Current Cost and Performance Requirements for Residential Cool Storage Systems

**D. R. Brown
G. E. Spanner**

August 1988

**Prepared for the U.S. Department of Energy
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Richland, Washington 99352

PREFACE

This study defines the current cost and performance requirements for residential cool storage technologies based on the characteristics of conventional air conditioning equipment and residential time-of-day (TOD) rate structures existing during the 1986-1987 time frame. A companion document, Estimating the Market Penetration of Residential Cool Storage Technology Using Economic Cost Modeling, has also been prepared.

Currently, rate structures are changing rapidly. Given the volatility of rate structures, the establishment of cost goals is challenging. The goals presented in this study are based on the utility rate structure as of 1986.

This study serves to define residential cool storage cost and performance requirements in the current economic environment as well as the many issues affecting the requirements for residential cool storage systems both now and in the future. The same methodology can be employed to establish long-run goals once future rate structures are adequately defined.

SUMMARY

Cool storage systems have the potential to reduce the overall cost of cooling for residential customers by shifting all or part of the electric load occurring during peak demand periods to off-peak periods, thus lowering the total electric bill. The objective of this study was to develop current system initial capital cost and annual performance requirements for cool storage technologies in residential applications. The requirements were developed by considering the cost and performance of currently available residential cooling equipment and the economic opportunity for employing storage. The resulting cost and performance requirements, if achieved, would make the new technologies economically competitive with the conventional technology, assuming that both provide the same or similar service. The following four steps outline the general procedure for developing the requirements:

1. Identify the service to be provided by the new technology.
2. Identify the conventional means of providing the same or similar service.
3. Characterize the cost, performance, and economic figure-of-merit for the conventional means of providing the service.
4. Solve for the combinations of cost and performance for the new technology that match the conventional technology's figure-of-merit.

Initial capital cost and annual coefficient-of-performance (COP) requirements were developed for one new construction and two retrofit scenarios for nine combinations of site and building type. Two retrofit scenarios were necessary to distinguish between thermal energy storage (TES)-augmented systems that would fully replace the conventional equipment and add-on TES equipment. St. Louis, Missouri; Pittsburgh, Pennsylvania; and Hartford, Connecticut were selected for analysis because they represented the 90th, 50th, and 10th percentile sites, respectively, when prospective sites were ranked by the combination of cooling-degree-days and peak/off-peak electric rate differential. The three building types included were ranch, two-story, and townhouse residences.

A TES-augmented system in the new construction scenario with the same annual COP as the reference system would be worth an additional \$999 above the initial cost of the reference system for a ranch house in St. Louis. Similarly, a TES-augmented system would be worth an additional \$860 and \$624, respectively, for two-story and townhouse residences in St. Louis. Alternatively, a TES-augmented system with the same initial cost as the reference system would need to have an annual COP roughly half that of the reference system for any of the three building types in St. Louis.

Conditions are less attractive in Hartford and Pittsburgh. Here the additional worth of a TES-augmented system with a COP equal to its reference system ranges from \$62 for the two-story house in Hartford to \$246 for the ranch house in Pittsburgh. St. Louis is more attractive because of its higher annual cooling load and large electric rate differential for moving to off-peak. Pittsburgh is more attractive for TES than Hartford because of its higher electric rate differential, even though it has the lowest annual cooling load. For TES-augmented systems with the same initial cost as the reference system, the annual COP need only be roughly 50% of the reference system in Pittsburgh, much like the case in St. Louis. In Hartford, where the benefit per kWh of shifting the electric load off-peak is lower than for either St. Louis or Pittsburgh, the annual COP required for a TES-augmented system with the same initial cost as the reference system must be greater than 80% of the COP for the reference system.

The prospects for TES in the retrofit/replacement system scenario are extremely limited. For each of the nine pairs of cities and buildings, the TES-augmented replacement system would have to either be less expensive than its corresponding conventional unit while achieving the same annual COP or achieve a higher annual COP for the same cost.

The general trends and prospects for TES in the retrofit/add-on system scenario are similar to those found for the new construction scenario and are caused by the same factors. For example, a TES add-on resulting in the same annual COP as the reference system would be worth an additional \$1105, \$951, and \$689, respectively, for ranch, two-story, and townhouse residences in St.

Louis. Alternatively, if the TES add-on was free, the resultant system would need to have an annual COP roughly half that of the reference system for any of the three building types in St. Louis.

Sensitivity analyses were conducted for alternative storage sizing, reference (conventional) system electric rate structure, and financing rate assumptions. As a general rule, the chill-generator and storage unit were assumed to be sized to allow all of the peak cooling load to be moved off-peak. Assuming the chill-generator and storage unit would be sized so that the chill-generator ran continuously (24 hours per day) on the peak cooling day of the year reduced the initial capital cost requirements by 15% or less for a given level of annual COP. Basing the reference (conventional) system's annual electric bill for cooling on the optional time-of-day (TOD) rate (which yielded a higher annual electric bill for cooling than the flat rate) increased the initial capital cost requirements by up to 30% for a given level of annual COP. Finally, using 5.9% rather than 10% as the financing rate increased the initial capital cost requirements by up to 15% for a given level of annual COP.

The prospects for residential cool storage vary dramatically, depending on the meteorology and utility rate structure at a particular site. Both the cooling load (for the same building size) and electric rates vary by more than an order of magnitude across the U.S. Selection of any specific combination of initial capital cost and annual COP as the singular requirement for residential cool storage must consider a specific target share of the residential market.

The prospects for residential cool storage also depend on the perspective of the homeowner and the nature of the TES-augmented system. Residential cool storage systems are much more likely to be economically attractive in new construction applications or as add-on technology in retrofit applications. Full replacement systems in retrofit applications are unlikely to be economically feasible.

The current cost and performance requirements identified in this study would be very difficult to achieve. A previous study conducted for the Electric Power Research Institute (Asbury, Giese, and Looney 1986) concluded that a

TES-augmented cooling system could probably be installed for a \$2000 premium above the cost of a conventional cooling system, but noted that very few utility rate structures provide the residential class with a sufficient level of financial incentive for shifting air conditioning demand to off-peak. The cost and performance requirements identified in this study confirm this dilemma. Based on the current characteristics of residential air conditioning equipment and rate structures, the allowable cost premium in St. Louis (the most attractive of the three sites evaluated in this study) was estimated to be only \$1000.

However, during the time frame this study was conducted (1987-1988), the availability of TOD rates for the residential class was rapidly increasing. Of particular importance, many Southern utilities (where cool storage technologies are expected to have the greatest potential) did not have TOD rates for the residential class at the beginning of the study, but were implementing this type of rate structure as the analytical portion of this study came to a close. The increased availability of TOD rates or other incentives for employing residential cool storage within Southern utilities would significantly change the results of this study. Follow-on efforts should be directed toward tracking the changes in residential rate structures and identifying future-oriented cost and performance requirements when the long-run characteristics of the structure for the residential rate class is more certain.

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CONTENTS

PREFACE	iii
SUMMARY	v
ACKNOWLEDGEMENTS	ix
1.0 INTRODUCTION	1.1
2.0 ANALYTICAL APPROACH	2.1
2.1 GENERAL PROCEDURE	2.1
2.2 KEY ISSUES	2.2
2.2.1 Reference Cooling System	2.2
2.2.2 Site Selection	2.2
2.2.3 Building Cooling Load	2.4
2.2.4 Storage System Size	2.5
2.2.5 Cost and Performance Requirement Calculations	2.6
2.2.6 Unique Perspectives and Applications	2.7
3.0 SITE SELECTION	3.1
4.0 BUILDING COOLING AND ELECTRIC LOADS	4.1
4.1 DOE-2	4.1
4.2 RESIDENTIAL BUILDINGS MODELED	4.2
4.3 COOLING SYSTEM PERFORMANCE	4.3
4.4 COOLING SYSTEM SIZING	4.4
4.5 COOLING AND ELECTRIC LOAD RESULTS	4.4
5.0 SYSTEM LEVEL REQUIREMENTS	5.1
5.1 REFERENCE SYSTEM COSTS	5.1
5.2 LIFE-CYCLE COST CALCULATIONS	5.2

6.0	TES-AUGMENTED SYSTEM COST AND PERFORMANCE REQUIREMENTS	6.1
6.1	ANALYTICAL APPROACH	6.1
6.2	COST AND PERFORMANCE REQUIREMENTS	6.3
6.3	SENSITIVITY CASES	6.11
6.3.1	Alternative Storage Sizing	6.13
6.3.2	Alternative Rate Structure	6.16
6.3.3	Alternative Financing Rate	6.19
7.0	CONCLUSIONS	7.1
	REFERENCES	R.1

FIGURES

2.1	The Boundary Between Acceptable and Unacceptable Combinations of Initial Capital Cost and Annual COP	2.8
6.1	Initial Capital Cost and Annual COP Requirements for a TES-Augmented System in the New Construction Scenario	6.5
6.2	Initial Capital Cost and Annual COP Requirements for a TES-Augmented System in the Retrofit/Add-on System Scenario	6.10
6.3	Storage-Sizing Sensitivity and Base-Case Figures	6.14
6.4	Rate Structure Sensitivity and Base-Case Figures	6.17
6.5	Financing Rate Sensitivity and Base-Case Figures	6.20

TABLES

3.1	Site Utility Data	3.2
3.2	Site Meteorological Data	3.3
3.3	Overall Site Ranking	3.4
3.4	Characteristics of Sites Selected	3.5
4.1	Annual Cooling and Electric Loads	4.5
4.2	Annual Electric Bills for Cooling	4.5
4.3	Hourly Cooling Loads on the Peak Cooling Day for the St. Louis Ranch House	4.8
4.4	Hourly Cooling Loads on the Peak Cooling Day for the Pittsburgh Ranch House	4.9
4.5	Hourly Cooling Loads on the Peak Cooling Day for the Hartford Ranch House	4.10
5.1	Reference Air Conditioning System Capital and Maintenance Costs	5.2
5.2	Economic Assumptions	5.3
5.3	Life-Cycle Cost Results	5.3
5.4	Life-Cycle Cost Components for the New Construction Scenario . .	5.4
5.5	Life-Cycle Cost Components for the Retrofit Scenario	5.4
6.1	New Construction Scenario Cost and Performance Requirements . . .	6.4
6.2	Retrofit/Replacement System Scenario Cost and Performance Requirements	6.7
6.3	Retrofit/Add-On System Scenario Cost and Performance Requirements	6.9
6.4	Retrofit/Add-On System Scenario Cost and Performance Requirements: Alternative Cost Units	6.12

6.5	Alternative Storage Sizing Results, St. Louis Ranch House	6.15
6.6	Alternative Rate Structure Results, St. Louis Ranch House	6.18
6.7	Alternative Financing Rate Results, St. Louis Ranch House	6.21

CURRENT COST AND PERFORMANCE REQUIREMENTS FOR RESIDENTIAL COOL STORAGE SYSTEMS

1.0 INTRODUCTION

Cool storage systems have the potential to reduce the overall cost of cooling for residential customers by shifting all or part of the electric load occurring during peak demand periods to off-peak periods, thus lowering the total electric bill. The potential energy cost savings are substantial. In some locales the difference between the peak and off-peak energy charges are greater than \$0.100/kWh. This savings potential is the primary driving force for developing cool storage systems for residential applications.

