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CONSUMER THERMAL ENERGY STORAGE COSTS
FOR RESIDENTIAL HOT WATER, SPACE HEATING
AND SPACE COOLING SYSTEMS

NOVEMBER 30, 1976

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CREDITS

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1.0 INTRODUCTION

This report presents the cost of household thermal energy storage (TES) in four utility service areas that are representative for hot water, space heating, and space cooling systems in the United States. There are two major sections of the report: Section 2.0 is a technology characterization of commercially available and developmental/conceptual TES systems; Section 3.0 is an evaluation of the consumer cost of the three TES systems based on typical designs in four utility service areas.

This report represents a portion of the analysis performed by TRW Energy Systems Planning Division for Argonne National Laboratory under Contract No. 31-109-38-3364.

2.0 TECHNOLOGY CHARACTERIZATION

Essential to the analysis or understanding of the commercialization of Thermal Energy Storage (TES) systems is the descriptive characterization of the various storage techniques. For the purposes of this study, only TES systems for supplying domestic hot water, space heating and space cooling were investigated. A further consideration was that the commercialization of such systems is dependent on their ability to reduce utility load variations.

In characterizing the technologies, extensive reliance was placed on the data from space heating and domestic hot water TES systems being utilized in Europe for utility load leveling purposes. Data that were available for systems operating in the United States were used where available. There are currently no TES space cooling systems commercially available and, consequently, data were acquired from systems which were either in the development or conceptual phases.

This section presents the basic system descriptions, costs, and performance data used as the input data for the Fiscal Year 1976 Study (Phase I) performed by Argonne National Laboratory and funded by the Thermal Energy Storage Program of the Energy Research and Development Administration.

2.1 HOT WATER STORAGE HEATERS

The use of hot water storage as a means of storing thermal energy is not a highly sophisticated technology. The technology is proven and requires only an economic application of such technology to the variety of end uses.

Storage hot water heaters for use in residential and commercial buildings vary in size and design characteristics. The specific size and design are dictated by the particular system requirements. For instance, the storage device may supply hot water to a single family detached dwelling, a multiple family apartment building, or a commercial business requiring large quantities of hot water.

The interruptibility of the end user is important to the system design. Does the system have a fixed "charged" period or can it be accomplished at the intermittent desires/requirements of the specific utility supplying the charging power? For a fixed daily charge period, the user must store enough hot water (or thermal energy) to meet the requirement of the next day. This normally results in an oversizing of the TES system to insure adequate capacity. However, a user who can accept an interruptible service has determined that the continuous available supply of hot water is not of paramount concern and therefore might use a smaller TES system.

2.1.1 Description of Basic System Types

There are three basic system types that have been considered in this study. They are described below.

2.1.1.1 Direct Storage Heaters

Direct storage heaters are electric hot water heaters with larger tanks and more effective insulation than the "standard" domestic electric hot water tanks. These larger tanks with better insulation allow for longer and more effective storage of thermal energy. The electrical heating element is sized to supply most of the heat requirements of the system during utility off-peak periods. The tank is sufficiently well insulated that tank losses during the diurnal cycle are small. A schematic diagram of this system is presented in Figure 2-1.

2.1.1.2 Indirect Storage Heaters

Indirect storage heaters utilize a separate water-to-water heat exchanger to isolate the feedwater, which is heated by the system, from the water utilized for storage of heat energy. The storage water is heated to a higher temperature by the electrical resistance heater and subsequently gives up this heat to the feedwater via the heat exchange loop. This is schematically depicted in Figure 2-1.

There are fewer corrosion and scaling problems for the tank and heating elements with this arrangement than with the direct heater system (Reference 1). The heat exchanger does, however, contribute to an increase in the cost for the indirect system.

FIGURE 2-1. ALTERNATE HOT WATER STORAGE HEATER ARRANGEMENTS

2.1.1.3 Fusion Storage Heater

The fusion storage heater is similar to the indirect storage heater with the exception that a phase change material is substituted for the water energy storage medium. The phase change material is heated by the electric resistance heater to temperatures above the range to be supplied by the TES storage heaters. The water is heated via the heat exchanger in the phase change material. Certain variations of this scheme (Reference 2) have some water storage capability to handle demand surges. This system is also illustrated in Figure 2-1.

All of the hot water storage systems described above can be operated in a fixed charge period or as an interruptible system. The different mode of operation would change the control systems, but not necessarily the basic system design. The control technologies are discussed in Section 2.4 of this report.

2.1.2 Storage Hot Water Costs and Performance

The costs and performance data for storage hot water heaters were extracted from U. S. literature and, as such, they represent what is commercially available.

2.1.2.1 Costs of Hot Water Storage Systems

The costs for hot water storage systems are presented in Figure 2-2. The data for the smaller household units, such as the single family dwelling, were obtained from manufacturers' price data (References 3 and 4). These data sources allowed for the development of household units costs and for the costs of additional storage tanks (see Figure 2-2). The principal cost component of systems of this size is the tank because the cost of the heater element and control is small.

For hot water storage systems for commercial use, information obtained from Reference 5 is presented in Figure 2-2. The costs for these units are somewhat higher on a dollars/kWh of energy stored than the household units. This increased cost is probably due to longer design lifetimes for the commercial units and more complex control systems.

