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# Open-Loop Transport of Solar Energy Using Natural-Gas Networks

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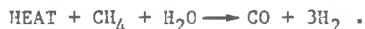
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## OPEN-LOOP TRANSPORT OF SOLAR ENERGY USING NATURAL-GAS NETWORKS

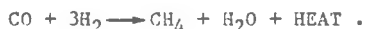
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**ABSTRACT**

This paper examines the feasibility of transporting solar energy via a thermochemical-energy process and natural-gas networks. The high-temperature solar energy from a central receiver is converted to chemical-bond energy by steam reforming of natural gas to synthesis gas:



The synthesis gas is dehydrated and transported in the natural-gas pipeline. At the user end, the synthesis gas is methanated to produce synthetic natural gas (SNG) and to release the stored energy:



The recovered heat is used in an industrial park to produce 944 GJ/h (895 MBtu/h) of 4.14 MPa (600 psig), 400°C (750°F) superheated steam which is piped to 10 equal-sized user facilities clustered in the industrial park. The SNG is distributed to natural gas users.

Two cases were examined--a new pipeline and an existing pipeline. The new pipeline must be 76 cm (30 in.) in diameter to carry the same fuel-gas energy using synthesis gas as is carried in a 51-cm (20-in.) natural gas line. The synthesis gas system is more efficient than molten-draw-salt energy transport for transport distances greater than about 50 km (30 miles). The solar system with transport is cost-effective compared with residual-oil or natural-gas-fired boilers. In the second case, an existing 76-cm line, pipeline operations both at capacity and at half-capacity with natural gas transmission were considered. For an existing line operating near capacity, there is a negative incentive to carry solar energy via synthesis gas, because the total energy flow decreases significantly relative to natural gas. If the existing line is operating at half-capacity or less prior to conversion, there is then an incentive to transport solar energy via synthesis gas. This case, then,

becomes more cost-effective than a new pipeline.

**1. INTRODUCTION**

An important requirement in the development of large-scale solar industrial process heat applications is the ability to transport large quantities of high-temperature thermal energy cost-effectively. Transport is necessary because there is often insufficient land for large collector fields near industrial users or because solar energy must be carried from a geographical region having high insolation to one having low insolation. Cost-effectiveness implies that minimal energy is lost in the transport system, that a reasonable investment in the system has been made, and that the system entails reasonably low operating and maintenance costs.

Possible techniques for transporting solar energy include the following:

- Thermochemical energy transport: conversion of high-temperature thermal energy to near-ambient-temperature chemical bond energy, using a pipeline or a mechanical means to transport the chemicals. Energy is recovered by performing the reverse chemical reaction to recover the heat and to regenerate the original chemicals.
- Thermal energy transport: pipeline transport of a high-temperature working fluid first heated in solar collectors. For this energy transport system, pipelines must be well insulated. The energy is recovered by cooling the working fluid.
- Electrical energy transport: the solar thermal energy is used to produce electricity which is transmitted over wires to the industrial user. Thermal energy is recovered via electric resistance or electric inductance heating.

There are two types of transport systems--open-loop and closed-loop. Open-loop trans-

port occurs from source to sink, no energy is returned and there is no transporting medium from sink to source. Electrical energy transport is open-loop; thermochemical energy transport can be open-loop if there is a use for the chemicals at the sink. Closed-loop transport involves returning the transport medium from sink to source for reuse. Thermochemical energy transport can be closed-loop, and thermal energy transport is generally closed-loop--i.e., the medium serves as an energy carrier and is not consumed to produce energy.

This paper addresses a very specific form of open-loop energy transport--natural gas transmission pipelines that convey solar thermal energy over significant distances.

**2. SYSTEM DEFINITION**

Many natural gas pipelines exist within the United States for transmitting gas from fields to users. Pipelines vary in size, material, age, length, and operating pressure. Natural gas varies in chemical composition, but it is generally in excess of 95 mol % methane with other lower alkanes, such as ethane and propane, present, as well as some inert gases such as CO<sub>2</sub> and N<sub>2</sub>. Pipeline operation and the quality of the natural gas are closely regulated to ensure both the safety and consistent performance of the product.