The overall objective of this study, conducted at Pacific Northwest Laboratory^(a), was to establish current system initial capital cost and annual performance requirements for cool storage technologies in residential applications. The requirements are intended to be used by developers and technology evaluators as a benchmark for comparison with the actual cost and performance characteristics of prospective cool storage systems. The requirements represent combinations of system cost and performance that, if achieved, would make the cool storage system economically competitive with a conventional air conditioning (AC) system. By comparing the actual or projected characteristics of cool storage systems with the requirements established in this study, technology developers, evaluators, and planners can obtain a better understanding of the potential for a prospective cool storage system and make more informed decisions about research and development directions.

Section 2.0 describes the general analytical approach. Sections 3.0 and 4.0 describe the site selection process, and building cooling and electric load modeling, respectively. System level (life-cycle cost) requirements are presented in Section 5.0. Section 6.0 presents the cost and performance requirements for the thermal energy storage (TES)-augmented systems. Finally, the study's conclusions are discussed in Section 7.0.

(a) Operated for the U.S. Department of Energy by Battelle Memorial Institute.

2.0 ANALYTICAL APPROACH

The objective of this study was to establish current cost and performance requirements for cool storage technologies in residential applications. Establishing these requirements would serve the following purposes.

- The requirements identify a set of cost and performance characteristics that would make cool storage an economically attractive option for different segments of the residential cooling market.
- The requirements provide a benchmark for measuring the research and development progress of concepts being developed.
- Development of the requirements focuses attention on the interaction of multiple factors affecting the potential attractiveness of cool storage.

2.1 GENERAL PROCEDURE

Cost and performance requirements for residential cool storage were developed by considering the cost and performance of currently available residential cooling equipment and the economic opportunity for employing storage. The resulting market-based requirements, if achieved, would make the new technologies economically competitive with the conventional technology or operating procedure, assuming that both provide the same or similar service. The following four steps outline the general procedure for developing market-based requirements:

1. Identify the service to be provided by the new technology.
2. Identify the conventional means of providing the same or similar service.
3. Characterize the cost, performance, and economic figure-of-merit for the conventional means of providing the service. This establishes the overall system level requirement.
4. Solve for the combinations of cost and performance for the new technology that match the conventional technology's figure-of-merit.

2.2 KEY ISSUES

The generalized framework described above requires the resolution of several issues to become a working analytical approach. Key issues impacting the direction of this study are discussed in the sections that follow.

2.2.1 Reference Cooling System

The following issues were considered in selecting the reference (conventional) residential cooling system:

- What criteria should be used to select the reference system(s)?
- Is more than one reference system necessary or desirable?
- Should the focus be on new construction or retrofit?
- How should combination heating and cooling equipment be treated?

The principal selection criterion was the market share of currently available residential cooling technology. The predominate technology, which was selected as the reference technology, was found to be a central cooling system consisting of an evaporator coil mounted in the indoor air circulating system and a remote air-cooled condensing unit. The condensing unit contains an electric motor-driven compressor, condenser, condenser fan and fan motor, and electric controls. The system working fluid is freon. This type of system was found to be the most common for homes built in the past and for new construction. Average system efficiencies have gradually improved over the years, but the basic system has remained relatively unchanged. Heat pump systems capable of providing heat or chill also represent a significant (although smaller) fraction of the market, but because they employ essentially the same equipment for supplying chill at approximately the same efficiency as the standard air conditioning (AC) system described above, they were not considered separately. Requirements developed based on competition with the standard AC systems will also be generally applicable to competition with (air-to-air) heat pumps.

2.2.2 Site Selection

The number of cooling-degree-days (a general indicator of expected relative residential cooling loads) and utility rate schedules each vary across the U.S. by an order of magnitude or more. The variability of these factors and

their impact on the development of the requirements make site selection an extremely important, if not the most important, factor to consider. The following specific issues were considered in selecting the sites:

- Should the climate and rate structure characteristics be associated with specific or generic sites?
- Should the rate structure characteristics be based on currently published rate tables or the utilities' avoided costs?
- Should sites be selected or site characteristics be developed to represent the most attractive (for chill storage) situations, median or typical situations, or less attractive situations?
- What characteristics of climate and utility rate structures make chill storage attractive?

A utility's avoided cost is its marginal cost of production, whereas the consumer's electric rate tends to represent the average cost of production plus transmission and distribution costs. The exact relationship between the utility's cost and the consumer's rate often involves a complex set of rules established by the local utility commission. The use of time-of-day (TOD) rates, seasonal rates, and demand charges are attempts to more precisely allocate a utility's cost of supplying power to its customers. However, these rates and charges do not exactly match a utility's supply cost at any given time. In fact, no matter how finely a utility segments its rate structure, the allowable charges in any one period will normally reflect the average cost of power for that period rather than the utility's marginal or avoided cost. Thus, the customer's rate structure does not usually reflect the total value to the utility of reducing the consumption of electricity during a peak demand period. Therefore, it may be in the best interest of the utility to offer additional incentives to consumers for certain load management practices. Incentives are common in the commercial sector, but few, if any, utilities currently offer special incentives (such as rebates for TES systems) to residential customers, perhaps because the cost of handling the additional paperwork outweighs the potential benefit to the utility in the residential sector.

Currently published rate structures were chosen as the basis for establishing the cost and performance requirements because they represent the actual current costs that a residential customer would use in making his or her decision on whether to purchase a TES system. Future movement by utilities toward residential rate structures and incentives that more closely account for their cost of production was judged to be too speculative to consider in this study. Approximately one-third of the investor-owned utilities (50) offer TOD rates for residential customers (as of 1986). A handful of these also impose demand charges for this type of service. In general, the following conditions make cool storage more attractive:

- a higher differential between peak and off-peak energy rates - This differential provides the primary economic driving force for considering chill storage when demand charges do not apply.
- a higher ratio of peak to off-peak energy rates - This ratio defines the minimum acceptable storage performance (for a storage system that costs nothing to build and maintain).
- a larger number of annual cooling-degree days - Residential cooling loads are strongly correlated with the number of cooling-degree-days. In general, the greater the cooling load, the greater the potential benefit of incorporating cool storage.

The approach used was to select three sites representing relatively attractive (but not the best), typical, and relatively unattractive (but not the worst) combinations of the above variables. The intent was to identify the sensitivity of the requirements to site selection and develop information that would allow the estimating of potential market penetration as a function of storage cost and performance. Additional details regarding the site selection procedure and the meteorological and utility characteristics of the sites selected are presented in Section 3.0.

2.2.3 Building Cooling Load

One of the critical issues facing the process of developing the requirements was the approach for calculating building cooling loads. The estimation

of a building's cooling load is a complex analytical calculation involving the following key building-specific factors, among many others:

- building floor area and layout
- type, quantity, and location of insulation
- internal heating loads
- ventilation practices
- target indoor temperature and humidity.

An additional complication is the desire to predict the load on an hourly basis. Hourly load estimates are required to segregate peak loads from off-peak loads. Relatively simple methods that produce annual, monthly, or even daily load estimates are not adequate. The DOE-2 model developed by the Lawrence Berkeley and Los Alamos laboratories has the capability to simulate hourly performance. In addition, the characteristics of five generic building types, representing more than 90% of all new residences built in the United States, have been specified for use with the model. The DOE-2 model was used to estimate the hour-by-hour cooling load over 1 year for three residential building types at each of three sites, thus creating a matrix of nine site and building type combinations.

2.2.4 Storage System Size

Selecting the system storage size is a key design factor that directly impacts the peak load that can be moved off-peak and the size of the chill-generating equipment. Two sizing options represent the most commonly chosen design conditions:

- Size storage and chill-generating equipment to move all of the peak cooling load off-peak on the day with the largest peak cooling load of the year (load-shifting strategy).
- Size storage and chill-generating equipment to require constant 24-hour operation of the chill-generating equipment on the day with the largest peak cooling load of the year (load-leveling strategy).

The first option moves the entire annual load occurring during peak hours to off-peak hours, resulting in the maximum potential energy cost savings. However, peak periods may last 12 hours, resulting in a larger chill-generating

device than the conventional system requires, which would reduce the energy cost savings. The second storage-sizing approach would typically result in lower potential energy cost savings, but would benefit the user by requiring a smaller chill-generating device. The optimal size for storage will depend on the site-specific load and electricity rate structure, as well as on the storage system cost and performance. Because the site-specific factors vary significantly and the analytical procedure solves for the storage system cost and performance, the optimal storage size and chill-generating capacity could not be determined in advance. The first option was selected as the reference case based on recommendations in Asbury, Giese, and Looney (1986), and the second option was considered in a sensitivity analysis.

2.2.5 Cost and Performance Requirement Calculations

At issue here are assumptions regarding the charging and discharging of storage, the displacement of peak energy demands, and the characterization of system performance. Specifically, the following issues are of concern.