FIGURE 2-2. HOT WATER STORAGE SYSTEM COSTS

The cost data discussed above were for direct water storage heaters. The costs are assumed to be similar for the indirect storage hot water heaters using a phase change material as the storage medium, e.g., Thermobank. The one data point for such a system is plotted with the other data in Figure 2-2. The Thermobank unit cost estimate is about \$25/kWh. These lower costs in comparison with commercial hot water storage tanks could be attributed to the compactness of a phase change storage system resulting in lower material and fabrication costs. However, the associated heat exchange system probably costs more.

2.1.2.2 Performance of Hot Water Storage System

In describing the performance of a TES system, efficiency and size are important: efficiency being defined, in this case, as the percent recovered of the total energy input; size being separable into weight and volume and with due consideration being given to energy density (kWh/ft^3 or Btu/ft^3).

Efficiency. For storage periods of 24 hours, hot water storage systems have efficiencies of 96 percent or better when only a few inches of fiberglass insulation are used on storage tanks with 200 kWh capacity. This high efficiency is attributable to the small temperature differential and the quality of insulating material which is relatively inexpensive and readily available. Similar storage efficiencies can be expected for the indirect and heat of fusion storage systems. Although the smaller domestic household hot water tanks may have lower efficiencies, they can be improved with the addition of inexpensive insulation.

Size. The size of the hot water storage system is dependent on the total requirements. With a 75 degree temperature differential between the inlet and outlet, the water storage system store approximately 1.3-1.4 kWh/ft^3 . This compares with about 4.0 kWh/ft^3 for the Thermobank system. On a weight basis, the 200 kWh Thermobank system, has about twice the storage density of a water storage system.

2.2 STORAGE SPACE HEATERS

TES systems for space heating have been used in Europe for the last 15-20 years. The Europeans have developed a fairly complete technology base for using TES to supply space heat by the use of off-peak power. The information from these systems is the basis for most of the cost and performance data used in this study.

2.2.1 Description of Storage Space heating Systems

The European TES systems utilize electric resistance heaters to heat cores made of magnesite, cast iron (Feolite), and other materials to 900°-1100°F (500°-600°C). The storage units are adequately insulated and sufficiently large to retain enough heat for a 13-16 hour heating period during the day following the off-peak charge (at night).

Categories of typical storage space heater systems are described below.

2.2.1.1 Storage Radiators

This is the simplest and smallest of the storage heaters. The only control is a timer to turn on the electrical heating elements at night and off again during the day. A fixed "charge" of energy is stored in the core of the radiator. A thermostatic control limits "overcharging."

The heat is drawn from the radiator core by a convective flow of room air over the core, controlled by a thermostatically actuated damper. Older models had provisions for a boost charge during the days (at normal electrical rates) of extremely cold weather. Storage radiators are designed to heat individual rooms and typically range from 10 to 30 kWh in total storage capacity.

2.2.1.2 Fan Storage Radiators

This is an improved version of the basic storage radiator with a small blower to circulate the air through the radiator core. The blower motor is usually thermostatically controlled to provide a given temperature level in the room. Storage systems range from 15 to 60 kWh total capacity. In general, both storage radiators, with and without the fan, are placed along the wall of a room to provide the heating requirements of the room. A typical unit is depicted in Figure 2-3.

FIGURE 2-3. STORAGE FAN RADIATOR (EUROPEAN)

2.2.1.3 Central Storage Systems

Central storage systems are designed to provide central heat to a building by means of a central furnace. The unit is placed in a central location such as a basement and connected to the building duct system. A central blower is used to circulate the warm air to individual rooms and then back to the heater via the return air duct.

Capacities of central storage systems are larger than the storage radiators, ranging from 40 to 240 kWh storage capacity. The size of these units usually means that the standby heat loss, when charged, is very small and, therefore, any charge not used in one diurnal cycle may be retained for the next cycle. A typical central storage system is illustrated in Figure 2-4.

2.2.1.4 Heat of Fusion Systems

The systems discussed above store energy by raising the temperature of the core material, i.e., sensible energy storage. The same types of systems can be conceptualized for a storage medium of some phase change material. Although no commercial heat of fusion systems have been produced, preliminary engineering designs for such systems have been made (Reference 6). The operation of a heat of fusion system would be similar to those systems using sensible storage of energy.

2.2.2 Storage Space Heater Cost and Performance

The cost and performance data in this section are based on the European sensible Thermal Energy Storage Systems since this represents the best information on what is commercially available. Although there are no heat of fusion storage space heaters commercially available, there are systems far enough into the development phase to allow cost and performance to be estimated.

2.2.2.1 Costs of Storage Space Heaters

Data from English, Swiss, and German manufacturers of electrical sensible heat storage systems have been gathered from References 7 through 12. Most of the English data from 1970 to the present can be escalated to 1975 dollars with a high degree of accuracy (Reference 12). Similarly,

FIGURE 2-4. ELECTRACAIRE CENTRAL STORAGE SYSTEM

the data on Swiss and German units, some of which are available in the United States commercial market, can be used as a basis for space storage heater systems costs. The resultant cost data are summarized graphically in Figure 2-5.

The English manufacture a wide variety of systems from storage radiators to large central systems at a cost range of \$5-10 per kWh. The English pricing seems to have been adjusted to minimize any economy of scale effects on a cost per kWh basis.

