SERI/TP-231-1966
UC Category: 62 e
DE83009110

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April 1983

To be presented at the
18th Intersociety Energy Conversion
Engineering Conference
Orlando, Florida
21-26 August 1983

Prepared under Task No. 1299.00
WPA No. 348-82

Solar Energy Research Institute
A Division of Midwest Research Institute

1617 Cole Boulevard
Golden, Colorado 80401

Prepared for the
U.S. Department of Energy
Contract No. EG-77-C-01-4042

Printed in the United States of America
Available from:
National Technical Information Service
U.S. Department of Commerce
5285 Port Royal Road
Springfield, VA 22161
Price:
Microfiche $4.50
Printed Copy $ 7.00

NOTICE

VALUE AND COST ANALYSES FOR SOLAR THERMAL STORAGE SYSTEMS

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ABSTRACT

Value and cost data for thermal energy storage are presented for solar thermal central receiver systems for which thermal energy storage appears to be attractive. Both solar thermal electric power and industrial process heat applications are evaluated. The value of storage is based on the cost for fossil fuel and solar thermal collector systems in 1990. The costing uses a standard lifetime methodology with the storage capacity as a parameter. Both value and costs are functions of storage capacity. However, the value function depends on the application. Value/cost analyses for first-generation storage concepts for five central receiver systems (molten salt, water/steam, organic fluid, air, and liquid metal) established the reference against which new systems were compared. Some promising second-generation energy storage concepts have been identified, and some more advanced concepts have also been evaluated.

INTRODUCTION

The ultimate user of electricity or heat is interested in reducing his product cost. He will invest in thermal energy storage only if such an investment provides him with lower-cost energy than he can obtain by other means. The investment that the user is willing to make in thermal energy storage represents the value of such storage. This paper addresses the issue of the value of thermal storage to a user and projected costs for mature thermal storage technology. The objective of this work is to identify promising thermal storage concepts for research and development.

Value is a measure of the economic worth of a system or subsystem; and value therefore represents the maximum allowable cost of that system or subsystem. That principle is applicable to all stages of research and development of a technology. We apply this principle to thermal storage technologies currently being investigated. The value-to-cost ratio is a figure of merit; ratios greater than unity are considered to indicate promising concepts. Technologies which have value-to-cost ratios less than unity have also been identified. For those technologies, either the concept as described must be altered to reduce the costs or the research should be terminated.

VALUE ASSESSMENTS

The value of a solar thermal system with thermal storage depends on the cost of fossil-fueled alternative systems (generally oil or gas). The overall attractiveness of the solar thermal system obviously depends on the cost of the solar system and the cost of thermal storage. Our approach is to identify promising solar thermal applications potentially economical in 1990. For these applications the value of the thermal storage subsystem within the solar thermal system is determined.

Value analyses were made for thermal electric power systems (1) and for industrial process heat applications (2). The analyses were performed by two different methods because different researchers did the work. The value analysis for thermal electric power systems used the partial derivative method (3). This method determines the value for the storage subsystem and this value is independent of the value for the overall solar energy system. That is, the storage subsystem may have a positive value in that it reduces the cost for electric energy as compared to a solar energy system without storage, although the cost for electric energy from the solar system with storage exceeds the electric energy cost from systems using fossil fuels.

The value analysis for the industrial process heat applications was made by the cost differential method, which establishes an allowable cost for the energy storage subsystem. In this method, a fossil-fueled system is compared with a solar-powered system that uses a fossil-fueled backup system. An analysis determines the cost of thermal energy output (e.g., steam at a given temperature and pressure) for both systems as a function of the capacity factor (i.e., the fraction of the year that the system is in operation). Only when the energy cost for the solar system is lower than for the fossil-fueled system is there a value (allowable cost) for the energy storage. The allowable cost is the difference in energy cost between the two systems. Only for oil and natural gas is there a positive value for energy storage. Coal having a lower price than oil or gas results in a negative storage value in large baseload industrial plants.

The values that have been determined for several thermal storage capacities are shown in Table 1, adjusted to 1980 dollars in all cases. These values are based on annual fixed charge rates for electric power systems and for industrial process heat applications of 17.0% and 27.6%, and service lives of 30 years and 20 years, respectively, and the fossil fuel cost for the year 1990 (in 1980

Table 1. Values of Thermal Storage in Solar Thermal Applications
(in 1980 dollars)

Storage Capacity (h)[b]	Value[a] Total Thermal Storage Subsystem ($/kW)	Per Unit Storage Capacity ($/kWh)
100 MW Electric Power[c]		
3	375	125
6	440	73
15	(560)[d]	(37)[d]
Industrial Process Heat[e]		
3	30-60	10-20
6	60-120	10-20
15	150-300	10-20

[a]The value is expressed in two different ways; the value per unit of storage capacity is the total thermal storage subsystem value divided by the hours of storage capacity. The watts or watt-hours are electric for the electric power application and thermal for the industrial process heat application.