- How much of the peak cooling demand is actually shifted to off-peak hours during operation?
- How much of the storage is charged each day?
- At what level of detail should system performance be characterized?

It was presumed that adequate chill would be available each day from the storage unit to displace the entire peak cooling demand for storage units sized via the reference method described above. Recharging of storage is presumed to occur after the peak period ends each day. From a practical operating standpoint, this implies that the storage unit would be fully charged at the start of each day or that a more sophisticated load projection technique would be employed to ensure that an adequate (usually less than fully charged) supply of chill is available to meet the following day's peak-period load. The resultant standby losses (from being partially or fully charged 24 hours a day) are a part of the overall system-level performance that also includes charging and discharging losses (e.g., transport losses) and any other operating inefficiencies. The procedure for developing the requirements solves for this

single overall performance figure-of-merit and leaves the individual components to the discretion of the storage technology developer.

As indicated above, the requirements were established by solving for combinations of initial capital cost and annual performance for the storage-augmented cooling system that match the conventional technology's life-cycle cost of cooling. The general calculational procedure was as follows.

1. Assume that adequate chill storage capacity will be available to move all of the peak electric demand to off-peak. (Note that not all of the peak cooling demand will be met by either the conventional or TES-augmented systems, per standard design practices.)
2. Make an initial assumption for the TES-augmented system annual round-trip efficiency (annual COP).
3. Calculate the annual consumption and cost of electricity for the TES-augmented system.
4. Solve for the TES-augmented system initial capital cost (and implied annual operation and maintenance cost) that results in the same system-level cost of delivered chill as the conventional system.
5. Repeat steps 3 and 4 for other round-trip efficiency assumptions.

The result of this procedure is a curve (see Figure 2.1) defining the boundary between acceptable and unacceptable combinations of initial capital cost and annual COP.

2.2.6 Unique Perspectives and Applications

Different decision-making perspectives of homeowners and the nature of the prospective cool-storage systems require separate cost and performance requirements. The two key issues considered can be summarized as follows:

- Is the prospective cool storage system being considered from the perspective of new construction or as a retrofit?
- Will the prospective cool storage system be an accessory to or completely replace a conventional air conditioning system?

FIGURE 2.1. The Boundary Between Acceptable and Unacceptable Combinations of Initial Capital Cost and Annual COP

The most common perception of a cool storage system is a storage unit with charging and discharging (e.g., transport) accessories augmenting conventional air conditioning equipment. However, an integrated chill-generating and storing unit (a single piece of equipment) that completely replaces the conventional system is possible. Thus, developing the requirements is focussed at the system level. Even if the cool storage technology is an add-on to a conventional system, restrictive assumptions regarding the nature of the technology would have to be made to develop requirements for the storage unit itself. Thus, the focus in this study is on system-level requirements.

The reference cost of cooling in a retrofit situation will be less than in a new construction situation because the homeowner would have to pay only for the continued operation and maintenance of an air conditioning system rather than the purchase, operation, and maintenance of a new air conditioner.

Thus, separate requirements were developed for new construction and retrofit situations. The retrofit situation was further subdivided to allow for the case where cool storage is an add-on to a conventional system and for the case where a cool-storage system completely replaces the conventional system.

3.0 SITE SELECTION

The importance of the cooling load and utility rate structure in determining cost and performance requirements for residential cool storage systems was discussed in Section 2.2.2. Utilities listed in the Electric Rate Book (CSA Energy Consultants 1986) who offered TOD rates for residential customers were identified as candidates for residential cool storage. Representative cities in or near the utility districts were identified to establish the meteorological basis. Prospective cities were limited to those with the Typical Meteorological Year (TMY) data required for the building cooling load calculations.

The prospective sites for residential cool storage were ranked by their two primary characteristics (cooling load and peak/off-peak electric rate differential) that make cool storage attractive. Sites close to the 90th, 50th, and 10th percentiles were selected for developing the requirements. The reason for this approach was to select multiple sites representing a broad range of rate structures and meteorological characteristics within the population of candidate sites. The approach specifically avoids selecting the best or worst sites, which would lead to a set of less meaningful requirements.

Without previous knowledge of their relative importance, the number of cooling-degree-days and the peak/off-peak electric rate differential were assigned an equal weight in developing the rankings. Raw data for cooling-degree-days and the peak/off-peak electric rate differential were normalized by dividing the actual value for a specific site by the average value for all of the sites. The normalized figures for cooling-degree-days and peak/off-peak electric rate differential were then added to yield a single figure-of-merit for ranking. Tables 3.1, 3.2, and 3.3 show the utility data, meteorological data, and subsequent overall ranking for the candidate sites. St. Louis, Pittsburgh, and Hartford were selected as representative of 90th, 50th, and 10th percentile sites, respectively. Utility rate structure and meteorological data are summarized in Table 3.4 for these three cities.

TABLE 3.1. Site Utility Data

City	Peak Rate, cents/kWh	Off-Peak Rate, cents/kWh	Differential, cents/kWh	Normalized Differential
Oklahoma City	16.96	3.84	13.13	2.131
Morristown	14.00	3.26	10.74	1.744
Madison	13.83	3.10	10.73	1.742
Milwaukee	13.05	2.75	10.30	1.672
Green Bay	13.20	2.96	10.24	1.662
St. Louis	14.77	4.59	10.18	1.652
Des Moines	13.97	4.08	9.89	1.605
Providence	11.13	1.41	9.72	1.577
Albuquerque	15.08	6.05	9.03	1.465
Tampa	10.48	1.49	8.99	1.459
Green Bay	12.01	3.15	8.86	1.438
Little Rock	13.26	4.42	8.84	1.435
Eau Claire	11.34	2.63	8.71	1.414
Newark	16.23	7.81	8.42	1.367
Bismark	11.00	2.63	8.37	1.359
Cincinnati	9.86	2.00	7.86	1.276
Fort Wayne	9.77	2.43	7.34	1.192
Pocatello	10.80	3.78	7.02	1.139
Port Arthur	8.50	1.59	6.91	1.122
Grand Rapids	11.00	4.20	6.80	1.104
Sioux Falls	9.93	3.16	6.77	1.099
Pittsburgh	10.45	4.05	6.40	1.039
Allentown	10.71	4.39	6.32	1.026
Minneapolis	9.65	3.69	5.96	0.967
Minot	8.56	2.79	5.77	0.937
Portland	9.98	4.32	5.67	0.920
Miles City	11.31	5.65	5.65	0.918
Binghamton	9.09	3.49	5.60	0.909
Concord	10.88	5.37	5.51	0.894
Boston	6.78	1.38	5.40	0.877
South Bend	7.72	2.90	4.82	0.782
Binghamton	8.50	3.77	4.73	0.768
Moline	7.17	2.56	4.61	0.748
Pittsburgh	8.04	3.57	4.47	0.726
Syracuse	8.40	4.04	4.36	0.708
Boston	5.88	1.58	4.30	0.698
New York	11.83	7.70	4.13	0.670
Knoxville	6.75	2.77	3.98	0.645
Hartford	10.92	7.42	3.50	0.568
Roanoke	5.10	1.79	3.30	0.536
Moline	7.08	4.37	2.71	0.440
Charleston	5.69	3.30	2.39	0.387
Pittsburgh	6.01	4.18	1.83	0.297
Moline	5.78	4.10	1.68	0.273
Moline	5.35	3.78	1.57	0.255
Cleveland	6.17	4.62	1.55	0.252
Columbia	4.10	2.90	1.21	0.196
Raleigh	4.02	2.88	1.14	0.185
Akron	1.50	1.50	0.00	0.000
Denver	2.60	2.60	0.00	0.000

TABLE 3.2. Site Meteorological Data

<u>City</u>	<u>Cooling-Degree-Days (CDD)</u>	<u>Normalized CDD</u>
Tampa	3366	3.732
Port Arthur	2797	3.101
Columbia	2086	2.313
Charleston	2077	2.303
Little Rock	1924	2.133
Oklahoma City	1876	2.080
Knoxville	1568	1.739
St. Louis	1474	1.634
Raleigh	1393	1.545
Albuquerque	1316	1.459
Cincinnati	1080	1.198
New York	1067	1.183
Roanoke	1030	1.142
Newark	1022	1.133
Des Moines	927	1.028
Moline	893	0.990
Allentown	770	0.854
Miles City	751	0.833
Fort Wayne	747	0.828
Sioux Falls	718	0.796
South Bend	695	0.771
Boston	661	0.733
Pittsburgh	646	0.716
Akron	634	0.703
Denver	625	0.693
Cleveland	612	0.679
Minneapolis	585	0.649
Hartford	583	0.646
Grand Rapids	574	0.636
Syracuse	551	0.611
Providence	531	0.589
Morristown	486	0.539
Bismark	486	0.539
Eau Claire	459	0.509
Madison	459	0.509
Milwaukee	450	0.499
Pocatello	436	0.483
Green Bay	385	0.427
Minot	369	0.409
Binghamton	369	0.409
Concord	347	0.385
Portland	252	0.279

TABLE 3.3. Overall Site Ranking

City	Normalized Differential + Normalized CDD	Ranking
Tampa	5.191	1
Port Arthur	4.223	2
Oklahoma City	4.211	3
Little Rock	3.568	4
St. Louis	3.286	5
Albuquerque	2.925	6
Charleston	2.691	7
Des Moines	2.633	8
Columbia	2.509	9
Newark	2.500	10
Cincinnati	2.473	11
Knoxville	2.384	12
Morristown	2.283	13
Madison	2.251	14
Milwaukee	2.171	15
Providence	2.166	16
Green Bay	2.089	17
Fort Wayne	2.020	18
Eau Claire	1.923	19
Bismark	1.898	20
Sioux Falls	1.895	21
Allentown	1.880	22
Green Bay	1.865	23
New York	1.853	24
Pittsburgh	1.755	25
Miles City	1.750	26
Grand Rapids	1.740	27
Moline	1.739	28
Raleigh	1.729	29
Roanoke	1.678	30
Pocatello	1.623	31
Minneapolis	1.616	32
Boston	1.610	33
South Bend	1.553	34
Pittsburgh	1.442	35
Boston	1.431	36
Moline	1.430	37
Minot	1.346	38
Syracuse	1.319	39
Binghamton	1.318	40
Providence	1.315	41
Concord	1.279	42
Moline	1.263	43
Moline	1.245	44
Hartford	1.215	45
Portland	1.199	46
Binghamton	1.177	47
Pittsburgh	1.013	48
Cleveland	0.931	49
Akron	0.703	50
Denver	0.693	51