Over the range of sizes, the Swiss and German space storage heaters cost considerably more than the English units. These higher costs are partly the result of higher labor costs in Germany and Switzerland, but some of this cost differential may also reflect the quality of the product in terms of characteristics such as increased durability and lower noise levels during operation. Also, the English cost data do not include shipping costs to the United States, which would make the cost of the English systems closer to the cost of German and Swiss systems. Although there are no cost data on space storage heaters manufactured in the U.S., some of the German cost data (Reference 11) are based on prices received in U.S. sales outlets.

Since no commercial heat of fusion systems have been produced in large quantities in the United States, only estimates of their eventual costs can be made. Data from a study performed by Comstock and Wescott in 1962 (Reference 6) for EEI were used for cost estimates of this type system. The 1962 cost estimates were escalated to 1975 dollars and the result indicated a cost of \$10 per kWh of storage. Storage material costs have been estimated by Telkes (Reference 13) at \$3-6 per kWh as compared to the Comstock and Wescott estimate of \$1.55 per kWh of storage material. If Telkes' high estimate is used for storage material with the Comstock and Wescott cost estimate for the other components of the system, then the system cost estimate is \$19 per kWh.

FIGURE 2-5. SUMMARY OF THERMAL ENERGY STORAGE PRICES

2.2.2.2 Performance of Storage Space Heaters

The efficiency of storage space heaters is essentially 100 percent because all the heat stored in the unit is released into the space being heated. A central system might be an exception to this since the heat escaping into the unit's central location might be heating an area which is unnecessary to heat, e.g., basement, and, therefore, it would be wasted heat. This particular circumstance is probably the exception and will not be considered in this study.

A key parameter in space storage heaters is the charge acceptance of the system. Charge acceptance is defined as the fraction of the electrical energy input to the unit that is available as heat during the on-peak heating period. Small storage radiators have the lowest storage charge acceptance with a value of 70 percent due to a high surface to volume ratio. Larger systems approach 90 percent charge acceptance with losses of only two percent per hour when fully charged. This means the stored heat can be effectively utilized during the discharge period and overheating problems are minimized.

The weight and volume of storage space heaters are dependent on the particular system and its application. The small individual room units are more carefully designed for compactness and are more amenable to a variety of retrofit situations. The central units, although designed for field assembly and installation, are by necessity much larger. Therefore, they are less attractive for retrofit applications.

Storage energy densities range from 2-6 kWh per ft³ of storage material. The higher energy densities are achieved by the units within the range of 25-50 kWh storage capacity. The system weights are 20-25 lbs/kWh with some units having values as low as 12 lbs/kWh. The heat of fusion systems have approximately the same energy density and weight with values of 2-3 kWh/ft³ and 20-30 lbs/kWh, respectively.

2.3 STORAGE SPACE COOLING SYSTEMS

There are no commercially available storage space cooling systems. Therefore, data presented in this document are based on prototype data and basic engineering estimates. Various system sizes were considered to cover the needs of the variety of building sizes in the different climatic zones.

2.3.1 Description of Storage Space Cooling Systems

The systems considered utilize a vapor compression heat pump to remove heat from the storage medium. The heat removal from the storage medium (cool charging) would be accomplished during utility off-peak periods, preferably at night when less work would be required. The storage system then serves as a heat sink for space cooling during the daytime hours or during on-peak periods. The four storage space cooling systems considered are discussed below.

All systems are amenable to operation under either fixed charge periods or an interruptible mode. The operating mode will dictate the design considerations relative to storage size and insulation requirements, and compressor size necessary to meet a specific application.

2.3.1.1 Ice-Making System

The ice-making system utilizes the heat of fusion of water to provide cooling during on-peak hours of maximum cooling requirements. Two system variations were considered. The first utilizes the ice storage for direct cooling with the evaporator operating at water freezing temperature. This system is schematically shown in Figure 2-6.

The second system variation is a hybrid system that uses direct expansion for light cooling loads, with supplemental ice water cooling during peak periods. The hybrid system has better refrigeration performance because of the higher suction temperature of the evaporator. The storage tank uses an ice detector to prevent complete freezing and a circulating pump to fully utilize the available heat of fusion (Reference 14 and 15).

2.3.1.2 Cool Water System

This system is similar to the ice-making system except that it would operate over a smaller temperature range, 35°F to 45°F and, therefore, it would require a larger storage tank to have a storage capacity equivalent to an ice-making system. The increased costs of the larger tank would be partially offset by elimination of the ice detector system and by operating at a more efficient suction temperature in the compressor.

FIGURE 2-6. ICE-MAKING SYSTEM (200,000 Btu STORAGE)

2.3.1.3 Glycol-Water System

This system would utilize a 50/50 mixture of ethylene glycol and water to lower the minimum operating temperature to 0°F. This would reduce the storage tank size, but would have to do more work to produce the same cooling effect because of the extremely low suction temperature of the evaporator.

2.3.1.4 Eutectic System

This system would utilize a phase change eutectic, e.g., salt hydrate, by freezing it around 55°F (Reference 16). Thermal storage material would be contained in tubes supported in an open crate structure providing circulating air passages. The total generating temperature range would be from 45 to 65°F. The eutectic system would require the addition of an inorganic thickening agent to prevent separation of the solid components.

2.3.2 Storage Space Cooling System Cost and Performance

The cost and performance data for storage space cooling systems has been estimated, since no systems are commercially available as a basis for direct analysis. These estimates are adequate for the objectives of this study.

