has the same availability problems that benzene does. For these reasons, the processes are ranked 1) VCM synthesis, 2) styrene production, 3) TPA production, and 4) methanol synthesis.

4.1.3. Feedstock Futures

Because of increased importation of paraffin-based crude oils, the primary source of aromatic-based feedstocks is less certain than is the aliphatic feedstock market. Cyclohexane could become a higher price source of benzene and xylenes, but that is probably far off. As in Section 4.2, ethylene and chlorine appear to have the greatest future availability, so that from the standpoint of feedstock futures the ranking is 1) VCM, 2) styrene, 3) TPA, and 4) methanol.

4.1.4. Demand Projections

On the basis of projects for demand of chemicals, the ranking should be 1) methanol, 2) TPA, 3) VCM, and 4) styrene. The projections for demand (to 1990) are shown in Table 12.

Table 12. MARKETS (United States) FOR SOLAR CHEMICALS

Solar Chemicals	1977 Capacity, 10^9 lb	1977 Demand, 10^9 lb	1980 Demand,* 10^9 lb	1985 Demand,* 10^9 lb	1990 Demand,* 10^9 lb
Methanol	8.7	6.4	8.4	13.3	18.7
Styrene Monomer	9.2	6.6	7.6	9.4	12.0
Vinyl Chloride Monomer	7.3	5.6	6.8	10.0	14.3
Terephthalic Acid	13.6	10.2	12.2	15.9	20.3

* Estimated from process literature: References 15-31.

4.1.5. Energy Conservation Potential

This category was used quite straightforwardly — in terms of energy saved (or displaced) for each pound of product synthesized. This criterion may be inferior to a normalized energy term based on time of operation. (The criterion used assumes identical rates of production.) However, to date, all assessments have been based on weight-specific figures. From Table 13 we can rank the four processes as energy consumers in the order 1) terephthalic acid, 2) styrene or methanol, and 3) VCM.

Table 13. FUEL AND ENERGY REQUIREMENTS FOR SOLAR CHEMICALS

Solar Chemical	Fuel, Btu/lb	Electricity, kWh/lb (Btu/lb)	Total Btu/lb
Terephthalic Acid	5500	0.11 (1126)	6626
Styrene	2780	0.04 (410)	3190
Methanol	2569	0.05 (512)	3081
Vinyl Chloride	1545	0.09 (921)	2466

4.2. The Processes Ranked

Left out of this analysis is a reasonable consideration of product distribution costs. This is a more complex issue than is immediately visible, because all these chemicals may be considered to be feedstocks for secondary processing. Methanol, of course, has considerable value as a fuel, as does styrene monomer. Neither TPA nor VCM have the obvious fuel values possessed by methanol and styrene monomer, but only methanol is characteristically stable enough to be easily transmitted without the addition of stabilizers and inhibitors.

For this reason, the ranking was done without a distribution criterion, and it was done by a simple linear weighting of the five ranking categories, using four points for a rank of 1, three points for a rank of 2, etc. By weighing the ranking categories equally, the aggregate scoring can be summarized simply, as in Table 14.

Table 14. RANKING CATEGORY FACTORS

Category	Process			
	Methanol	Styrene	TPA	VCM
Process Complexity	1	4	2	3
Feedstock Availability	1	3	2	4
Feedstock Futures	1	3	2	4
Demand Projections	4	1	3	2
Energy Conserved	2	3	4	3
Totals	9	14	13	16

Vinyl chloride monomer and styrene production appear to be the better pair of processes, with TPA and methanol synthesis less to be recommended. In any case, if the ranking criteria were weighed differently, taking into account distribution factors or weighing the categories more heavily according to conservation potential or feedstock availability, the rankings could vary slightly. What is required is the development of a broad-based ranking procedure to include specific rate of production (Btu/lb-hr) data for projected processing plants and an appropriate category weighing system for comparing category importance.

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APPENDIX. VCM Key Variable Sensitivity Analysis

In parallel with the economic analysis of solar energy process heat substitution for the VCM process, we performed a first-order sensitivity analysis on certain key economics variables. This analysis focused on the economics of substituting a central receiver, direct solar thermal energy (DSTE) system for conventional fuels in a steam generation facility. The analysis examined the normalized costs of conventional fuels and of solar energy process heat substitution on the rate of return and return on investment. The variables analyzed were —

- Cost of Capital
- System Life
- 1978 Conventional Energy Cost
- Escalator for Conventional Energy Prices
- DSTE System Capital Cost
- Escalator for Capital Costs
- Starting Year.