TABLE 3.4. Characteristics of Sites Selected

90th Percentile City: St. Louis, Missouri

Peak rate: \$0.1477/kWh
Off-peak rate: \$0.0459/kWh
Differential: \$0.1018/kWh
On-peak period: 1:00 p.m. to 8:00 p.m.
Cooling-degree-days: 1474

50th Percentile City: Pittsburgh, Pennsylvania

Peak rate: \$0.1045/kWh
Off-peak rate: \$0.0405/kWh
Differential: \$0.0640/kWh
On-peak period: 8:00 a.m. to 8:00 p.m.
Cooling-degree-days: 646

10th Percentile City: Hartford, Connecticut

Peak rate: \$0.1092/kWh
Off-peak rate: \$0.0742/kWh
Differential: \$0.0350/kWh
On-peak period: 8:00 a.m. to 8:00 p.m.
Cooling-degree-days: 583

4.0 BUILDING COOLING AND ELECTRIC LOADS

Cooling loads and their associated electric loads and electric bills were calculated for ranch, two-story, and townhouse residences in St. Louis, Hartford, and Pittsburgh. This section provides additional detail regarding the analytical approach and presents and discusses the load modeling results.

4.1 DOE-2

A building energy simulation model known as DOE-2 (version DOE-2.1C) was used to calculate cooling coil loads, electric loads, and electric bills for the residences evaluated in this study. The model, originally called Cal-ERDA, was developed in 1975 by Lawrence Berkeley Laboratory with funding from the State of California and the Energy Research and Development Administration. The model was renamed DOE-2 in 1979 with the creation of the U.S. Department of Energy. Lawrence Berkeley Laboratory has continued to develop the model, releasing four versions since 1979. The current version, DOE-2.1C, was released in 1985.

DOE-2 is a computer model that simulates energy use in buildings. It is typically used for building design, research, and code compliance analysis. DOE-2 was selected for this study because it calculates energy demands on an hourly basis. Hourly load calculations are required to accurately determine electric bills when subject to a TOD rate structure, and hence determine the potential benefit of residential cool storage systems. A more detailed discussion of DOE-2 is contained in Overview of the DOE-2 Building Energy Analysis Program (Lawrence Berkeley Laboratory 1985).

The DOE-2 model required three types of input for this study: 1) hourly weather data, 2) building construction details, and 3) electric rates. In order for the results to reflect typical cooling loads, hourly weather data in the form of a Typical Meteorological Year (TMY) was used. A TMY is a hypothetical, composite year that represents typical weather patterns, means, and extremes for a given location. The composite year is created by combining actual months of hourly weather observations that most closely represent typical conditions. Typical meteorological year weather data were developed by the

National Climatic Center, National Oceanic and Atmospheric Administration (1984).

Three buildings, which are described in detail below, were modeled by DOE-2. Building construction details were specified in terms of dimensions, floor plan, orientation, and insulation levels for each building type. Each building was equipped with a central air conditioning system of the type described in Section 2.2.1. Internal thermal loads from appliances and occupants were assumed equal for all buildings.

For each of the three sites, the peak and off-peak electric rates and hourly periods were provided to the model. Two of the sites, Hartford and St. Louis, also offer flat rates to residential customers. The cost of electricity in the flat-rate cases was calculated by hand.

DOE-2 offers a large variety of output options to the user. For the purposes of this study, two types of output were specified: 1) hourly cooling and electric loads and 2) summaries of cooling and electric loads and electric bills. For each building and location, the model output lists the hourly cooling coil load (in Btus), the hourly cooling system electric load (in kWh), and the hourly fan electric load (also in kWh). For each day of the cooling season, the model determined the minimum value, maximum value, sum, and average for the loads that were listed hourly. Monthly and yearly extremes, sums, and averages of the loads were also determined and included in the output. In addition to the energy usage data described above, the model also calculated monthly and annual electric bills in an economics subroutine.

4.2 RESIDENTIAL BUILDINGS MODELED

Three different buildings were modeled at each site to determine the impact of residential building size and type on the conventional cost of cooling and to generally broaden the applicability of the subsequent cost and performance requirements. These three building types are considered typical of the vast majority of single-family houses in the United States (Lawrence Berkeley Laboratory 1983). Specifically, the three buildings are a one-story ranch house of 1540 square feet, a two-story house of 2240 square feet, and a middle-unit townhouse of 1200 square feet.

After the most common building types were selected, construction details were specified for each building to accurately reflect typical building practices at each site. Energy saving design practices, such as roof or wall insulation levels, were obtained from the American Society of Heating, Refrigeration, and Air Conditioning Engineers (ASHRAE) Standard (ASHRAE 1980), which describes typical good building practices throughout the United States. Each of the buildings at all three sites have full basements. Including the basement, the two-story house has the greatest volume with 26,880 cubic feet. The ranch house is next at 26,640 cubic feet and the townhouse is smallest with a total of 14,400 cubic feet.

4.3 COOLING SYSTEM PERFORMANCE

Nominal electric loads were first determined from hourly building cooling loads based on an electric input ratio (EIR) ($EIR = 1/COP = \text{Btu in/Btu out}$) of 0.438 (ASHRAE 1980). This is equivalent to an energy efficiency ratio (EER) of 7.792. The actual electric loads were then calculated from the nominal loads by correcting for variations in inside and outside temperatures and for part-load operation of the air conditioning system. Equations that correct the nominal EIR for temperatures and part-load operation are built into the DOE-2 model and are reproduced below.

$$\text{Corrected EIR} = (0.438) * (Z_1/Z_2) \quad (4.1)$$

$$Z_1 = 0.500 - 0.00766T_1 + 0.0107T_2 \quad (4.2)$$

$$T_1 = \text{indoor wet bulb temperature, degrees Fahrenheit} \quad (4.3)$$

$$T_2 = \text{outdoor dry bulb temperature, degrees Fahrenheit} \quad (4.4)$$

$$Z_2 = 0.125 + 0.875X \quad (4.5)$$

$$X = \text{hourly cooling load/hourly cooling capacity} \quad (4.6)$$

Electric loads were also calculated for older, less efficient air conditioning systems that might be candidates for retrofitting with cool storage technology. Air conditioners have an expected useful life of approximately 15 years. According to the Air Conditioning and Refrigeration Institute (1986), residential air conditioning efficiency improved 16% over a recent 7-year period (corresponding to one half of the average air conditioner life). Therefore, the cost of cooling a house with an older air conditioning system was modeled by inserting an EIR into DOE-2 that was 16% greater than the nominal value of 0.438.

4.4 COOLING SYSTEM SIZING

The DOE-2 model sized the air conditioning systems for each of the three buildings in each of the three sites using a sizing procedure nearly identical to the one recommended by ASHRAE. In this procedure, the thermal cooling loads required to maintain the building interior at a constant temperature for each hour of the cooling season are calculated. One day that includes an hour whose cooling load is greater than 97.5% of all hours in the year is selected as the design day. An air conditioning system capacity is then determined that can supply the necessary cooling for the 97.5 percentile hour. The air conditioning system size is then determined by rounding the required cooling capacity up to the nearest half ton.

For the buildings modeled in this study, air conditioner system size varies from 2 tons to 4 tons. Townhouses at all three sites require air conditioning systems of 2 tons, while the two-story house in St. Louis requires a system of 4-ton capacity. The ranch house in St. Louis has a 3-1/2-ton air conditioning system and the remaining four buildings all have 3-ton systems.

4.5 COOLING AND ELECTRIC LOAD RESULTS

The results of modeling nine houses with the DOE-2 computer model are shown in Tables 4.1 and 4.2. Table 4.1 lists the annual cooling loads and annual electric loads for both new and older air conditioning equipment. Table 4.2 lists the annual electric bills for TOD and optional (in St. Louis and Hartford) flat-rate structures for both new and older air conditioning equipment.

TABLE 4.1. Annual Cooling and Electric Loads

City	Building	Cooling Load, MBtu	Electric Load for Cooling, MBtu	
			New System	Old System
St. Louis	ranch	23.47	13.09	15.36
St. Louis	two-story	19.28	11.03	12.90
St. Louis	townhouse	16.34	8.69	10.17
Hartford	ranch	6.56	3.86	4.53
Hartford	two-story	3.61	2.28	2.65
Hartford	townhouse	4.42	2.44	2.86
Pittsburgh	ranch	4.99	2.83	3.33
Pittsburgh	two-story	2.46	1.50	1.77
Pittsburgh	townhouse	3.55	1.94	2.27

TABLE 4.2. Annual Electric Bills for Cooling
(1986 \$)

City	Building	New System, \$		Old System, \$	
		Flat	TOD	Flat	TOD
St. Louis	ranch	330.12	374.51	387.37	438.70
St. Louis	two-story	278.36	317.75	325.54	372.30
St. Louis	townhouse	219.30	230.89	256.63	270.45
Hartford	ranch	100.64	113.38	118.11	132.85
Hartford	two-story	59.45	66.17	69.07	77.57
Hartford	townhouse	63.55	69.79	74.48	81.76
Pittsburgh	ranch	NA	71.49	NA	83.64
Pittsburgh	two-story	NA	36.06	NA	42.24
Pittsburgh	townhouse	NA	44.89	NA	52.59

The cooling loads in St. Louis were approximately four times those estimated for either Pittsburgh or Hartford. Although the St. Louis load was expected to be higher given its greater number of cooling-degree-days, the ratio was greater than the factor of two difference in cooling-degree-days predicted. Annual COPs ranged from a low of 1.582 in the Hartford two-story residence to 1.879 for the St. Louis townhouse. The impact of older equipment is reflected by a 16% to 17% increase in the electric load for all cases.