The major limitation for the cost data of these systems is the large discrepancy between the upper and lower bounds of the estimated unit storage tank costs. While this cost uncertainty does not have a drastic effect in identifying the cheaper of the four systems, it is important in determining optimum storage size in balancing cooling capacity and system storage size against off-peak rate differentials. The lack of real cost data will make it necessary to conduct a parametric cost study on a broad range of values.

2.3.2.1 Costs of Storage Space Cooling System

One major component of a storage space cooling system is the storage material container. Data for a variety of potential materials and construction techniques are summarized in Figure 2-7. These data provide upper and lower cost bounds for the storage material containment system.

The data for the storage material costs of the four systems are presented in Table 2-1. The unit material costs are based on an estimated glycol cost of \$1.50 per gallon. The cost data for the eutectic system was obtained from Reference 17.

FIGURE 2-7. TANK UNIT STORAGE COSTS (INSTALLED) VS TANK STORAGE CAPACITY

TABLE 2-1. COOL STORAGE SYSTEM PARAMETERS

STORAGE SYSTEM PARAMETERS	ICE MAKING	COOL WATER	GLYCOL-WATER (50/50)	EUTECTIC
Operating Range, °F	32-55	35-55	0-55	55
Btu/Pound	~144	20	42.5	80
Pounds/Gallon	8	8	~8	13.3
Storage Material Cost (\$/Pound)	0	0	.10	.016
Pounds/KWH	23.8	171	80.6	42.7
KWH/FT ³	2.6	.361	.77	2.34

The unit tank costs are a function of system storage size and are compared in Figure 2-8 for the stainless steel tanks and in Figure 2-9 for plastic or concrete tanks. The ice-making and the eutectic systems have a substantial cost advantage over the full range of storage capacities. The additional costs for the ice sensor, the cooling tubes and circulating pumps are excluded in the cost curves of Figures 2-8 and 2-9.

The costs presented in Figures 2-8 and 2-9 do not include any operating or maintenance costs. The low suction temperature of the glycol-water system reduces its efficiency relative to the 55°F operating temperature of eutectic systems. However, all these cool storage systems would benefit from a higher coefficient of performance if they are operated in the "charging" mode during the coolness of the night.

The eutectic system would require a more sophisticated heat exchange system than the other systems that would probably increase the costs. Estimates from Reference 18 indicate that a plastic pipe eutectic storage system can be fabricated, filled and sealed at a cost of \$800 for a 750 gallon or 10,000 pound system. This cost estimate falls about 20 percent higher than the estimated lower bound curve of Figure 2-9.

The actual cost estimates given in Section 3 are based on tank costs about twice the lower bound of Figure 2-7.

FIGURE 2-8. COOLING STORAGE UNIT COSTS STAINLESS STEEL TANKS (UPPER BOUND)

FIGURE 2-9. COOLING STORAGE UNIT COSTS PLASTIC-CONCRETE TANKS (LOWER BOUND)

2.3.2.2 Performance of Storage Space Cooling System

Efficiency. Storage space cooling systems should exhibit fairly high storage efficiencies because the temperature differentials are low and the storage systems tend to have large volume to surface ratios. With good insulation, the storage efficiencies of these systems should be 90 percent or better for even the smaller units.

Size. The energy density of the four cooling storage systems are summarized in Table 2-1. The ice-making and eutectic systems are more compact and lighter than the cool water and the glycol-water systems.

2.4 CONTROL TECHNOLOGY

The implementation of TES for hot water supply, space heating, and space cooling in building requires economic advantages/incentives for the utility and the customer. The customer incentive is obtained from favorable off-peak electricity rates. The utility advantage is obtained from load level management that reduces the peak loads and results in more efficient use of the utility system. Load management employs control technology that allows the electric utilities to manage the TES load either by time of day or direct control.

2.4.1 Description of Control Systems

The two control systems described herein are the clock activated control (with dual rate meter) and dynamic control systems.

2.4.1.1 Clock Activated Control (with dual rate meter)

A simple timer unit is used to set peak or off-peak periods. The same time periods are usually used each day, although a more sophisticated clock could have a weekly cycle. A dual rate meter can be used in conjunction with the clock control, or the clock can simply cut off certain loads at specified times.

2.4.1.2 Dynamic Controls

Dynamic control systems fall into two broad classes, ripple or radio. Ripple control uses either a low frequency (200 Hz) or medium frequency (6 Hz) signal transmitted along the power line and received at each user's storage system on a special receiver. Lower frequency systems have a longer range, but involve more costly equipment and reduced flexibility. Some

systems combine meter reading with load control. Most control systems involve the use of coded signals that allow multiple switches at each load point so the load can be "turned down" as opposed to "turned off".

2.4.2 Costs and Control Systems

The costs associated with the various control systems have been approximated and are as follows:

Demand and Total Energy Meters	\$60-80/Unit
Ripple Control	\$70-100/Unit
Two-Way Control and Data Acquisition	\$150-200/Unit

3.0 CONSUMER STORAGE COSTS FOR HOT WATER, HEATING AND COOLING

A preliminary evaluation of the incremental capital investment costs to the consumer for TES has been performed in four geographical areas. These areas are referred to as Utility Service Areas A, B, C, and D.* The analysis considers three forms of TES (domestic hot water, space heating and space cooling) under three storage intervals (16 hours, 8 hours, and 4 hours). The incremental equipment and installation costs include both the TES and associated control system.