Natural gas may be reformed with steam to produce synthesis gas, a mixture of hydrogen and carbon monoxide. The major reaction is



The reaction is reversible as a function of both temperature and pressure. The reaction, in both directions, has relatively fast kinetics and generally is heat-transfer-limited; i.e., the reaction rate is determined by the rate of heat transfer. Reaction in both directions requires a catalyst to occur; e.g., the reforming reaction typically uses a NiO catalyst on an Al<sub>2</sub>O<sub>3</sub> support. Both reaction directions are well understood and are practiced commercially.

The solar energy transport scheme involves using a solar source to provide the heat input for reaction (1). The resulting synthesis gas is dried and then transported in the natural gas pipeline to the user. Synthesis gas is withdrawn from the pipeline and methanated to produce heat and a wet synthetic natural gas. The SNG is then dried and distributed to natural gas users.

Figure 1 presents a schematic of the open-loop transport system, and Fig. 2 shows an approximate balance of mass flows for the system, based on the use of 3 moles of steam per mole of methane in the reformer to prevent deposition of carbon on the catalyst. The overall efficiency (based on useful heat out relative to heat in) is 71%.

**3. FEASIBILITY STUDY**

Determining feasibility entails considering both technical and economic factors. Technical feasibility is attained when a suf-

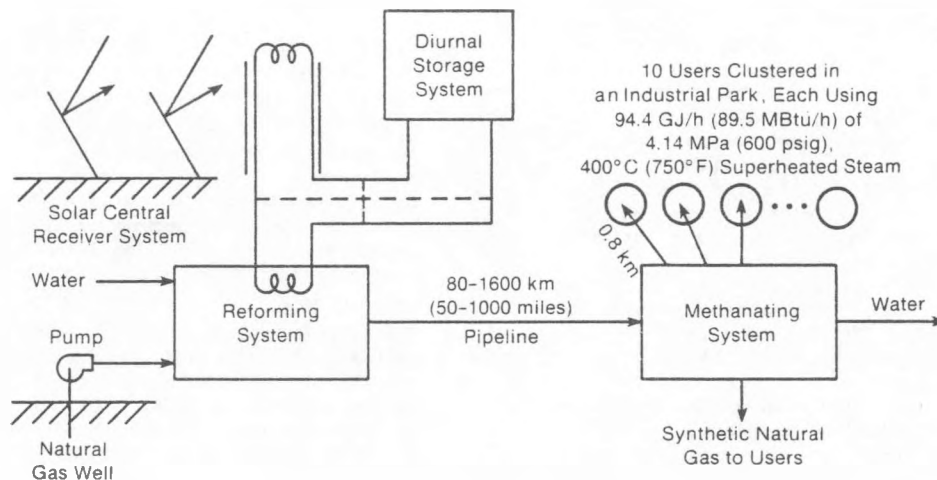


Fig. 1. Open-Loop Transport of Solar Energy Using Natural Gas Systems

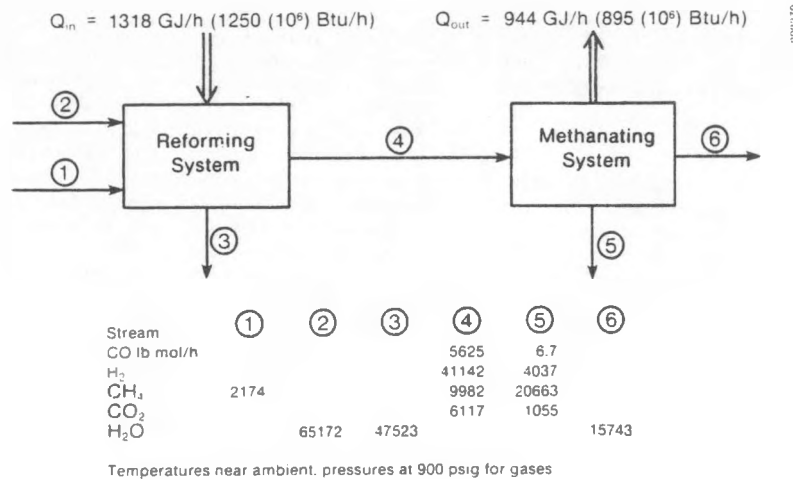


Fig. 2. Flowsheet for Open-Loop Thermochemical Energy Transport Using Natural Gas Networks

efficient scientific and engineering basis exists to design the process and equipment with a reasonable degree of confidence that the result will work as anticipated. Economic feasibility is indicated when cost is equal to or lower than value. Cost is estimated for the process under consideration and value is determined by estimating the cost of the best alternative.