The cooling load estimates calculated by DOE-2 do not follow the intuitive expectation that loads will rank according to floor area. In St. Louis, the cooling load is externally dominated by the climatic conditions; internal cooling loads are relatively insignificant. The two key factors affecting the external cooling load are external surface area and glazing area. In addition, the amount of roof area, where most of the heat gain is seen, is generally more important than wall area. The ranch house, with a larger roof area and larger window area, has a greater total cooling load than the two-story house (despite the larger exterior wall area of the two-story house), which, in turn, has a larger cooling load than the townhouse.

In Hartford and Pittsburgh, with their relatively mild summer climates, the total cooling load is dominated by the internal cooling loads, which were set equal for each of the three buildings. In general, the result is that all three loads in these cities are about equal and the ability to differentiate among the three buildings is close to the limits of accuracy available in DOE-2. Given the constant internal heating load, the smaller air volume of the townhouse tends to heat up faster. In addition, the much smaller wall area of the townhouse limits the release of internal heat to the outdoors via natural mechanisms. This results in a lower cooling balance point temperature. The effect is to cause the townhouse to heat up more quickly and require cooling earlier in the day, or require cooling on days when the bigger buildings would not. This internal load effect is enough to outweigh the external load effect of the two-story house but not that of the ranch house.

In general, the city and residence-type rankings for the annual electric bills shown in Table 4.2 parallel the rankings seen for the electric load in Table 4.1. Both flat and TOD rate structures are offered to residential customers in St. Louis and Hartford. In both of these cities, the flat-rate structure resulted in a lower annual electrical bill for cooling. The lower flat-rate figure was used in the base case calculations for determining the annualized cost of cooling for a conventional system because this represents the least-cost option to the homeowner. The impact on the annualized cost of cooling and the resultant initial capital cost and annual COP requirements of

having the TOD rate required in St. Louis was evaluated as a sensitivity analysis to the standard assumption.

The hourly cooling loads on the peak day of the year are shown for the ranch houses in St. Louis, Pittsburgh, and Hartford in Tables 4.3, 4.4, and 4.5, respectively. As noted in Table 3.4, the on-peak period for St. Louis runs from 1:00 p.m. to 8:00 p.m. while the on-peak periods for Pittsburgh and Hartford both run from 8:00 a.m. to 8:00 p.m.

When the total daily cooling load for St. Louis is spread evenly over the off-peak period, the resultant peak hourly chill-generating capacity ($435,156 \text{ Btu}/17 \text{ hours} = 25,597 \text{ Btu/hour}$, neglecting thermal losses from the storage unit) is less than the peak hourly chill-generating capacity (29,367 Btu) required from a conventional system. This would seem to indicate that the TES-augmented system would not likely require a compressor that is larger than the conventional system. Note that the rated capacity of the conventional air conditioner selected by the DOE-2 model for the St. Louis ranch house was actually 42,000 Btu/hour.

When the total daily cooling load for Pittsburgh is spread evenly over the off-peak period, the resultant peak hourly chill-generating capacity ($343,656 \text{ Btu}/12 \text{ hours} = 28,638 \text{ Btu/hour}$, neglecting thermal losses from the storage unit) is greater than the peak hourly chill-generating capacity (25,192 Btu) required from a conventional system. This would seem to indicate that the TES-augmented system would likely require a compressor that is larger than the conventional system. Note that the rated capacity of the conventional air conditioner selected by the DOE-2 model for the Pittsburgh ranch house was actually 36,000 Btu/hour.

When the total daily cooling load for Hartford is spread evenly over the off-peak period, the resultant peak hourly chill-generating capacity ($293,227 \text{ Btu}/12 \text{ hours} = 24,436 \text{ Btu/hour}$, neglecting thermal losses from the storage unit) is slightly less than the peak hourly chill-generating capacity (25,498 Btu) required from a conventional system. This would seem to indicate that the TES-augmented system may not require a compressor that is larger

TABLE 4.3. Hourly Cooling Loads on the Peak Cooling Day for the St. Louis Ranch House

<u>Date</u>	<u>Hour</u>	<u>Cooling Load, Btu</u>
6/19	1	7587
6/19	2	6445
6/19	3	5975
6/19	4	5415
6/19	5	6447
6/19	6	7765
6/19	7	14550
6/19	8	16225
6/19	9	18274
6/19	10	20445
6/19	11	24005
6/19	12	23898
6/19	13	25792
6/19	14	25996
6/19	15	27797
6/19	16	29367
6/19	17	28800
6/19	18	27378
6/19	19	26705
6/19	20	21987
6/19	21	20232
6/19	22	18171
6/19	23	15267
6/19	24	10633

Daily Summary (June 19)

Minimum hourly load	5415
Maximum hourly load	29367
Daily load	435156
Average hourly load	18131

TABLE 4.4. Hourly Cooling Loads on the Peak Cooling Day for the Pittsburgh Ranch House

<u>Date</u>	<u>Hour</u>	<u>Cooling Load, Btu</u>
7/21	1	4522
7/21	2	3252
7/21	3	2386
7/21	4	1161
7/21	5	1111
7/21	6	1467
7/21	7	6261
7/21	8	8479
7/21	9	12080
7/21	10	16931
7/21	11	20846
7/21	12	21231
7/21	13	21788
7/21	14	22396
7/21	15	22956
7/21	16	24080
7/21	17	24360
7/21	18	25192
7/21	19	25163
7/21	20	20790
7/21	21	18225
7/21	22	16409
7/21	23	13898
7/21	24	8672

Daily Summary (July 21)

Minimum hourly load	1111
Maximum hourly load	25192
Daily load	343656
Average hourly load	14319

TABLE 4.5. Hourly Cooling Loads on the Peak Cooling Day for the Hartford Ranch House

<u>Date</u>	<u>Hour</u>	<u>Cooling Load, Btu</u>
7/1	1	4960
7/1	2	4759
7/1	3	4107
7/1	4	3779
7/1	5	3883
7/1	6	6249
7/1	7	12881
7/1	8	13782
7/1	9	15909
7/1	10	18224
7/1	11	20762
7/1	12	22796
7/1	13	23696
7/1	14	25498
7/1	15	22965
7/1	16	21784
7/1	17	14771
7/1	18	10981
7/1	19	10293
7/1	20	8689
7/1	21	7811
7/1	22	7095
7/1	23	5603
7/1	24	1951

Daily Summary (July 1)

Minimum hourly load	1951
Maximum hourly load	25498
Daily load	293227
Average hourly load	12218

than the conventional system. Note that the rated capacity of the conventional air conditioner selected by the DOE-2 model for the Hartford ranch house was actually 36,000 Btu/hour.

5.0 SYSTEM LEVEL REQUIREMENTS

As was discussed in Section 2.1, the general procedure for developing cost and performance requirements involves characterizing the cost, performance, and economic figure-of-merit for the conventional means of providing the service. This establishes the overall system level requirement. In the case of a residential cooling system, the annualized cost of cooling for conventional air conditioning systems (\$/MBtu) becomes the target figure-of-merit for TES-augmented systems.

5.1 REFERENCE SYSTEM COSTS

Initial capital, annual maintenance, and interim capital costs were estimated for each of the system sizes required by the building size and site combinations. Initial capital and interim capital (compressor replacement) estimates were developed from information in Gladstone, Humphreys, and Lunde (1987) and Mahoney (1987). Purchased equipment and installation labor charges are included in the initial cost figure, which covers the evaporator unit, condenser unit (condenser coil, fan, compressor, and mounting pad), interconnecting piping, and thermostat.

Annual maintenance costs were estimated by averaging the costs estimated for optimistic and pessimistic scenarios. The optimistic scenario included one routine annual maintenance call plus an allowance for the possible replacement of the compressor. The latter cost was estimated by multiplying the cost to replace the compressor by its failure rate (Commonwealth Edison Co. 1986). The conservative estimate included these cost elements plus an additional charge of 2% of initial capital to account for unforeseen repairs to other system components. The resultant maintenance cost estimates are consistent with what a standard rule-of-thumb (2% to 6% of initial cost) would predict for maintenance of a "simple chemical process" (Peters and Timmerhaus 1980). Table 5.1 lists the initial capital, annual maintenance, and compressor replacement costs for each of the building and site combinations evaluated.

TABLE 5.1. Reference Air Conditioning System Capital and Maintenance Costs (1987 \$)

City	Building	Capacity, Tons	Initial Capital, \$	Annual Maintenance, \$	Compressor Replacement, \$
St. Louis	ranch	3.5	2685	125	875
St. Louis	two-story	4.0	2990	130	950
St. Louis	townhouse	2.0	2040	115	700
Hartford	ranch	3.0	2380	120	800
Hartford	two-story	3.0	2380	120	800
Hartford	townhouse	2.0	2040	115	700
Pittsburgh	ranch	3.0	2380	120	800
Pittsburgh	two-story	3.0	2380	120	800
Pittsburgh	townhouse	2.0	2040	115	700

5.2 LIFE-CYCLE COST CALCULATIONS

Separate life-cycle costs (system-level requirements) were calculated for TES-augmented systems competing with conventional systems in either a new construction or a retrofit situation. In a new construction scenario, a complete new conventional AC system is installed and operated over a nominal system life of 15 years. In a retrofit situation, a currently installed system is operated an additional 15 years. The retrofit system is presumed to be 7.5 years old at the start of the 15-year operational period and will require replacement of the compressor after another 7.5 years. Power consumption is higher for the retrofit system during the first 7.5 years of operation when the older, less efficient equipment is used. Replacement of the compressor is assumed to make the retrofit system as efficient as the new system.

With the exception of the financing rate, the life-cycle cost estimates were calculated by using the methodology and economic assumptions specified in Brown et al. (1987). The financing rate specified in Brown et al. (1987) for residential applications (5.9%) is based on historical long-run rates of return rather than on current rates. The cost and performance requirements were calculated using a finance rate of 10%, a figure representative of conventional home mortgage rates in recent years. The lower long-run rate of 5.9% was used

in a sensitivity analysis conducted for the St. Louis ranch house. Estimates of initial capital, interim capital, maintenance, and electricity costs and the economic assumptions listed in Table 5.2 were input to the economic methodology to produce an estimate of the life-cycle cost of cooling, expressed in \$/MBtu. The resultant total life-cycle costs are shown in Table 5.3. Total life-cycle costs are broken into capital, maintenance, electricity, and property tax components in Tables 5.4 and 5.5.