3.1 DOMESTIC HOT WATER

Domestic hot water heating, where accomplished electrically, can offer significant potential for utility load management through TES. Calculations of the hot water storage capacities required to service the four utility areas and three storage intervals are made. These storage capacities are then translated into customer incremental costs relative to the baseline (zero storage) case.

3.1.1 Required Storage Capacity

The average per capita daily hot water usage has been estimated (Reference 19) in each of the four geographical areas as shown in Table 3-1.

TABLE 3-1. AVERAGE PER CAPITA DAILY HOT WATER USAGE

Function	GALLONS/DAY/PERSON		
	Minimum	Maximum	Average
Personal	10	23	16.50
Laundry	2	4.5	3.25
Dishes	1	2.5	1.75
Total	13	30	21.50

* A,B, Northeast; C, Midwest; D, Southwest

For an average household of 3.1 persons, the average daily hot water load would then be 66.6 gallons. In a 16-hour storage interval, it is assumed that the entire load will be consumed, and that the hot water heater must also provide storage margins for imperfect stratification and insulation losses. Reference 20 shows that the thermocline is about 1.25 feet thick for an inlet-outlet water temperature differential of 70°F. During a northern winter, this differential will be approximately 100°F so that a 1.8 foot thermocline is assumed. Based on winter inlet temperatures and a nominal tank height of 5 feet, the storage unit in Utility Areas A, B, and C would be only 64 percent useful, resulting in a 104-gallon capacity to overcome imperfect stratification. In Utility Area D, imperfect stratification could be compensated for by an 89-gallon tank.

In an eight hour storage interval it is assumed that half of the personal usage can be deferred to off-peak hours, reducing storage requirements with imperfect stratification to 62.5 gallons in the northern regions and 53.3 gallons in Utility Area D. When the storage interval is reduced to four hours, it is assumed that half of the total daily hot water usage can conveniently be deferred to off-peak hours, reducing imperfect storage requirements to 52 gallons in the three northern regions and 44.5 gallons in Utility Area D.

In calculating the capacity of the baseline (zero storage) hot water systems for comparison with storage systems, it was determined that the 18 gallon/hour recovery rate (100°F temperature rise) of 4.5 kW electric heaters was adequate to handle the estimated peak rate usage of 14.3 gallons/hour for the 3.1 person family unit. The lower insulation losses of small units would then suggest the use of 30-gallon water heaters for the baseline case. However, the small incremental capital cost of 50-gallon heaters that can accommodate larger family units has clearly shown itself to be a desirable feature for the resale market. For this reason, the 50-gallon heater is assumed as the minimum storage size.

The required hot water heater capacities are listed in Table 3-2.

Table 3-2. Required Hot Water Heater Capacities

Utility Area	Hot Water Storage (Gallons)			
	No Storage Use Time*	4 Hour Storage Use Time*	8 Hour Storage Use Time*	16 Hour Storage Use Time*
A, B, C	50	52	62.5	104
D	50	50	53.3	89

3.1.2 Incremental Cost of TES for Domestic Hot Water

The cost of the top of the line (10-year, high insulation) electric hot water heater is approximated by, $\$175 + \$2.80/\text{gallon}$, where \$75.00 of the fixed cost is an installation charge (Sears). The load management controls for storage systems must be added to this cost. The cost of a ripple control installation is \$105 which includes \$70.00 for the receiver plus 50 percent for installation and its share of the transmitter cost. Although time clock control is considerably less expensive than ripple control, it was not considered here since the flexibility of ripple control appears to be advantageous.

The incremental equipment and installation cost of ripple-controlled hot water storage systems is shown in Table 3-3. These incremental costs will be modified by the actual availability of the required unit sizes, i.e., standard manufactured sizes.

*"Storage Use Time" is synonymous with "Discharge Time."

Table 3-3. Incremental Installation Cost of Ripple-Controlled Hot Water Storage Systems

Utility Area	Incremental Installed Cost (\$)*		
	4-Hour Storage Use Time	8-Hour Storage Use Time	16-Hour Storage Use Time
A, B, C,	111	140	256
D	105	114	214

An additional factor to consider is the increased insulation losses of the larger storage tanks. The effect of these losses on the consumer's heating/cooling costs will vary with the time of year, geographical location and placement of the hot water heater in the residence. As a first approximation, it is assumed that this hot water heat loss has no net effect on the annual home heating/cooling loads, and thus will be treated as an added cost of hot water storage.

The insulation heat losses would be increased by the larger surface area of the storage tanks. Reference 21 shows that the daily heat loss of a 50-gallon electric hot water heater with 2 inches of thermal insulation is 21.2%. Assuming that the surface area varies as the $2/3$ power of volume, then the daily insulation loss (in equivalent gallons) as a function of tank size is approximately $10.6 \left[\frac{\text{gallons}}{50} \right]^{2/3}$. If the insulation thickness of the 104-gallon tank were not increased, the daily insulation loss would be about 26 percent of the daily consumption. This annual loss of 17.4 gallons is equivalent to 1400 kWh, assuming an average temperature differential of 90°F. It is clear that increased insulation would be a substantial benefit to the consumer.

*The ANL study increased the fractional tank sizes to standard hot water heater sizes and employed a differential cost of \$3.15/gallon to arrive at somewhat larger increment costs.

