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ABSTRACT

The value of thermal storage for three solar industrial process heat systems has been determined for storage capacities of 3 to 4000 hours. The dominant source of storage value is backup fuel savings with additional value derived from increased capital equipment utilization and elimination. A computer simulation was used to model the operation of the solar IPH system and predict the amount of fuel saved by heat delivered from storage.

Sensitivity of storage value to process temperature, collector cost, load profile, insolation and storage efficiency have been calculated. Storage values ranged from near zero to as high as $42 per Kw-hr of storage capacity.

NOMENCLATURE

CEC = Capital Equipment Cost
CEES = Capital Equipment Elimination Savings
CEUS = Capital Equipment Utilization Savings
C_F = Levelized cost of the fossil fuel used for backup,
C_S = Cost of the solar energy,
ESS = Total annual energy delivered from storage,
EST = Total amount of energy delivered from the solar plant,
η_F = Fossil fuel burner efficiency,
FCR = Effective cost of capital, fixed charge rate,
OMC = Operations and maintenance cost of the solar plant,
η_S = Round trip efficiency of storage, and
TCS = Installed cost of the solar plant.

INTRODUCTION

The industrial process heat (IPH) market in this country has early potential for solar energy. The market is characterized by a wide range in energy delivery temperature and maximum power demand. Before solar energy can significantly penetrate into this market, energy storage systems must be developed that can deliver solar energy when it is not directly available.

The purpose of the study is to determine the value of storage in a solar IPH system. The value to the user is the amount that could be paid for storage to break even with the next alternative. Hence, the value of thermal storage is useful in setting economic goals for storage research and development.

We considered three energy delivery temperatures in this study. For each delivery temperature, we selected an appropriate collector. Nominal energy demand was 5 MW_{th}, with a plant startup in 1990.

METHODOLOGY

In this study, the value of storage will be defined as the price that an IPH user could pay for the benefits of the storage system to break even compared with a selected alternative. Three sources of value were evaluated in this study: fuel cost savings, capital equipment utilization savings, and capital equipment elimination savings.

Energy Cost Savings

The energy delivered from an economic solar IPH system will cost less than energy delivered from a fossil fuel system. If the lower cost solar energy can be stored for use when solar energy is not available, the fuel cost saving can be attributed to storage.

The value of the energy cost savings can be calculated as follows:

$$\text{ECS} = \frac{(\text{Levelized Value of the Annual Fossil Fuel Savings})}{(\text{Effective Cost of Capital})} \text{ or}$$

$$\text{ECS} = \frac{\text{ESS}\ (C_F/\eta_F - C_S/\eta_S)}{\text{FCR}} .$$

ECS is the present worth of the annual savings resulting from the difference between the cost of solar energy and the fossil backup fuel. ECS is negative if the cost of backup fuel is less than the cost of solar energy.

The values of the variables used are shown in Table 1, except for ESS, C_S, and η_S. ESS, the energy delivered from storage, is calculated by an hourly simulation of plant operations by the BALDR [1] computer code; η_S, the storage round trip efficiency, is a parameter in the study. C_S, the cost of the solar energy, is calculated with the following equation:

$$C_S = \frac{\text{(Installed Cost of the Solar Plant) (FCR) + (O \& M Costs)}}{\text{Total Amount of Energy Delivered from the Solar Plant}} \quad \text{or}$$

$$C_S = \frac{\text{(TSC) (FCR) + OMC}}{\text{EST}} \ .$$

TCS, the installed cost of the solar plant, is shown in Table 1. The operations and maintenance costs were assumed to be 2%/yr of the installed cost of the plant. EST was calculated by the BALDR computer code, which is described later.

Capital Equipment Utilization

In a solar system, some of the equipment is sized to accommodate the maximum solar input and the maximum user demand. The cost of the equipment sized to maximum user demand is not affected by the addition of solar collectors and storage, which allows this equipment to operate more hours per day and, therefore, reduces the fixed cost per unit of energy delivered. In this study, the equipment sized to maximum user demand is the solar heat exchangers.