TABLE 5.2. Economic Assumptions

System life	15 yr
Property taxes	2% of initial capital per yr
Financing rate	10.0%/yr
General inflation rate	3.1%/yr
Electricity escalation rate	2.5%/yr
Maintenance escalation rate	3.1%/yr
Capital escalation rate	3.1%/yr

TABLE 5.3. Life-Cycle Cost Results
(annualized cost, 1986 \$/MBtu)

<u>City</u>	<u>Building</u>	<u>New Construction, \$/MBtu</u>	<u>Retrofit \$/MBtu</u>
St. Louis	ranch	30	23
St. Louis	two-story	36	26
St. Louis	townhouse	33	24
Hartford	ranch	70	44
Hartford	two-story	116	68
Hartford	townhouse	87	53
Pittsburgh	ranch	86	52
Pittsburgh	two-story	161	89
Pittsburgh	townhouse	103	61

TABLE 5.4. Life-Cycle Cost Components for the New Construction Scenario
(annualized cost, 1986 \$/MBtu)

City	Building	\$/MBtu				Total
		Capital	Maintenance	Electricity	Taxes	
St. Louis	ranch	10	5	13	2	30
St. Louis	two-story	13	7	14	2	36
St. Louis	townhouse	11	7	13	2	33
Hartford	ranch	31	18	15	6	70
Hartford	two-story	58	32	16	10	116
Hartford	townhouse	40	25	14	8	87
Pittsburgh	ranch	42	23	14	7	86
Pittsburgh	two-story	85	47	14	15	161
Pittsburgh	townhouse	50	32	12	9	103

TABLE 5.5. Life-Cycle Cost Components for the Retrofit Scenario
(annualized cost, 1986 \$/MBtu)

City	Building	\$/MBtu				Total
		Capital	Maintenance	Electricity	Taxes	
St. Louis	ranch	1	5	15	2	23
St. Louis	two-story	2	7	15	2	26
St. Louis	townhouse	1	7	14	2	24
Hartford	ranch	4	18	16	6	44
Hartford	two-story	8	32	17	11	68
Hartford	townhouse	6	25	15	7	53
Pittsburgh	ranch	6	23	15	8	52
Pittsburgh	two-story	11	47	16	15	89
Pittsburgh	townhouse	7	31	14	9	61

New construction life-cycle cooling costs range from \$30/MBtu for a ranch house in St. Louis to \$161/MBtu for a two-story house in Pittsburgh. Although the peak cooling load and total capital-related (initial or interim capital, maintenance, and property taxes) costs are roughly the same for each of the applications (see Table 5.1), the higher annual load in St. Louis (see Table 4.1) results in a lower cost per unit of cooling. Retrofit life-cycle cooling costs, with lower capital-related charges, are approximately 2/3 to 3/4 of the cost for the new construction scenario.

6.0 TES-AUGMENTED SYSTEM COST AND PERFORMANCE REQUIREMENTS

The annualized cost of conventional cooling or system-level requirements calculated in Section 5.0 represent the overall cost of cooling that a TES-augmented system would have to meet or beat to be an economically attractive option. The overall cost comprises several cost elements, namely initial capital, interim capital, annual maintenance, annual electricity, and property taxes. The overall requirement can be achieved by an innumerable number of possible combinations of the above cost elements. In general, a tradeoff exists between the capital-related cost elements (initial capital, interim capital, annual maintenance, and property taxes) and the performance-related cost element (electricity); the same overall cost of cooling could be achieved by a system with a higher initial cost, but better performance (lower electric bill) or a system with a lower initial cost, but poorer performance (higher electric bill). This section defines alternative combinations of initial capital cost and round-trip energy efficiency (annual COP) for TES-augmented systems that yield the system-level requirements defined in Section 5.0.

6.1 ANALYTICAL APPROACH

As discussed in Section 2.2.4, adequate chill-storage capacity was assumed to be available to move all of the peak electric demand to off-peak. Annual maintenance and property tax rates were set at the same percent of initial capital as for each of the reference cooling systems. Thus, initial capital and annual performance are the only independent variables. Given these assumptions, the following procedure was conducted for each combination of site, building type, and new construction or retrofit situation:

1. Make an initial assumption for the TES-augmented system annual round-trip efficiency (COP)
2. Calculate the annual electricity consumption and cost
3. Solve for the TES-augmented system initial capital cost that results in the same system-level annualized cost of delivered chill.

Steps 1-3 were then repeated for other round-trip efficiency assumptions. The result of this procedure was a set of initial capital cost and annual

performance pairs that could be plotted into a curve defining the boundary of acceptable cost and performance characteristics for TES-augmented cooling systems.

Separate cost and performance requirements were developed for one new construction and two retrofit scenarios for each combination of site and building type. In addition, three sensitivity cases were conducted for one site and building combination to determine the impact on cost and performance requirements of 1) having storage sized so that the chill-generator runs at full capacity for 24 hours on the peak day of the year, 2) basing the reference (conventional) system annual electric bill on the optional TOD rate structure rather than on the flat rate, and 3) lowering the financing rate from 10% to 5.9%. Altogether, 30 separate scenarios were evaluated.

Separate cost and performance requirements were developed for new construction and retrofit scenarios because of the different system-level requirements for these two reference scenarios. In addition, separate cost and performance requirements were developed for two possible retrofit situations: 1) where TES would be an add-on to a conventional system and 2) where a new TES system would completely replace the conventional system. Separate requirements were necessary because performance changes after 7.5 years for the first case when the old compressor is replaced, whereas performance for the second case remains the same over the 15-year system life. Although TES could be either an add-on to a conventional system or a complete replacement for a conventional system in the new construction scenario, in either case the performance of the alternative remains constant through the 15-year system life.

An attempt was made to cover a reasonable range of cost and performance combinations without including unlikely combinations. For the new construction scenario, the upper design point was set at the same annual COP as the reference new construction system. The lower design point was set at the same initial cost as the reference new construction system. The upper and lower design points for the retrofit scenario/replacement system are the same as for the new construction scenario. For the retrofit scenario/add-on system, the upper design point was set at the same annual COP as the reference retrofit system.

The lower design point was set at no cost for the add-on. Although a zero cost add-on is unlikely, no other obvious lower cost limit exists. In addition, this lower limit is essentially equivalent to the other two scenarios where a complete replacement system with TES is assumed to cost no more than the reference conventional system.

6.2 COST AND PERFORMANCE REQUIREMENTS

The initial capital cost and annual COP requirements for a TES-augmented system in the new construction scenario are listed in Table 6.1 and plotted in Figure 6.1. These requirements apply to the entire cooling system, including chill generation, storage, and delivery, and not just to the storage unit itself. System COP is defined as the total chill provided to the residence divided by the total electric energy input to the system on an annual basis. Table 6.1 identifies three different combinations of initial capital cost and annual COP for the TES-augmented system for each city and building pair. Each of these three combinations of initial capital cost and annual COP will result in a system with exactly the same life-cycle cost of cooling as the corresponding basis system (same city and building) for the new construction scenario. Thus, these are the cost and performance characteristics that a prospective TES-augmented system in a new construction scenario must meet to be economically attractive. Because the absolute cost and performance numbers for any city and building pair vary with the many site-specific factors, the differences in initial capital cost and annual COP between the TES-augmented systems and reference cooling systems are shown to help gauge the attractiveness of TES among the city and building pairs. The reference new construction system was chosen as the basis for comparison to highlight the incremental initial capital cost and/or reduction in system annual COP allowed with the TES-augmented system.

The data in Table 6.1 indicate that a TES-augmented system with the same annual COP as the reference system would be worth an additional \$999 above the initial cost of the reference system for a ranch house in St. Louis. Similarly, a TES-augmented system would be worth an additional \$860 and \$624,

TABLE 6.1. New Construction Scenario Cost and Performance Requirements

City	Building	TES-Augmented System Requirements (a)		Differentials TES-Conventional	
		Initial Capital Cost (b)	Annual COP	Cost	COP
St. Louis	ranch	3684	1.794	+ 999	0
		3337	1.375	+ 652	-0.419
		2685	0.956	0	-0.838
St. Louis	two-story	3850	1.747	+ 860	0
		3551	1.339	+ 561	-0.408
		2990	0.931	0	-0.816
St. Louis	townhouse	2664	1.879	+ 624	0
		2447	1.440	+ 407	-0.439
		2040	1.002	0	-0.877
Hartford	ranch	2486	1.700	+ 106	0
		2438	1.559	+ 58	-0.141
		2380	1.418	0	-0.282
Hartford	two-story	2442	1.582	+ 62	0
		2414	1.450	+ 34	-0.132
		2380	1.319	0	-0.263
Hartford	townhouse	2104	1.814	+ 64	0
		2075	1.663	+ 35	-0.151
		2040	1.513	0	-0.301
Pittsburgh	ranch	2620	1.767	+ 240	0
		2543	1.298	+ 163	-0.469
		2380	0.829	0	-0.938
Pittsburgh	two-story	2496	1.643	+ 116	0
		2457	1.227	+ 77	-0.416
		2380	0.810	0	-0.833
Pittsburgh	townhouse	2174	1.834	+ 134	0
		2128	1.386	+ 88	-0.448
		2040	0.938	0	-0.896

(a) These requirements apply to the entire cooling system including chill generation, storage, and delivery.

(b) All costs in 1986 dollars.

FIGURE 6.1. Initial Capital Cost and Annual COP Requirements for a TES-Augmented System in the New Construction Scenario

respectively, for two-story and townhouse residences in St. Louis. Alternatively, a TES-augmented system with the same initial cost as the reference system would only need to have an annual COP roughly half that of the reference system for any of the three building types in St. Louis.