Assuming that insulation losses from the stored hot water must be held to 10 percent of the hot water consumption, then the annual insulation losses in Area C are restricted to about 500 kWh. Using the data in Reference 21, but modifying the insulation loss calculations to use the mean tank diameters rather than the external insulation diameter for heat flow determination, leads to an insulation requirement of 3.4 inches for a 50-gallon tank. The 62.5-gallon (8-hour storage) tank has a 16 percent greater surface area so that the insulation must be increased to 4.0 inches to hold the losses to 500 kWh. In the same manner, it can be determined that the 104-gallon tank would require 5.5 inches of insulation.

The cost of this additional insulation and the increased areas of the steel jacket can be calculated from data supplied in Reference 21. The area of steel jacket and volume of insulation required for each tank are as follows:

<u>Tank Storage (Gallons)</u>	<u>Insulation (Inches)</u>	<u>Jacket Area (Sq. Ft.)</u>	<u>Insulation Ft³</u>
50	2	30.3	4.4
50	3.4	36.0	10.6
62.5*	4.0	46.5	12.2
104*	5.5	60.0	19.7

Based on 1973 prices from Reference 21, the incremental insulation costs over those of a 50-gallon unit with 2 inches of insulation would be \$7 for the 50-gallon unit, \$13 for the 62.5-gallon unit and \$25 for the 104-gallon unit. Thus, additional insulation costs are small and can be ignored in calculating TES costs to the consumer.

3.2 SPACE HEATING

Two basic types of space heating are considered; central and room. TES storage requirements for each case are calculated and compared with the baseline (zero storage) case to obtain incremental customer costs.

* Five foot storage tank height assumed.

3.2.1 Required Central Heat Storage Capacity

The incremental cost of TES for home heating was evaluated in the three northern geographical areas for storage durations of 4, 8, and 16 hours. The design temperatures and degree days/day assumed for the three areas were:

<u>Utility Areas*</u>	<u>Design Temperature</u>	<u>Design DD/D (Ref. = 65°F)</u>
A	0°F	65
B	-7°F	72
C	1°F	64

An average well-insulated single-family unit was assumed to require 4 kWh of heating per degree day (Reference 23). Assuming a uniform diurnal heating load and 100 percent storage efficiency leads to the TES storage and charging requirements**in Table 3-4.

Table 3-4. Space Heating Storage and Charging Requirements

AREA	DIRECT HEATING LOAD (KW)	STORAGE USE TIME					
		4 HOURS		8 HOURS		16 HOURS	
		REQUIRED STORAGE (KWH)	HEAT LOAD & CHARGE RATE (KW)	REQUIRED STORAGE (KWH)	HEAT LOAD & CHARGE RATE (KW)	REQUIRED STORAGE (KWH)	HEAT LOAD & CHARGE RATE (KW)
A	10.8	43.3	13.0	86.8	16.3	173.3	32.9
B	12	48.0	14.4	96.0	18.0	192	36.0
C	10.7	42.9	12.9	85.8	16.0	171.6	32.0

*Service Area D did not require significant heating and, therefore was not considered in this study.

**The ANL study, to which this report provides input, assumes a 90 percent efficiency for central heating systems and incorporates a 20 percent overdesign factor for short storage periods that leads to somewhat higher storage requirements and charging rates. A 100 percent efficiency was assumed for disbursed heating systems by the ANL study.

The storage and charging requirements shown above are somewhat conservative due to the assumed constant daily temperature profile. However, the 100 percent efficiency assumption is not considered to have significant effect since the TES storage unit is located inside the residence.

3.2.2 Incremental Cost of TES for Central Storage

The incremental cost of TES heating can now be determined by assuming that both the baseline system (no TES) and the TES systems would be new construction central electric units that operate with the same duct system. The cost of installed central electric furnaces was estimated by \$400 + \$20/kW (excluding ductwork). This algorithm includes the furnace cost plus a 100 percent installation charge based on data obtained in the Washington, D.C. area.

The cost of central storage units is based on the lower bound of English Central Systems increased by 30 percent to translate the costs to port of entry. These costs are then increased by 100 percent for installation and a \$105 ripple control cost is added to obtain the algorithm, \$375 + \$12/kWh (excluding ductwork).* The direct heat and TES cost algorithms lead to incremental costs as shown below for central heat storage.

Table 3-5. Incremental Costs for Central Heat Storage

Utility Service Area	Incremental Customer Cost (\$)		
	4-Hour Storage Use Time	8-Hour Storage Use Time	16-Hour Storage Use Time
A	279	799	1839
B	311	887	2039
C	276	791	1820

*The ANL study adds a storage furnace cost of \$23/kW and \$140 per unit for the cost of relay control that lead to a considerably larger incremental cost for TES. For charging times of eight hours or more it is estimated that the charging rate can be handled by the storage unit and that the only incremental costs due to charging rate are in additional household wiring. ANL has extra cost for relay controls of \$140.

The longer storage times may have an additional cost increment imposed by additional house wiring required to accommodate the short storage charging time. For example, in Area B an eight-hour charging interval will require 50 amps (at 240 volts) for direct heating plus another 100 for storage charging. This possible additional cost (or service limitation) is not considered in this analysis.