The capital equipment utilization savings CEUS can be calculated with the following equation:

$$\text{CEUS} = \frac{\text{Energy Delivered from Storage}}{\text{Total Solar Energy Delivered}} \text{(Capital Equipment Cost)} \quad \text{or}$$

$$\text{CEUS} = \frac{\text{ESS}}{\text{EST}} \text{(CEC)} \ .$$

The capital equipment cost (i.e., solar heat exchanger costs) for each of the systems studied are shown in Table 1. ESS, the energy delivered from storage, and EST, the total solar energy delivered, are from the BALDR computer simulation.

Capital Equipment Elimination Savings

The addition of storage to a solar system can reduce the investment required in backup, fossil-fueled equipment. If sufficient collectors and storage can be added to a solar IPH system so that the fossil backup system is not required, then the cost of the fossil backup system can be assigned to the storage value.

In this study, the fossil-fueled boiler is eliminated by large amounts of storage in the system. The cost of the fossil-fueled boilers is then the capital equipment elimination savings, or CEES equals the cost of the capital equipment eliminated. The cost of the fossil-fueled boilers is shown in Table 1.

The Total Value of Storage

The total value of storage to the user is then:

Storage Value = ECS + CEUS + CEES.

This storage value is the amount that an industrial user would be willing to pay for a storage system in a solar IPH system. The values in this study are in 1980 dollars with a solar plant start-up for 1990. From the user viewpoint, the storage value must cover the initial installed equipment costs, as well as the present worth of the operation and maintenance costs for the economic life of the storage system.

TABLE 1. INPUT ASSUMPTIONS*

Parameter	Cost	Reference
Solar Systems		
Flat-Plates	$100 to $200/m^2	SERI
Parabolic Troughs	$ 90 to $188/m^2	Estimate
Central Receiver	$150 to $276/m^2	
Solar Heat Exchangers		
Flat-Plates	$ 37,500	SERI
Parabolic Trough	$139,000	Estimates
Central Receiver	$370,000	
Fossil Backup Systems (5 MW_{th})		
Gas η= 0.78	$ 74,000	Vendor
Oil η= 0.8	$139,000	Quotes
Levelized Fuel Cost		
Albuquerque		
Gas	$.0343/$kW_{th}$	Solar Thermal
Residual Oil	$.0292/$kW_{th}$	Cost Goals
Distillate Oil	$.0447/$kW_{th}$	Committee
Fort Worth		
Gas	$.0404/$kW_{th}$	Solar Thermal
Residual Oil	$.0313/$kW_{th}$	Cost Goals
Distillate Oil	$.0473/$kW_{th}$	Committee
Economic Parameters		
Fixed Charge Rate	0.25	Solar Thermal
Solar O&M	0.02	Cost Goals
		Committee

*All costs are in $ 1980 with a plant startup in 1990

BALDR COMPUTER CODE DESCRIPTION

The computer code that was used to model the solar thermal systems performance is a slightly modified version of BALDR-1, a simulation code developed by SERI [1]. The original code is divided into three separate modules to facilitate expansion and modification: FIELD, POWER, and ECON. Only the FIELD and POWER modules were used for this study, since the ECON module performs economic functions that were not relevant to this application. Instead, a subroutine was added as an option to the POWER code, to determine the desired economic values. A flowchart is presented in Fig. 1. General results from BALDR code compare well with results from the STEAEC computer code [2]. Additional BALDR verification work is planned.

FIELD Code

The FIELD code models the optical and thermal performance of the collector field and has separate optical and thermal performance routines for each generic collector type. For this study, this code was used to model the performance of the flat-plate collector, the parabolic trough collector, and the point-focus central receiver systems. Meteorological data are read in 15-min. increments from SOLMET format weather tapes. The simulation was run for Albuquerque, NM and Fort Worth, TX.