The results were not surprising; however, they do describe the effects of changes in these assumptions.

Cost of Capital

The cost of capital is the minimum average after-tax return on investment assumed to be required by any company on funds invested in a solar energy process heat (SEPH) system. The study used an 8% cost of capital. In this analysis a range from 6% to 20% was used. Table A-1 shows the results: These indicate that from the point of view of return on investment, the substitution of SEPH for conventional fuels will not break even unless the cost of capital is below 6%.

System Life

The system life is the economic life that the SEPH systems would be expected to have from the point of view of a chemical company (~15 years). In this analysis, a range from 10 to 30 years was used. Table A-2 presents the results; the implications are that because of the anticipated constant escalation of conventional fuels, the chances that the SEPH system will be economically feasible increase substantially as the economic life of the system

Table A-1. SENSITIVITY ANALYSIS — KEY VARIABLE: COST OF CAPITAL

Cost of Capital, %	Energy Cost (1990 Dollars), $\$/10^6$ Btu		Annual Rate of Return, %	Annual Return on Investment, %
	DSTE	Conventional		
6	5.29	9.00	6.0	—1.2
8	6.84	8.72	3.0	—8.4
10	7.72	8.44	1.2	—16.7
12	8.65	8.19	—0.8	ND
14	9.61	7.95	—2.7	ND
16	10.62	7.73	—4.7	ND
18	11.65	7.53	—6.7	ND
20	12.71	7.34	—8.8	ND

ND = Not determined, below —12.0%.

Table A-2. SENSITIVITY ANALYSIS — KEY VARIABLE: SYSTEM LIFE

System Life, yr	Energy Cost (1990 Dollars), $\$/10^6$ Btu		Annual Rate of Return, %	Annual Return on Investment, %
	DSTE	Conventional		
10	7.80	7.07	—1.2	ND
15	6.84	8.71	3.1	—8.4
20	6.46	10.63	6.8	3.1
25	6.33	12.84	10.6	9.5
30	6.30	15.35	14.8	14.5

ND = Not determined, below —12.0%.

increases. Because the system life is a subjective choice, often dependent on a company's planning habits, it can be changed either by giving the company a credible reason for assuming a longer useful life (to exceed the company's normal expectations of life) or by having the SEPH owned separately and operated as a utility.

1978 Conventional Energy Cost

This is the delivered 1978 cost of conventional fuels for the steam system in terms of cost per million Btu. The study used an estimate of \$3.00/million Btu, assuming that a portion of these fuels would be supplied from waste process hydrocarbons and be priced accordingly. These costs are adjusted by various factors to determine what they would be on a normalized basis during the life of the project. In this analysis, summarized in Table A-3, a range from \$1.50 to \$7.50/million Btu was used. The implication of this analysis is that the economic feasibility of SEPH increases substantially if the 1978 cost of conventional energy is underestimated. Return on investment exceeds zero, and substitution becomes financially feasible when the 1978 conventional energy cost exceeds \$3.75/million Btu (delivered).

Table A-3. SENSITIVITY ANALYSIS — KEY VARIABLE: 1978 CONVENTIONAL ENERGY COST

Conventional Energy Cost (1978 Dollars), $\$/10^6$ Btu	Energy Cost (1990 Dollars), $\$/10^6$ Btu		Annual Rate of Return, %	Annual Return on Investment, %
	DSTE	Conventional		
1.50	6.84	4.36	—4.0	ND
3.00	6.84	8.71	3.1	8.4
4.50	6.84	13.07	10.2	5.8
6.00	6.84	17.43	17.3	15.2
7.50	6.84	21.78	24.4	23.3

ND = Not determined, below —12.0%.