It should be noted in the above table that the per unit incremental storage cost increases at a faster rate than the required storage. This is because the algorithms are similar in base cost with most of the cost difference arising from the component dependent on kWh. If the importing costs were 15 percent instead of the assumed 30 percent, then the storage cost algorithm would become $\$335 + \$10/\text{kWh}$ and the incremental costs presented in the table would decrease about 40 percent for 4 hour storage and 20 percent for 16 hour storage.

3.2.3 Required Room Heat Storage Capacity

The design heating in region B is 72 DD/day, or 288 kWh for a nominal dwelling. Assuming six rooms with equal heating load results in the following heating load for baseboard heat and required capacity of room storage units.

Table 3-6. Heating Load and Required Capacity
of Room Storage Units

BASEBOARD	STORAGE DURATION (HRS)		
	4	8	16
2kW	8 kWh	16 kWh	32 kWh
8 Amps @ 240 Volts	9.6 Amps	16 Amps	24 Amps

3.2.4 Incremental Cost of Room Storage

The cost of uninstalled baseboard units available in the range of 0.5 to 2KW is \$11.00 + \$18.00/kW for all-electric and \$13.00 + \$21.00/kW for fluid-electric. The single room cost for the fluid-electric baseboard would be \$55 plus installation of an 8 Amp circuit. The estimated per room installation cost in new construction is \$60 labor plus \$25 for 50 feet of wire and a circuit breaker at a total room cost of \$140.

The TES room units are available in a range of 12kWh to 38 kWh with a cost algorithm of \$225 + \$6/kWh. The ripple control cost which is divided among the number of rooms that are heated should be added to this cost, for a total cost per room of $\$225 + \frac{\$105}{\text{\# of Rooms}} + \$6/\text{kWh}$. The additional wiring costs will depend on the circuit configuration. If individual room circuits are used, the labor costs should remain similar with roughly linear increases in the wire/circuit breaker cost. Table 3-1 shows the per room cost of installed baseboard and TES units.

Table 3-7. Cost Per Room of Installed Baseboard and TES Units

<u>BASEBOARD</u>	<u>STORAGE DURATION</u>		
	<u>4 HOURS</u>	<u>8 HOURS</u>	<u>16 HOURS</u>
140.	$390 + \frac{105}{n}$	$435 + \frac{105}{n}$	$560 + \frac{105}{n}$

Thus, the incremental (new construction) cost of TES for a four hour storage duration is $250 + \frac{105}{n}$; for an eight hour storage duration is $295 + \frac{105}{n}$; and for a sixteen hour storage duration is $420 + \frac{105}{n}$, where "n" equals the number of rooms with TES units.

3.3 SPACE COOLING

TES space cooling has been evaluated in utility source areas C (cold climate) and D (hot climate) for storage usage times of 4, 8 and 16 hours.

3.3.1 Required Cool Storage Capacity

Based on the design daily cooling loads defined by the National Association of Home Builders Association (NAHB) and assuming a COP of 2, the required daily electrical usage is

<u>SERVICE AREA</u>	<u>WELL-INSULATED</u>	<u>MEDIUM-INSULATED</u>
C	80.2 kWh _e /day	96.7 kWh _e /day
D	89.7 kWh _e /day	112.5 kWh _e /day

If a uniform diurnal load and a 95% cool storage efficiency are assumed, then the cool storage capacity and charging rates required for each situation are as shown in Table 3-8.*

Table 3-8. Cool Storage Capacity and Charging Requirements

SERVICE AREA	DIRECT COOLING LOAD (kW _e)	STORAGE USE TIME					
		4 HOURS		8 HOURS		16 HOURS	
		REQUIRED STORAGE (kWh _e)	COOLING LOAD & CHARGE (kW _e)	REQUIRED STORAGE (kWh _e)	COOLING LOAD & CHARGE (kW _e)	REQUIRED STORAGE (kWh _e)	COOLING LOAD & CHARGE (kW _e)
C WELL-INSULATED	3.3	13.9	4.0	27.8	5.0	55.6	10.3
C MEDIUM-INSULATED	4.0	16.8	4.8	33.7	6.1	67.4	12.4
D WELL-INSULATED	3.7	15.6	4.5	31.2	5.7	62.3	11.5
D MEDIUM-INSULATED	4.7	19.8	5.7	39.7	7.2	79.2	14.6

*The ANL study assumed a non-uniform diurnal cooling load equivalent to 18 hours of daily operation in Area D and 17 hours in Area C. This assumption led to higher TES incremental costs.

3.3.2 Incremental Cost of TES for Space Cooling

The incremental cost of TES cooling can be determined in a manner similar to TES heating by assuming new construction central units that require no modifications to the duct system. The three basic added costs introduced by TES cooling are the cool storage system, a larger condenser/compressor unit to handle loads as high as 14.6 kW, and a slightly increased use of energy resulting from storage inefficiency. The equipment costs of TES cooling storage (including the evaporators, water pump, ice sensor, and expansion valve) have been estimated in reference 23 as having a lower bound value of $\$200 + \$8.00/\text{kWh}_e$. In discussions with air conditioning firms in the Washington, D.C. area, it appears that A/C system installation charges approximate the cost of the equipment. Thus, total installed cool storage costs including load maintenance equipment are approximately $\$500 + \$16/\text{kWh}_e$. The storage system costs as defined above (including ripple control) are listed in Table 3-9.