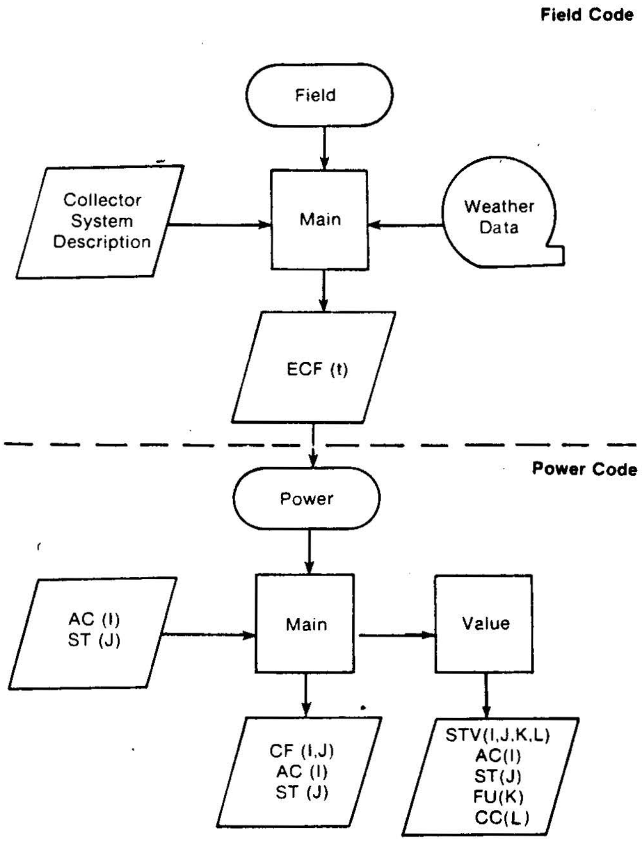
The optical and thermal performance of each collector type was determined for each location by using the following meteorological data as inputs: direct normal insolation, solar time, global insolation, ambient temperature, dew point, and day of the year. The radiative losses from the receiver are calculated based on the effective receiver temperature, the effective absorptivity and emissivity of the receiver, the effective receiver temperature, and normalized receiver area. The convective and conductive losses are assumed to be a constant fraction of the radiative losses. The energy collected at the receiver is the incident energy minus the calculated thermal losses. The thermal transport efficiency is used to determine the final result of the energy collected by the field.

The outputs from FIELD include a computer printout and a file that stores the variables that are necessary for the operation of POWER, the next module of BALDR. These passed-on variables include an array of values of the energy collected from the field for each time step, dry-bulb and wet-bulb temperatures, and unit collector area.

POWER Code

The POWER code models the performance of power conversion and storage components. It calculates the total thermal and electrical energy produced during the year for a set of plant configurations composed of different collector field sizes and thermal storage sizes. Control dispatch strategies for the thermal storage can be selected from several options.

The decision of how to dispatch the energy is made for the current time step. Knowledge of future insolation is not used. The energy collected by the field is used to supply heat to the load whenever the load exists. If there is no load during the time step, or if excess energy is being collected by the field, then the energy is fed into the thermal storage. Storage is discharged when the energy from the field is insufficient to meet the load. The priority for this control strategy is meeting the demand load primarily directly from the field and secondly from thermal storage.



AC(I) - Collector Areas
ST(J) - Thermal Storage Size
FU(K) - Fossil Fuel Cost
CC(L) - Collector System Cost
CF(I,J) - Capacity Factor
STV(I,J,K,L) - Storage Value

Figure 1. BALDR Computer Model Flowchart

The POWER code calculates the energy delivered to the load at each time step and sums it for one year. Other values that are stored and listed in the output for each combination of collector area and storage size include:

- Energy from the field,
- Energy dumped,
- Energy lost through pipe insulation,
- Energy delivered to the load,
- Energy to storage,
- Energy from storage,
- Demand not met, percentage of demand not met,
- Electricity to pumps,
- Efficiency of transport, storage, and system, and
- Capacity factor.

In addition to the above parameters, storage value calculations were required, so an optional subroutine (VALUE) was added to the POWER code. The storage value calculation described previously is performed in this subroutine. The value of the thermal storage is then output for a range of solar system costs and for each fuel type supplying the fossil heater, as a function of collector area and storage size.