[b]One hour of storage is enough energy to drive the plant at its nameplate rating for one hour.

[c]Storage efficiency and power conversion efficiency affect the value; the data are for a net heat-from-storage-to-electric-energy efficiency of 25.5%, which corresponds to Solar 1-Barstow technology.

[d]Extrapolated data.

[e]Analysis done for 5 MW_t, but value is nearly independent of plant size.

dollars) as shown in Table 2. Fuel price projections involve large uncertainties. This must be remembered when one examines the values established and the subsequently derived value-to-cost ratios.

For diurnal storage, that is, storage for up to 18 hours, the value per unit of storage capacity is independent of storage capacity for industrial process heat applications (2). For electric power applications, the value per unit of storage capacity declines with increasing storage capacity (1) as shown in Table 1. The reason for this decline is that for larger storage capacity, the optimum fuel shifts from the more expensive oil and gas to coal or nuclear.

Table 2. Projected Fossil Fuel Costs in 1990

Fossil Fuel	For Electric Power		For Industrial Process Heat	
	$/GJ	FLF[a]	$/GJ	FLF[a]
Distillate oil	4.62	2.0	—	—
Residual oil	4.14	2.0	4.57	1.71
Natural gas	4.62	2.0	4.83	1.71
Coal	1.60	2.0	1.13	1.71

[a]Fuel levelizing factor. Electric power application costs are levelized over 30 years and industrial process heat applications over 20 years.

COST ANALYSES

Dubberly et al. estimated the costs of solar thermal storage subsystems (4,5). The capital investment cost (CI) for energy storage subsystems was calculated for each system by estimating the energy-related (CE) and power-related (CP) equipment costs including the field installation costs, the storage (SM) media costs, and the indirect costs, using the following equation:

$$CI = A[B(CE + CP) + SM] \ . \qquad [1]$$

The factor A includes allowance for engineering; interest during construction; indirect field costs such as temporary facilities, construction equipment, insurance, performance bonds, fees and taxes; and contingency.

The factor B accounts for field labor installation costs. A value of 1.8 was assigned to factor B. We have modified the Dubberly data to make them consistent with the costing methodology for solar thermal systems established by the Solar Thermal Cost Goals Committee. (This committee was set up by the DOE Solar Thermal Technology Division and chaired by R. Edelstein of the Solar Energy Research Institute.) The difference is mainly the use of 1.44 for factor A, as recommended by the committee, instead of 1.95, as used by Dubberly.

The total cost is then obtained from the present worth of revenue requirements, which is the sum of the present worth of fixed costs, variable costs, and replacement costs.

All costing was done in 1980 dollars assuming mature technology. The costing for all concepts used the same data base; thus the same costs for steel, piping, heat exchangers, etc. were used. The costing was based on conceptual designs for each system that defined specific sizes for tanks, pipes, and heat exchangers; specific material types and dimensions; and specific quantities. In spite of this detail, the cost estimates probably have a relative uncertainty of ±30%, a typical magnitude for conceptual designs. The absolute accuracy of the costs is probably not better than ±50%.

The cost of energy storage is a function of the quantity of storage. In equation [1], CE and SM are directly proportional to the quantity of storage, h, and are approximately given by the following:

$$CE = dh$$

and

$$SM = eh,$$

where d is the cost per unit of storage capacity for tankage, e is the cost per unit of storage capacity for the storage media, and h is the storage capacity, generally expressed as hours and literally kWh per kW of plant nameplate rating.

Our analyses have shown that diurnal thermal storage (1 to 18 hours) is the most economical range (6). For solar thermal electric applications, 1 to 6 hours has been shown to be the optimum range. For solar thermal industrial process heat, 6 to 15 hours is the optimum range. Because 6 hours of storage is common to both applications, 6 hours is employed as a working nominal figure for comparing cost and value.

VALUE-TO-COST RATIO

System analyses were performed for solar central receiver systems. The value-to-cost ratios for a number of attractive first-generation storage concepts were determined as shown in Table 3. The five central receiver systems investigated use molten salt, water/steam, organic fluid, gas (air), or liquid metal. Only the storage concepts having value-to-cost ratios above unity for six hours of storage capacity are shown. All these systems have been developed or are under development. For molten salt receivers, two-tank draw salt storage has a very high value-to-cost ratio both for electric power generation and for process heat applications. The various systems are described in Refs. 4 and 5.

Once we had established the cost-effective systems that already have been developed, we could identify potentially more cost-effective storage systems that still need research and development to achieve their potential. These systems are called second-generation systems.

The most promising second-generation storage concepts for the central receiver systems are shown in Table 4. The concepts are described in Refs. 4 and 5. Only concepts for molten salt, water/steam, and liquid metal receivers were identified as having higher value-to-cost ratios than the first-generation systems. The development and research activities that would be required to bring the second-generation systems to the fully developed stage have been identified. This includes development work for underground pressurized storage, for latent-heat tube-intensive heat exchange, and for heat exchangers for molten draw salt. Research needs were also identified for latent-heat direct-contact (4) and air/rock storage (5).