Table 3-9. Cool Storage System Costs (\$)

SERVICE AREA	STORAGE USE TIME		
	4 HOURS	8 HOURS	16 HOURS
C Well-insulated	723	946	1392
C Medium-insulated	769	1038	1576
D Well-insulated	750	1000	1500
D Medium-insulated	817	1134	1768

The second incremental cost component is the larger outside unit required to handle the large night time loads of direct cooling plus charging the storage system. Total compressor/condenser equipment costs to the dealer can be tripled to cover dealer markup and installation so that the

installed costs (assuming COP = 2) can be written as $\$600 + \$68/\text{kW}_e$.*

Table 3-10. Incremental Costs for Larger Compressor/
Condenser Unit (\$)

SERVICE AREA	STORAGE USE TIME		
	4 HOURS	8 HOURS	16 HOURS
C Well-insulated	48	116	476
C Medium-insulated	54	143	570
D Well-insulated	54	136	530
D Medium-insulated	68	170	673

Finally, the inefficiency of the storage system will cause higher power consumption than in the baseline system.** This additional cost typically adds a few percent to the annual cost of a cool storage system. Since our estimates are rough, detailed calculations for these losses were not made.

*The total cost algorithm for storage and compressor/condenser installation with ripple control in them $\$1100 + \$68/\text{kW}_e + \$16/\text{kWh}_e$. This compares to the ANL algorithm of $\$740 + \$210/\text{kW}_e + \$16/\text{kWh}_e$.

**There may be an additional change in power consumption caused by COP changes resulting from operating at an evaporator temperature of 32° rather than 55°F . However, this reduction in COP appears to be offset by the advantage of the lower condenser temperature during night operation. It was, therefore, assumed that there would be no net affect on the COP of cool TES storage operation.

4.0 SUMMARY

This report has characterized TES technology and estimated the incremental capital cost to consumers for TES storage for domestic hot water, space heating and space cooling. Table 4-1 shows the household storage requirements in kWh_e for each of the three functions in the four utility service areas. The cool storage requirements are those for a medium insulated residence.

Table 4-2 shows the incremental costs to the consumer for installation of the levels of TES storage specified in Table 4-1. In Service Area C, it can be seen that increasing the storage interval from 4 hours to 16 hours increases the TES incremental cost for hot water and space cooling by a factor of about 2-1/2, while the cost for space heating is increased by a factor of six. This rapid increase in incremental cost for space heating arises from a substantial cost for direct central heaters and a storage cost algorithm that increases almost linearly with storage capacity.

Table 4-3 roughly compares the characteristic costs (in dollars/kWh_e) of the three types of storage as a function of the storage duration. As can be seen, hot water and space heat storage systems have the lowest costs, and the cost rises slowly with the storage duration. That implies these systems can be easily tailored to produce the greatest utility savings, once the utility system characteristics are known.

Storage air conditioning is characteristically considerably more expensive than the other systems, and appears to exhibit some economies of scale in that the longer duration storage systems cost less on a per unit basis. Storage air conditioning is only going to be attractive in utility systems which show a sharp summer peak with the consequent large potential savings from capacity reduction with storage.

TABLE 4-1. HOUSEHOLD STORAGE REQUIREMENTS

SERVICE AREA	DESIGN DAILY LOAD (kWh _e)			INSTALLED STORAGE (kWh _e)								
	H ₂ O WITH 10% INSULATION LOSS	HEAT	COOL WITH 5% INSULATION LOSS	4 Hour Storage Use Time			8 Hour Storage Use Time			16 Hour Storage Use Time		
				H ₂ O	HEAT	COOL	H ₂ O	HEAT	COOL	H ₂ O	HEAT	COOL
C	15.0	257	96	11.8	42.8	16.8	14.2	85.6	33.7	23.6	171.3	67.4
D	15.0	NA	113	8.8	NA	19.8	9.4	NA	39.7	15.6	NA	79.2
A	11.6	259	NA	11.8	43.2	NA	14.2	86.3	NA	23.6	172.6	NA
B	15.0	288	NA	11.8	48	NA	14.2	96	NA	23.6	192	NA

NA = Not Analyzed

TABLE 4-2. CUSTOMER INCREMENTAL COST FOR INSTALLED STORAGE

SERVICE AREA	CUSTOMER INCREMENTAL COST FOR INSTALLED STORAGE SYSTEMS (\$)								
	4 HOURS STORAGE USE			8 HOURS STORAGE USE			16 HOURS STORAGE USE		
	H ₂ O *	HEAT (CENTRAL)	COOL	H ₂ O *	HEAT (CENTRAL)	COOL	H ₂ O *	HEAT (CENTRAL)	COOL
C	111	276	788	140	791	1093	256	1820	2090
D	105	NA	924	114	NA	1382	214	NA	2597
A	111	279	NA	140	799	NA	256	1839	NA
B	111	311	NA	140	887	NA	256	2039	NA

NA = Not Analyzed

TABLE 4-3. ALTERNATE STORAGE SYSTEM SUMMARY COMPARISON

STORAGE SYSTEM TYPE	RANGE OF SYSTEM COSTS (\$/KWh)		
	<u>4 HOUR STORAGE</u>	<u>8 HOUR STORAGE</u>	<u>16 HOUR STORAGE</u>
HOT WATER	9.4-11.9	9.8-12.1	10.8-13.7
SPACE HEAT	6.4-6.5	9.2	10.6
SPACE COOLING	46.7-46.9	32.4-34.8	31.0-32.8

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