Technically, transmitting solar energy via open-loop natural gas pipelines appears to be quite feasible. Both steam reforming of natural gas (and other petroleum fractions) and methanation of synthesis gas are reasonably well understood and are practiced in industry. The major unknowns involve appropriate construction materials for the process vessels and the performance of the catalytic reactors. Some additional development work is required, however, before open-loop energy transmission systems can be built. Nevertheless, there do not appear to be any insurmountable or extremely difficult impediments to implementation of the process.

System economics are estimated by sizing process equipment based on the process requirements, estimating equipment costs, estimating total installed investment and process operating and maintenance costs, and using an economic model to calculate delivered energy costs. The details of this procedure are found in Refs. 1 and 2. Estimating details for this system in closed-loop applications are found in Ref. 3.

The appropriate economic figure of merit is the levelized revenue requirement. This is the average price that the industrial user would have to pay for delivered energy over

the life of the plant, expressed in 1981 dollars. The appropriate formula for calculating the levelized revenue requirement is

$$LRR = \frac{(PI \times LAFCR) + [(O\&M) \times LF] + Fuel}{8760 \times LACF \times Capacity}$$

where

- LRR = levelized annual revenue requirement, in \$/GJ
- PI = installed plant investment, in \$
- LAFCR = levelized annual fixed charge rate, which accounts for and averages all annual charges associated with investment, in \$/\$ per year
- (O&M) = annual operating and maintenance costs, excluding cost of input solar or fossil heat, in \$/year
- LF = levelizing factor, which averages expenses over the life of the plant (dimensionless)
- Fuel = levelized annual cost of input solar or fossil heat, in \$/year
- 8760 = number of hours in year
- LACF = annual fractional average of the total energy that would be produced were the plant operated continuously at nameplate capacity (dimensionless)
- Capacity = plant nameplate capacity rating, in GJ/h.

This model is discussed in Ref. 4. System life was designated to be 30 years (1990-2020). LACF was 0.65, LAFCR was 0.14, and LF was 1.386. Fuel (solar input to the reformer) was \$6.64/GJ (\$7/MBtu) and system

efficiency was calculated as 0.712 (heat out/heat in). Capacity was 944 GJ/h (895 MBtu/h). These numbers are consistent with Ref. 3.

There are two rather simple alternative methods of obtaining the same result for the energy requirements of the industrial park: (1) local fossil-fuel-fired boilers and (2) a solar system with closed-loop thermal energy transfer using molten draw salt. Details about these alternatives, including fuel escalation scenarios, can be found in Ref. 3.

#### 4. RESULTS

- Case 1-- New investment in gas pipelines to carry a fixed amount of fuel value for either natural gas or synthesis gas.
- Case 2-- Existing fixed-size pipeline system carrying less fuel gas energy for the synthesis gas application.

Table 1 summarizes the results for Case 1, where the fuel gas energy delivered to natural gas consumers is constant. A 51-cm (20-in.) pipeline is required for simple natural gas transport, and a 76-cm (30-in.) pipeline is required for the synthesis gas pipeline. The investment and operating costs associated with solar energy delivery are the costs associated with the reformer and methanator plants and incremental costs associated with the larger pipeline system. The cost of the input solar energy is assumed to be constant at \$6.64/GJ (\$7/MBtu), a figure which is believed to be attainable with a large, central receiver solar system (Ref. 5). Table 1 also lists the delivered solar energy costs for various transport distances. These are plotted on Fig. 3. Figure 3 also shows the cost of energy produced by local fossil-fuel-fired boilers at the industrial park and by a central receiver solar system with closed-loop thermal energy transport using molten draw salt (60:40 NaNO<sub>3</sub>:KNO<sub>3</sub>).