The reason that the costs are lower for electric power applications than for industrial process heat is because the fixed charge rate for utilities is 17% while that for private industry is 27.6% in our study. Private industry requires a higher rate of return on capital than the regulated utilities.

Storage systems have been identified that are beyond the current state of the art. Some of these advanced systems are the subject of experimental research at the Solar Energy Research Institute. A value and cost analysis was performed on several of these systems to identify which of them have high economic potential, which aspects are not cost-effective, and which areas research should address to reduce costs. This research includes concepts having storage temperatures ranging from 385°C to 1450°C. The projected value and costs for some of these systems are shown in Table 5.

Table 3. Value-to-Cost Ratios for First-Generation Storage Concepts and 6-Hour Storage Capacity

Storage Technology	Central Receiver[a]						
	Molten Salt		Water/ Steam		Organic Fluid	Gas	Liquid Metal
	Pwr	Pro	Pwr	Pro	Pro	Pwr	Pwr
Oil/rock thermocline	—	—	1.1[b]	1.0	1.3	—	—
Molten draw salt, 2-tank	2.6	1.8	—	—	—	—	—
Air/alumina brick	—	—	—	—	—	2.8[c]	—
Liquid sodium, 2-tank	—	—	—	—	—	—	1.0

[a]Pwr = electric power generation; Pro = process heat application.

[b]Two-stage system: oil/rock and molten draw salt (nitrate salt).

[c]For 1 hour of storage capacity. At 6 hours of storage capacity this concept has a value-to-cost ratio below unity.

Table 4. Value-to-Cost Ratios for Promising Second-Generation Storage Concepts and 6-Hour Storage Capacity[a]

Storage Technology	Central Receiver			
	Molten Salt	Water/Steam		Liquid Metal
	Electric Process	Electric Power	Process Heat	Electric Power
Underground pressurized water	—	1.2[b]	1.4[c]	—
Latent-heat tube intensive	—	1.4[b]	—	—
Latent-heat direct-contact	—	1.1	—	—
Molten draw salt, 2-tank	—	—	—	1.4
Air/rock	2.4[d]	—	—	1.7

[a]Exceptions are indicated.

[b]Two-stage system with high-temperature molten salt.

[c]15-hour storage, 288°C saturated steam. No significant improvement over first generation found for 6 hours storage.

[d]Two-stage system with molten nitrate-salt, for 15 hours of total thermal storage capacity. No significant improvement over the first-generation system was found for 6 hours of storage.

Table 5. Value-to-Cost Ratio for Advanced Thermal Storage Concepts with Appropriate Advanced Central Receivers

Storage Technology	Storage Capacity (hours)	Application	Value[a] ($/kWh$_t$)	Cost and Reference ($/kWh$_t$)	Value/Cost Ratio
Molten slag	6	Electric Power	20-25	28 (8)	0.7-0.9
High-temperature molten salt[b]	6	Electric Power	25	5.0 (9)	5
Draw salt/air-rock	48	Process Heat	10-20	6.7 (10)	1.5-3.0
Phase-change salt/ ceramic pellets	1-15	Process Heat	20	25-30 (11)	0.7-0.8
Metal/phase-change salt	1-15	Process Heat	20	10 (3)	2

[a]From Refs. 1 and 2.

[b]System described in Ref. 7.

Certain of these concepts, such as high-temperature molten salt, draw salt/air-rock, and metal/phase-change salt, show very high value-to-cost ratios. These concepts remain attractive even if the projected costs would double. For some other concepts, such as molten slag and salt/ceramic pellet energy storage, the value-to-cost ratio is not attractive. For these concepts, the cause for the high cost has been identified and research is underway to remedy the situation.

Applications for storage temperatures above 800°C include fuels and chemicals production, process heat, and electric power. Solar central receivers using molten nitrate salts are limited to temperatures of 570°C. Higher temperatures can be reached using salts such as carbonates or chlorides, or sodium hydroxide, glassy slag, or air as a heat transfer medium in the solar central receiver.

CONCLUSIONS

We have identified near-term thermal storage concepts that have attractive value-to-cost ratios. There are several longer-term thermal storage concepts that, with additional development, will be even more attractive than the corresponding near-term concepts.

Advanced, long-range concepts offer even higher promise. The value-to-cost analyses have been used to focus research efforts. Advanced solar energy storage concepts having high value-to-cost ratios have been identified—namely, high-temperature molten salt, draw salt with air-rock, and metal/phase-change salt—and have been selected for further research.

As storage concepts are better defined, better cost estimates are possible. This in turn allows revision of the original value-to-cost ratios. By identifying the elements of high cost in each concept, research can be directed to those elements to find lower-cost solutions.

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