SOLAR IPH SYSTEM DESCRIPTIONS

Three basic solar system designs were chosen for this study. The system schematics are all similar, except for the type of collectors employed and energy delivery temperatures. The first system (Fig. 2), uses a field of flat-plate collectors, the second (Fig. 3), parabolic troughs, and the third collector system type, (Fig. 4) has a point-focus central receiver. These systems supply heat at a constant temperature to the user. The type of storage for each system was not defined; however, the operating performance characteristics, such as efficiency, were specified to allow the results to be more general and applicable to different types of thermal storage with similar performance.

Flat-Plate System

The first system type, shown in Fig. 2, uses flat-plate collectors to convert the incident solar radiation to heat. The heat transport fluid for both the collector loop and the process is water. The water enters the collector field at 37.8° C (100° F) and is heated to an exit temperature of 71.1° C (160° F). This hot water then flows either directly to the solar heater (a shell and tube carbon steel counter flow heat exchanger with 1-in diameter, 60-ft-long tubes), and/or to the thermal storage system (the nominal storage efficiency is defined as 1.0). The temperature drop across both options is the same, providing the low 37.8° C (100° F) temperature water to be recycled through the collectors with efficiency of 69%. The area of the flat-plate collectors was varied from 7000 m^2 (75,350 ft^2) to 40,000 m^2 (430,570 ft^2), while the thermal storage capacity was simultaneously varied from 3 h to 4000 h.

The process is provided with heat from the solar heat exchanger, and from the backup fossil heater that is used only when sufficient heat is not available directly from the collectors or from the thermal storage. Both the solar heater and the fossil boiler heat the feed water from the process at 16° C (60° F) to 66° C (150° F) to supply the process load, which is defined as a 5-MW_{th} load. The load is met 100% of the time, either with solar energy or energy from the fossil heater. Three fuel types were investigated to fuel the backup heater for each case: residual oil, natural gas, and distillate oil.

Parabolic Trough System

Figure 3 depicts the second system type which employs parabolic troughs as the solar collector component of the system. An organic heat transfer fluid, caloria HT 43, flows through the collector loop. The inlet temperature of the fluid to the collectors is 176.7° C (350° F), and the outlet temperature is 260° C (500° F). The collector + is higher than that provided by the flat-plate collectors so that the flow rate is correspondingly lower to provide the same 5-MW_{th} load. The flow rates in this system are in the range of 2.5 kg/s to 56.1 kg/s in the collector loop, depending on the collector area, which is in the range of 5000 m^2 (53,821 ft^2) to 40,000 m^2 (430,570 ft^2). The storage capacity was varied between 3 h and 4000 h.

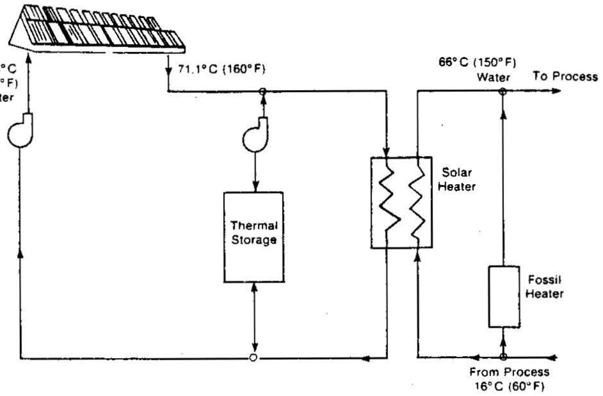


Figure 2. **Low-Temperature Solar IPH System with Flat-Plate Collectors**

The process heat load of 5-MW_{th} is met through the solar heater providing backup. The 140° C (300° F) water that is returned from the process is heated by either the solar boiler or the fossil boiler to saturated steam at 177° C (350° F) and 135 psia and returned to the process.