Conditions are less attractive in Hartford and Pittsburgh. Here the additional worth of a TES-augmented system with a COP equal to its reference system ranges from \$62 for the two-story house in Hartford up to \$240 for the ranch house in Pittsburgh. St. Louis is more attractive because of its higher annual cooling load and large electric rate differential for moving to off-peak. Pittsburgh is more attractive for TES than Hartford due to its higher electric rate differential, even though it has the lowest annual cooling load. For TES-augmented systems with the same initial cost as the reference system, the annual COP need only be roughly 50% of the reference system in Pittsburgh, much like the case in St. Louis. In Hartford, where the benefit per kWh of shifting the electric load off-peak is lower than for either St. Louis or Pittsburgh, the annual COP required for a TES-augmented system with the same initial cost as the reference system must be greater than 80% of the COP for the reference system. Although the order of attractiveness for the three cities is consistent with the rankings developed in the site selection process, the relative attractiveness of the St. Louis site is even greater than the rankings predicted. This result can be attributed to the fact that the actual cooling load in St. Louis, compared to Pittsburgh and Hartford, was greater than predicted by their relative number of cooling-degree-days.

The initial capital cost and annual COP requirements for a TES-augmented system in the retrofit/replacement system scenario are listed in Table 6.2. Again, these requirements apply to the entire cooling system, including chill generation, storage, and delivery, and not just to the storage unit itself. System COP is still defined as the total chill provided to the residence divided by the total electric energy input to the system on an annual basis. Table 6.2 identifies one combination of initial capital cost and annual COP for the TES-augmented system for each site and building pair. Each of these combinations of initial capital cost and annual COP will result in a system with

TABLE 6.2. Retrofit/Replacement System Scenario Cost and Performance Requirements

City	Building	TES-Augmented System Requirements (a)		Differentials TES-Conventional	
		Initial Capital Cost (b)	Annual COP	Cost	COP
St. Louis	ranch	2535	1.794	-150	0
St. Louis	two-story	2473	1.747	-517	0
St. Louis	townhouse	1830	1.879	-210	0
Hartford	ranch	1370	1.700	-1010	0
Hartford	two-story	1295	1.582	-1085	0
Hartford	townhouse	1170	1.814	-870	0
Pittsburgh	ranch	1484	1.767	-896	0
Pittsburgh	two-story	1335	1.643	-1045	0
Pittsburgh	townhouse	1230	1.834	-810	0

(a) These requirements apply to the entire cooling system, including chill generation, storage, and delivery.

(b) All costs in 1986 dollars.

exactly the same life-cycle cost of cooling as the corresponding reference system (same city and building) for the retrofit scenario. Thus, these are the cost and performance characteristics that a prospective TES-augmented system in a retrofit/replacement scenario must meet to be economically attractive. Again, because the absolute cost and performance numbers for any city and building pair vary with the many site-specific factors, the differences in initial capital cost and annual COP between the TES and conventional cooling systems are shown to help gauge the attractiveness of TES among the city and building pairs. The reference new construction system was chosen as the basis for comparison to highlight the incremental initial capital cost and/or reduction in system annual COP allowed with the replacement TES-augmented system.

The data in Table 6.2 indicate that the prospects for TES in the retrofit/replacement system scenario are extremely limited. For each of the nine pairs of cities and buildings, the TES-augmented replacement system would have to be less expensive than its corresponding conventional unit, while achieving the same annual COP or a higher annual COP for the same cost. Neither of these two requirements, while possible, are likely to be met.

The initial capital cost and annual COP requirements for a TES-augmented system in the retrofit/add-on system scenario are listed in Table 6.3 and plotted in Figure 6.2. The initial capital cost requirement includes the cost of the add-on (storage) unit plus any other costs associated with modifications required of the conventional equipment being retrofit. The annual COP requirement, on the other hand, applies to the entire resulting system, including chill generation, storage, and delivery. System COP is still defined as the total chill provided to the residence divided by the total electric energy input to the system on an annual basis. Table 6.3 identifies three combinations of initial capital cost and annual COP for the TES-augmented system for each site and building pair. Each of these combinations of initial capital cost and annual COP will result in a system with exactly the same life-cycle cost of cooling as the corresponding reference system (same city and building) for the retrofit scenario. Thus, these are the cost and performance characteristics that a prospective TES-augmented system must meet to be economically attractive in the retrofit/add-on system scenario. Again, because the absolute cost and performance numbers for any city and building pair vary with the many site-specific factors, the differences in initial capital cost and annual COP between the TES systems and the reference cooling systems are shown to help gauge the attractiveness of TES among the city and building pairs. The reference retrofit system was chosen as the basis for comparison to highlight the initial capital cost and/or reduction in system annual COP allowed with the add-on TES unit.

The data in Table 6.3 indicate that the general trends and prospects for TES in a retrofit/add-on system are similar to those seen in Table 6.1 for the new construction scenario. The explanations for each of the trends are identical to those described for the new construction scenario and are not repeated here.

TABLE 6.3. Retrofit/Add-On System Scenario Cost and Performance Requirements

City	Building	TES-Augmented System Requirements (a)		Differential TES-Conventional	
		Initial Capital Cost (b)	Annual COP	Cost	COP
St. Louis	ranch	1105	1.662	+1105	0
		720	1.274	+ 720	-0.388
		0	0.886	0	-0.776
St. Louis	two-story	951	1.621	+ 951	0
		620	1.242	+ 620	-0.379
		0	0.864	0	-0.757
St. Louis	townhouse	689	1.743	+ 689	0
		450	1.335	+ 450	-0.408
		0	0.928	0	-0.815
Hartford	ranch	117	1.575	+ 117	0
		64	1.443	+ 64	-0.132
		0	1.311	0	-0.264
Hartford	two-story	63	1.459	+ 63	0
		34	1.347	+ 34	-0.112
		0	1.235	0	-0.224
Hartford	townhouse	70	1.681	+ 70	0
		38	1.542	+ 38	-0.139
		0	1.403	0	-0.278
Pittsburgh	ranch	264	1.633	+ 264	0
		180	1.201	+ 180	-0.432
		0	0.770	0	-0.863
Pittsburgh	two-story	126	1.518	+ 126	0
		84	1.137	+ 84	-0.381
		0	0.755	0	-0.763
Pittsburgh	townhouse	149	1.700	+149	0
		99	1.282	+ 99	-0.418
		0	0.864	0	-0.836

(a) The initial capital cost requirement covers the cost of the add-on (storage) system plus any other costs associated with modifying the system being retrofit. The annual COP requirement applies to the entire resulting system, including all generation, storage, and delivery.

(b) All costs in 1986 dollars.

FIGURE 6.2. Initial Capital Cost and Annual COP Requirements for a TES-Augmented System in the Retrofit/Add-on System Scenario

A TES add-on resulting in the same annual COP as the reference system would be worth an additional \$1105, \$951, and \$689, respectively, for ranch, two-story, and townhouse residences in St. Louis. Alternatively, if the TES add-on was free, the resultant system would only need to have an annual COP roughly half that of the reference system for any of the three building types in St. Louis.

Again, conditions are less attractive in Hartford and Pittsburgh. Here the additional worth of an add-on TES unit resulting in a system with a COP equal to its reference system ranges from \$63 for the two-story house in Hartford to \$264 for the ranch house in Pittsburgh. If the TES add-on was free, the annual COP for the resultant system need only be roughly 50% of the reference system in Pittsburgh. In Hartford, the annual COP required for the resultant system for a free TES is roughly 80% of the COP for the reference system.

Because the initial capital cost requirements for the retrofit/add-on system scenario primarily encompass only the cost of the add-on (storage) unit, the cost requirements for this scenario are also expressed in \$/ton-hour and \$/million Btu in Table 6.4.

6.3 SENSITIVITY CASES

The initial capital cost and annual COP requirements reported above were developed under the following three (among other) ground rules or assumptions. 1) Adequate storage capacity is available with the TES-augmented systems to allow all of the peak electric demand to be moved off-peak. 2) For utilities offering a choice between flat and T00 rates (St. Louis and Hartford), the rate structure yielding the lower annual electric bill for cooling (the flat rate, for each of the buildings in St. Louis and Hartford) is used for the reference (conventional) system. 3) Financing costs are based on recent loan rates.

Sensitivity cases were evaluated to look at the effect on the cost and performance requirements when these three assumptions were independently altered. Specifically, initial capital cost and annual COP requirements were calculated under the following alternative conditions. 1) Storage capacity

TABLE 6.4. Retrofit/Add-On System Scenario Cost and Performance Requirements: Alternative Cost Units

City	Building	TES-Augmented System Requirements ^(a)		
		Initial Capital Cost ^(b)		Annual COP
		\$/MBtu	\$/ton-hour	
St. Louis	ranch	5880	66.3	1.662
		3830	46.0	1.274
		0	0	0.886
St. Louis	two-story	5000	60.0	1.621
		3260	39.1	1.242
		0	0	0.864
St. Louis	townhouse	6080	72.9	1.743
		3970	47.6	1.335
		0	0	0.928
Hartford	ranch	541	6.49	1.575
		296	3.55	1.443
		0	0	1.311
Hartford	two-story	287	3.46	1.459
		155	1.87	1.347
		0	0	1.235
Hartford	townhouse	492	5.90	1.681
		267	3.20	1.542
		0	0	1.403
Pittsburgh	ranch	1020	12.3	1.633
		698	8.38	1.201
		0	0	0.770
Pittsburgh	two-story	485	5.82	1.518
		323	3.88	1.137
		0	0	0.755
Pittsburgh	townhouse	913	11.0	1.700
		606	7.28	1.282
		0	0	0.864

- (a) The initial capital cost requirement covers the cost of the add-on (storage) system plus any other costs associated with modifying the system being retrofit. The annual COP requirement applies to the entire resulting system, including all generation, storage, and delivery.
- (b) All costs in 1986 dollars.

for the TES-augmented systems is sized so that the chill-generator runs 24 hours a day at a constant rate on the peak day of the year. 2) The reference (conventional) system electric bill for cooling is based on TOD rates. 3) Financing costs are based on historical long-run average loan rates.