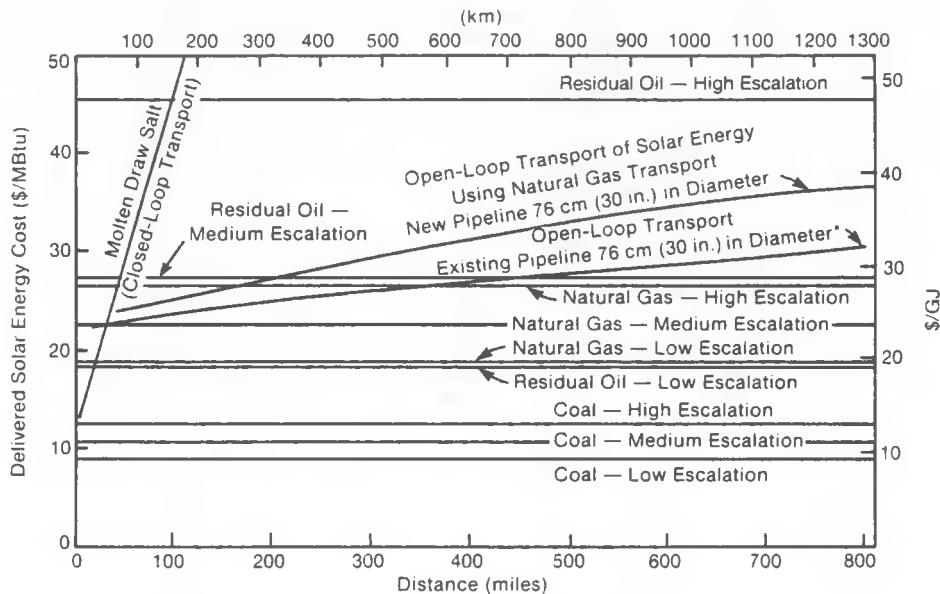
Figure 3 indicates that open-loop solar energy transport using natural gas is more

Table 1. Open-Loop Transport Using CH<sub>4</sub> Networks With New Investment and Fixed Fuel Value Transport

Case	1A	1B	1C	1D	1E	1F	1G	1H
Pipeline length [km (miles)]	80 (50)	80 (50)	322 (200)	322 (200)	644 (400)	644 (400)	1288 (800)	1288 (800)
Pipeline diameter [cm (in.)]	51 (20)	76 (30)	51 (20)	76 (30)	51 (20)	76 (30)	51 (20)	76 (30)
Gas <sup>a</sup>	Nat	Syn	Nat	Syn	Nat	Syn	Nat	Syn
Δ Energy (solar) [GJ (MBtu)]	--	944 (895)	--	944 (895)	--	944 (895)	--	944 (895)
Investment (M\$)	41.56	345.22	169.95	501.00	338.85	718.32	674.04	1151.94
Operating cost (M\$)	1.973	19.147	5.448	27.371	10.568	39.931	20.837	65.185
Δ Fuel gas energy [GJ (MBtu)] <sup>b</sup>		0		0		0		0
Δ Investment (M\$) <sup>b</sup>		303.66		331.05		379.97		447.90
Δ Operating cost (M\$) <sup>b</sup>		17.174		21.923		29.413		44.348
Transport cost of solar energy (CF = 0.65)[\$/GJ (\$/MBtu)] <sup>b</sup>		13.94 (14.70)		16.31 (17.21)		20.21 (21.32)		27.23 (28.72)
Delivered cost of solar energy [\$/GJ (\$/MBtu)] <sup>b</sup>		23.25 (24.53)		25.63 (27.04)		29.53 (31.15)		36.55 (38.55)

<sup>a</sup>Nat: natural gas; Syn: synthesis gas.

<sup>b</sup>Δ (quantity) is the difference in quantity between the case with solar energy transport and the corresponding case without solar energy transport; i.e., the change attributable to transport of solar energy relative to the corresponding transport of natural gas. Costs associated with a 51-cm (20-in.) pipeline are considered to be borne by the natural gas selling price. This defines the basis for determining Δ (quantity).



\*Valid only if existing pipeline is at least 50% underutilized before conversion.

**Fig. 3. Open-Loop Transport of Solar Energy via Natural Gas Networks**  
(Fossil fuel curves are from Ref. 3.)

cost-effective than closed-loop solar energy for distances exceeding around 50 km. Solar energy systems are competitive with local fossil-fuel-fired boilers only if they use natural gas or residual oil fuel at medium to high fuel price escalation rates. If prices of these fossil fuels begin to rise at a sufficiently high rate, solar central receiver systems with long-distance transport would then become cost-effective. But if the prices of natural gas and residual oil remain sufficiently low, the solar system with transport will not be an attractive alternative. Under no circumstance studied here, however, will solar energy with long-distance transport be cost-effective compared with local coal-fired boilers.