Point-Focus Central Reciever System

The collector system for the last system type studied is the point-focus central receiver, as shown in Fig. 4. This receiver is located atop a tower surrounded by a field of heliostats that focus the solar radiation on the relatively small area of the receiver. This technology yields very high temperatures in the working fluid of the receiver. Because of its extremely high temperature, the heat transfer medium chosen was a salt. The molten salt enters the receiver at 288° C (550° F) and exits at 565° C (1050° F). The range of areas that the heliostats covers is from 7000 m^2 (75,350 ft^2) to 40,000 m^2 (430,570 ft^2), with flow rates through the receiver varying from 10.2 kg/s to 38 kg/s with increasing collector area.

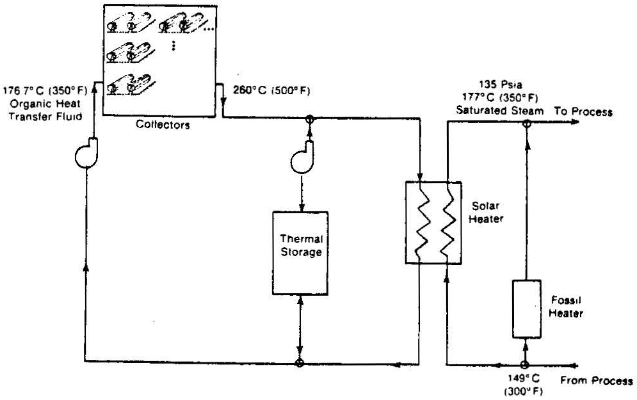


Figure 3. **Mid-Temperature Solar IPH Systems with Parabolic Trough Collectors**

The molten salt, after exiting the receiver, flows either through the solar heater, which for this system is a

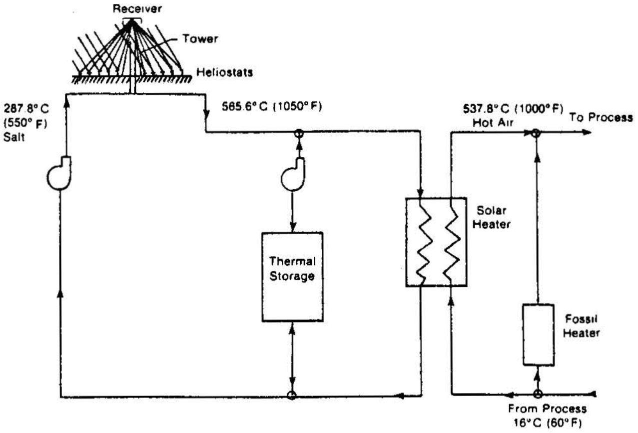


Figure 4. **High-Temperature Solar IPH Systems with Point-Focus Central Receiver**

finned air cooler with stainless steel tubes, or into the thermal storage. If there is energy in excess of that demanded by the load, the excess will be channeled through storage. The storage capacity ranges from 3 h to 4000 h.

The solar heater transfer the thermal energy from the molten salt to the air for the process. Ambient air at a temperature of 16° C (60° F) is heated to 537.8° C (1000° F) in both the solar and fossil heaters.

RESULTS

Figure 5 shows the results for the high temperature, central receiver system. Figure 6 shows the results for the mid-temperature, parabolic trough collector system and Fig. 7 shows the results for the low temperature flat-plate collector system. All of these data are for an Albuquerque, NM location with distillate oil as the backup fuel and a 24-hour per day, 7-day per week process heat demand. Three collector costs are shown which represent the expected solar system (collector, receiver, piping, etc.) cost for a 1990 plant startup in 1980 dollars.

The fuel savings value and the capital equipment utilization value are shown separately in the figures. The fuel savings value is the dominant source of storage value. The capital equipment elimination value occurs at storage capacities of 1000 hours or more, but the value is $.015/kWh and therefore does not show up in the figures.

The storage value remains nearly constant for the first 12 hours of storage, then begins to decline rapidly. Storage with a capacity of 12 hours or less can be charged and discharged daily. The more storage is charged and discharged, the larger the backup fuel savings. Storage with a capacity larger than 12 hours can not be cycled daily, and therefore its value decreased. At very high storage capacities, storage can be cycled only a couple of times per year resulting in very low values.