Escalator for Conventional Energy Prices

The energy price escalator is used to adjust the 1978 conventional energy price to account for inflation and other factors. The study uses a 10% per annum escalator. In this analysis, a range from 8% to 12% is used, with the resulting calculations summarized in Table A-4. The results of this analysis show that the escalation would have to exceed 11% per annum for the SEPH system to approach financial feasibility (ROI > 0). The likelihood of that escalation exceeding 11% is remote unless the general rate of inflation is subject to major increases in the future or there is a major dislocation in international fuel trade. Were either to occur, the capital cost escalator would probably increase, offsetting the impact of the fuel price increases.

Table A-4. SENSITIVITY ANALYSIS —
KEY VARIABLE: ESCALATOR FOR CONVENTIONAL ENERGY PRICES

Escalator, %/yr	Energy Cost (1990 Dollars), $/10^6 Btu		Annual Rate of Return, %	Annual Return on Investment, %
	DSTE	Conventional		
8	6.84	6.62	−0.4	ND
9	6.84	7.31	0.8	−19.6
10	6.84	8.71	3.1	−8.4
11	6.84	10.39	5.8	−1.7
12	6.84	12.38	9.0	4.1

ND = Not determined, below −12.0%.

SEPH System Capital Cost

The capital cost of the system is the total amount of capital funds required to build and to operate the SEPH system. For the central receiver system used in the VCM case, an investment of $1,014,000 (1978 dollars) was required.[39] In this analysis, the capital cost was varied from $1,622,400 to $811,200 — a range of +60% to −20%. The range was chosen because of the uncertainty of the energy distribution, energy transfer and interface costs, and because the collector costs were those estimated for the 1990 time frame. The results are shown in Table A-5.

Table A-5. SENSITIVITY ANALYSIS —
KEY VARIABLE: DSTE SYSTEM CAPITAL COST

DSTE System Capital Cost, $	Energy Cost (1990 Dollars), $/10^6 Btu		Annual Rate of Return, %	Annual Return on Investment, %
	DSTE	Conventional		
1,622,400	10.47	8.71	−1.9	ND
1,419,600	9.26	8.71	−0.7	ND
1,216,800	8.05	8.71	0.9	−18.3
1,014,000	6.84	8.71	3.1	−8.4
811,200	5.63	8.71	6.1	−1.0

ND = Not determined, below −12.0%.

Escalator for Capital Costs

The capital cost escalator is the rate at which capital costs are expected to increase between the price year (1978) and the year operations are expected to start (1990). This escalator should have an important influence on the cost of SEPH and its subsequent financial feasibility. In the study, the escalator was assumed to be 8%. In this analysis, it was varied from 7% to 11%, with the results listed in Table A-6. The effect on the return on investment indicates that strong increases (over 7%) in capital equipment costs between 1978 and the system starting year would have a strong negative influence on the financial feasibility of the SEPH systems.

Table A-6. SENSITIVITY ANALYSIS — KEY VARIABLE: ESCALATOR FOR CAPITAL COSTS

Escalator, %	Energy Cost (1990 Dollars), $\$/10^6$ Btu		Annual Rate of Return, %	Annual Return on Investment, %
	DSTE	Conventional		
7	6.28	8.71	4.4	—4.8
8	6.84	8.71	3.1	—8.4
9	7.45	8.71	1.9	—12.9
10	8.14	8.71	0.8	—19.6
11	8.89	8.71	—0.2	ND

ND = Not determined, below —12.0%.

Starting Year

The starting year is the year which the SEPH system goes into operation. In the study, 1990 was chosen as the starting year. In these calculations, it is also the base year for present value and cost calculations; that is, all return and cost calculations are based on 1990 dollars. The results of this analysis are shown in Table A-7. The implication of these results is that the financial feasibility of SEPH will increase as the starting year is made more distant. However, this relationship is primarily due to relative values of the escalators for the conventional fuel and capital costs.

Table A-7. SENSITIVITY ANALYSIS — KEY VARIABLE: STARTING YEAR

Starting Year	Energy Cost (1990 Dollars), $\$/10^6$ Btu		Annual Rate of Return, %	Annual Return on Investment, %
	DSTE	Conventional		
1990	6.84	8.71	3.1	—8.4
1995	10.05	14.03	4.4	—4.8
2000	14.81	22.60	5.8	—1.8
2005	21.87	36.40	7.2	1.1
2010	32.35	58.62	8.8	3.7

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