Table 2 lists the economic figures for the case of converting an existing natural gas pipeline to transport solar energy with synthesis gas. There are two subcases:

- The pipeline is operating at capacity with natural gas (the most likely situation);
- The pipeline is operated at approximately less than 50% of capacity, with natural gas (an unlikely situation).

As Table 2 indicates, the loss in fuel value when the existing pipeline system is converted to solar energy transport is approximately 58%, or about 12 times the solar energy transported if the pipeline were initially operating at capacity with natural

gas. This is very unfavorable; this subcase presents an economically unacceptable method of transporting solar energy. Although the cost of delivered solar energy appears to be reasonable, the cost of delivered SNG would be significantly higher than the cost of natural gas with no solar energy transport. Table 2 indicates that if the existing pipeline is operating at less than half capacity, then delivered solar energy costs range from \$23.86 to \$30.50/MBtu. These values are plotted on Fig. 3. Results suggest that conversion of an underutilized pipeline in Case 2 is a more cost-effective situation than Case 1. However, solar energy with transport is still competitive only with local oil- and gas-fired boilers at medium to high fuel price escalation rates.

## 5. CONCLUSIONS

- Solar central receiver systems with long-distance energy transport via new natural gas pipelines can compete cost-effectively with local natural-gas or residual-oil-fired boilers at medium to high fossil fuel price escalation rates.
- Solar central receiver systems with long-distance energy transport via new or old natural gas pipelines cannot compete cost-effectively with local coal-fired boilers, regardless of projected coal prices.
- Solar energy transport via open-loop natural gas pipelines is more cost-

**Table 2. Open-Loop Transport of Solar Energy Using an Existing Natural Gas Pipeline System**

Case	A	B	C	D	E	F	G	H
Pipeline length [km (miles)]	80 (50)	80 (50)	322 (200)	322 (200)	644 (400)	644 (400)	1288 (800)	1288 (800)
Pipeline diameter [cm (in.)]	76 (30)	76 (30)	76 (30)	76 (30)	76 (30)	76 (30)	76 (30)	76 (30)
Gas <sup>a</sup>	Nat	Syn	Nat	Syn	Nat	Syn	Nat	Syn
Fuel value transported [GJ (MBtu)]	19000 (18020)	7950 (7540)	19000 (18020)	7950 (7540)	19000 (18020)	7950 (7450)	19000 (18020)	7950 (7540)
Solar energy transported [GJ (MBtu)]	--	944 (895)	--	944 (895)	--	944 (895)	--	944 (895)
Investment (M\$)	55.04	345.22	205.12	501.00	407.35	718.32	810.54	1151.94
Annual op. cost M\$	2.764	19.147	8.940	27.371	17.565	39.981	34.669	65.185
Δ Fuel value delivered [\$/GJ (\$/MBtu)] <sup>b</sup>	11050 (10480)		11050 (10480)		11050 (10480)		11050 (10480)	
Δ Investment (M\$) <sup>b</sup>	290.18		295.88		310.97		341.40	
Δ Operating cost (M\$) <sup>b</sup>	16.383		18.431		22.416		30.516	
Transport cost [\$/GJ (\$/MBtu)] <sup>b</sup>	13.30 (14.03)		14.17 (14.95)		15.96 (16.84)		19.60 (20.67)	
Delivered cost of solar energy [\$/GJ (\$/MBtu)] <sup>b</sup>	22.61 (23.86)		23.49 (24.78)		25.28 (26.67)		28.91 (30.50)	

<sup>a</sup>Nat: natural gas; Syn: synthesis gas.

<sup>b</sup>Δ (quantity) is the difference in quantity between the case with solar energy transport and the corresponding case without solar energy transport; i.e., the incremental change associated with transporting solar energy. Solar energy transport costs do not include the 76-cm (30-in.) pipeline investment.

effective than transport via closed-loop molten draw salt systems for distances greater than 50 km.

- If an existing pipeline is operating near capacity, it is not cost-effective to convert to open-loop transport of solar energy.
- If an existing pipeline is operating at less than half capacity, then conversion to open-loop solar energy transport is cost-effective, consistent with the conclusions for new pipelines.

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