Figure 8 shows the effect of alternate fuels on the value of storage. The costs associated with the alternate fuels are shown in Table 1. The value of storage in systems with lower cost backup fuels is lower since there is less economic benefit in storing solar energy as opposed to burning the backup fossil fuel.

Figure 9 shows the effect of changes in location on the value of storage. Fort Worth, TX has a lower insolation and slightly higher fuel costs. The lower insolation has a significant effect on the value of storage.

Several energy demand scenarios were analyzed, and the results are shown in Fig. 10. The 7-day per week, 2-shift per day scenario is similar to the 7-day per week, 3-shift scenario, except the value of storage begins to drop sooner. The 5-day per week, 2-shift energy demand is similar to the 7-day week, 2-shift demand except the value of storage is somewhat lower because storage can be cycled only 5/7 as much. The 5-day per week, 1-shift per day demand results in the lowest storage value of any of the demands anlayzed because the hours of energy demand are the same as the hours that direct solar energy is available.

Figure 11 shows the effect of decreases in storage efficiency. The value of storage decreases as a rate significantly above the rate that storage efficiency decreases.

CONCLUSIONS

The value of thermal storage varies widely in IPH systems from $42/kWh of capacity to zero and below. The value is particularly sensitive to solar system cost, cost of backup fuel and insolation. The value of storage is highest in application where the economics of the solar energy system are the best. The value of storage reflects the solar system economics.

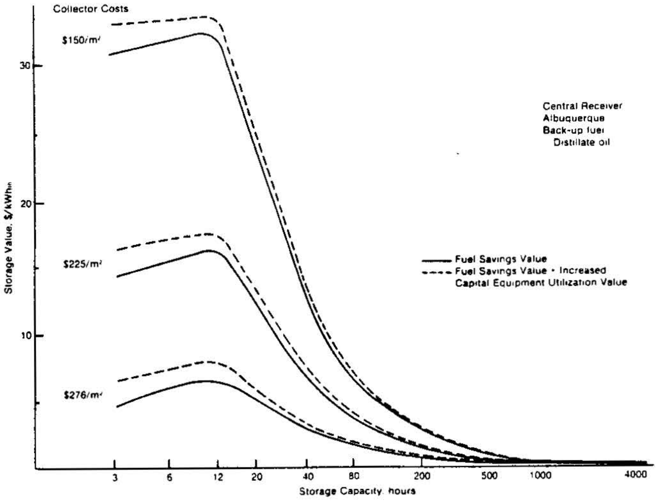


Figure 5. Effects of Collector Cost on Storage Value for Central Receiver

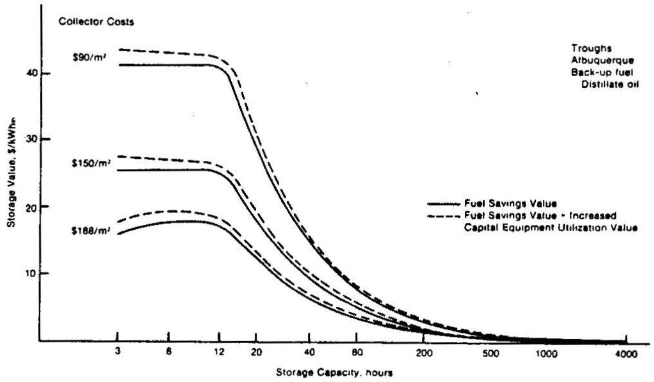


Figure 6. Effects of Collector Cost on Storage Value for Trough System

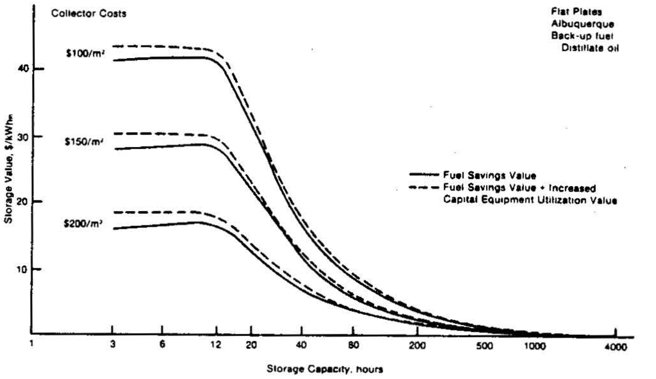


Figure 7. Effects of Collector Cost on Storage Value for Flat-Plate System

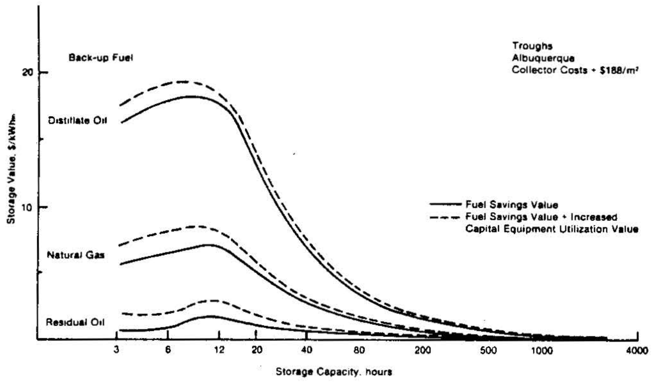


Figure 8. Effect of Back-up Fuel Type on Value of Storage

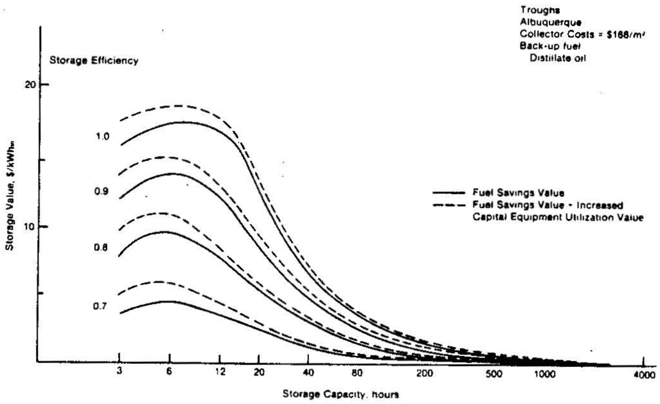


Figure 11. Effect of Storage Efficiency on the Storage Value

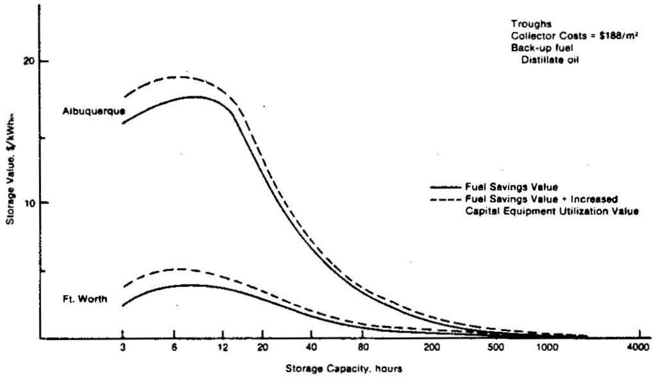


Figure 9. Effect of Location on the Storage Value

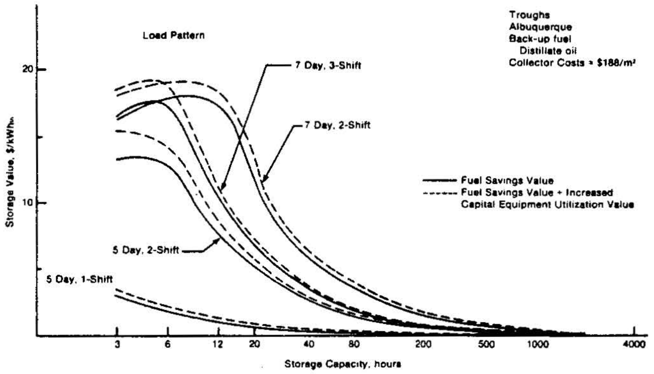


Figure 10. Effect of Load Pattern on the Value of Storage

ACKNOWLEDGEMENT

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