6.3.1 Alternative Storage Sizing

The initial capital cost and annual COP requirements reported in Section 6.2 were developed under the assumption that adequate storage capacity would be available with the TES-augmented system to allow all of the electric demand to be moved to the off-peak period. While this assumption allows the maximum possible savings in the electric bill, it would generally require a larger chill-generator and storage unit than might be required with some other design options. As a sensitivity analysis to the general storage sizing assumption, alternative cost and performance requirements were determined under the assumption that storage was sized so that the chill-generator would run 24 hours a day at a constant rate on the peak cooling day of the year.

The sensitivity analysis was conducted for the St. Louis ranch house. This particular house has a peak daily cooling load of 435,000 Btu, or about 18,000 Btu/hour for a chill-generator operating continuously for 24 hours. In St. Louis, the off-peak period lasts for 17 hours. Thus, approximately 306,000 Btu of chill could be generated during the off-peak period. Over an entire cooling season, a day-by-day analysis of the cooling loads indicated that all but 1.47 MBtu of the total 23.47 MBtu cooling load for the St. Louis ranch house could still be met by off-peak chill generation. A new set of initial capital cost and annual COP requirements were calculated from this basis for the new construction and retrofit scenarios.

Sensitivity and base-case figures are compared in Figure 6.3 and Table 6.5. For each scenario (new construction, retrofit/replacement, and retrofit/add-on) the impact of the alternative storage sizing assumption is initial capital cost and annual COP requirements that are slightly more restrictive than the requirements calculated for the base-case design assumption; i.e., at the same initial capital cost, the annual COP must be higher and at the

FIGURE 6.3. Storage-Sizing Sensitivity and Base-Case Figures

TABLE 6.5. Alternative Storage Sizing Results, St. Louis Ranch House
(all costs in 1986 dollars)

<u>System</u>	<u>Initial Capital Cost, \$</u>	<u>Annual COP</u>
New construction		
Reference ^(a)	2685	1.794
Base case ^(b)	3684	1.794
	3337	1.375
	2685	0.956
Sensitivity case ^(c)	3525	1.794
	3207	1.442
	2685	1.089
Retrofit/replacement		
Reference	2685	1.794
Base case	2535	1.794
Sensitivity case	2376	1.794
Retrofit/add-on		
Reference	0	1.662
Base case	1105	1.662
	720	1.274
	0	0.886
Sensitivity case	929	1.662
	600	1.352
	0	1.042

- (a) Conventional air conditioning system
 (b) TES system with storage sized to allow all electric demand to be moved off-peak.
 (c) TES system with storage sized so that the chill-generator operates 24 hours a day at a constant rate on the peak cooling day of the year.

same annual COP, the initial capital cost must be lower. Of course, these requirements may be just as easy, if not easier, to achieve because both the chill-generator and storage unit would be smaller and less costly under the sensitivity case assumptions. The optimum storage size depends on the actual cost and performance of the TES-augmented cooling system and the actual building cooling load and utility rate structure. This will likely be a unique storage size for every installation considered.

6.3.2 Alternative Rate Structure

The initial capital cost and annual COP requirements reported in Section 6.2 were developed under the assumption that the reference (conventional) system would be operated with the rate structure that resulted in the lowest annual electric bill for cooling, where alternative rate structures were available. Both flat and TOD rate structures are available in St. Louis and Hartford, whereas in Pittsburgh the TOD rate structure is mandatory. For each of the six buildings evaluated in St. Louis and Hartford, the annual electric bill for cooling was determined to be lower with the flat rate for the reference (conventional) system. For these two cities, the cost and performance requirements of the TES-augmented systems were then determined by incorporating the effects of switching from a flat rate to a TOD rate as well as the effects of implementing TES to take advantage of the TOD rate structure. No attempt was made in this study to characterize the cost or savings associated with a switch from flat to TOD rates and the resulting impact on the use of electricity in non-cooling applications.

As a sensitivity analysis, initial capital cost and annual COP requirements were calculated for the St. Louis ranch house based on the annual electric bill for the reference (conventional) system using TOD rates. When TOD rates are already in place, any potential impact on the use and cost of electricity in non-cooling applications because of switching from flat to TOD rates becomes moot.

Sensitivity and base-case figures are compared in Figure 6.4 and Table 6.6. For each scenario (new construction, retrofit/replacement, and retrofit/add-on), the impact of assuming a TOD rate structure for the reference system

FIGURE 6.4. Rate Structure Sensitivity and Base-Case Figures

TABLE 6.6. Alternative Rate Structure Results, St. Louis Ranch House
(all costs in 1986 dollars)

<u>System</u>	<u>Initial Capital Cost, \$</u>	<u>Annual COP</u>
New construction		
Reference ^(a)	2685	1.794
Base case ^(b)	3684	1.794
	3337	1.318
	2685	0.843
Sensitivity case ^(c)	3972	1.794
	3560	1.318
	2685	0.843
Retrofit/replacement		
Reference	2685	1.794
Base case	2535	1.794
Sensitivity case	2851	1.794
Retrofit/add-on		
Reference	0	1.662
Base case	1105	1.662
	720	1.274
	0	0.886
Sensitivity case	1421	1.662
	967	1.221
	0	0.781

(a) Conventional air conditioning system

(b) TES system with conventional system life-cycle costs based on flat rates.

(c) TES system with conventional system life-cycle costs based on TOD rates.

in the St. Louis ranch house is initial capital cost and annual COP requirements that are less restrictive than the requirements calculated for the base-case assumption; i.e., at the same initial cost, the allowable annual COP is lower and at the same annual COP, the allowable initial capital cost is higher. This impact on the cost and performance requirements follows from the increase in the electric bill for the reference (conventional) system under the TOD rate sensitivity assumption. In general, any increase in the on-peak part of the electric bill for cooling will result in cost and performance requirements for the TES-augmented system that are less restrictive.

6.3.3 Alternative Financing Rate

The initial capital cost and annual COP figures reported in Section 6.2 are the current requirements of TES-augmented cooling systems. These requirements were calculated assuming a finance rate of 10%, a figure representative of conventional home mortgage rates in the past couple of years. A sensitivity analysis was conducted for the St. Louis ranch house to determine the impact on cost and performance requirements if financing were available at 5.9%, the historical long-run average home mortgage rate (Brown et al. 1987).

Sensitivity and base-case figures are compared in Figure 6.5 and Table 6.7. For each scenario (new construction, retrofit/replacement, and retrofit/add-on), the results of the alternative financing assumption for the St. Louis ranch house are initial capital costs and annual COP requirements that are slightly less restrictive than the requirements calculated for the base-case assumption; i.e., at the same initial cost, the allowable annual COP is lower and at the same annual COP, the allowable initial capital cost is higher. This impact on the cost and performance requirements follows directly from the fact that lowering the financing costs makes the more capital-intensive TES-augmented systems more attractive.

FIGURE 6.5. Financing Rate Sensitivity and Base-Case Figures

TABLE 6.7. Alternative Financing Rate Results, St. Louis Ranch House
(all costs in 1986 dollars)

<u>System</u>	<u>Initial Capital Cost, \$</u>	<u>Annual COP</u>
New construction		
Reference ^(a)	2685	1.794
Base case ^(b)	3684	1.794
	3337	1.375
	2685	0.956
Sensitivity case ^(c)	3811	1.794
	3419	1.375
	2685	0.956
Retrofit/replacement		
Reference	2685	1.794
Base case	2535	1.794
Sensitivity case	2836	1.794
Retrofit/add-on		
Reference	0	1.662
Base case	1105	1.662
	720	1.274
	0	0.886
Sensitivity case	1234	1.662
	805	1.274
	0	0.886

-
- (a) Conventional air conditioning system
 (b) TES system with 10% financing.
 (c) TES system with 5.9% financing.

7.0 CONCLUSIONS

The economic opportunity for residential cool storage is proportional to the potential savings available by moving all or part of the building's cooling load to a utility's off-peak period. The potential savings is composed of two parts: 1) the magnitude of the cooling load and 2) the savings per kWh available by shifting the load to off-peak hours. The prospects for residential cool storage vary depending on the meteorology and utility rate structure at a particular site. Both the cooling load (for the same building size) and electric rates vary by more than an order of magnitude across the United States. Thus, it is not surprising that the prospects for residential cool storage vary dramatically, depending on site conditions.

The prospects for employing residential cool storage also depend on the perspective of the homeowner and the nature of the TES-augmented system. Costs for TES-augmented systems compete with the full cost of acquiring, operating, and maintaining a conventional air conditioning system in a new construction scenario. In a retrofit scenario, however, the TES-augmented system costs compete with the cost of operating and maintaining a conventional air conditioning system. The lower overall reference cost of cooling for the retrofit scenario makes it more difficult for a replacement TES system to be competitive in the retrofit scenario compared to an add-on TES unit.

In St. Louis, where the number of cooling-degree-days and utility rate structure ranked it at the 90th percentile (5th highest out of 50) of locations offering time-of-day rate structures to residential customers, a TES-augmented system in the new construction scenario would be worth \$2700 to \$3900 (depending on building size and type) if the TES-augmented system could achieve the same annual COP as the conventional system (1.747 to 1.879, depending on building size and type). This represents an allowable increase in initial system cost of \$600 to \$1000 or approximately 30 to 40% of the initial cost of a conventional cooling system. Alternatively, a TES-augmented system with the same initial cost as a conventional system would only need to have an annual COP roughly half that of the conventional system for any of the St. Louis residences. These requirements for the new construction scenario apply to the

entire cooling system, including chill generation, storage, and delivery, and not just to the storage unit itself. System COP is defined as the total chill provided to the residence divided by the total electric energy input to the system on an annual basis.

As expected, residential cool storage prospects in Pittsburgh and Hartford were found to be less attractive. Pittsburgh and Hartford represented the 50th and 10th percentile cities, respectively, in the location rankings developed from the number of cooling-degree-days and electric rate structure. In these two cities, the TES-augmented system in the new construction scenario would be worth \$2100 to \$2600 (depending on the site and building type) if it had a COP equal to its reference conventional system (1.582 to 1.834, depending on site and building type). This represents an allowable increase in initial system cost of \$60 to \$240 or approximately 3% to 10% of the initial cost of a conventional cooling system. While the rate structure in Pittsburgh would allow a 50% reduction in annual COP for a TES-augmented system with the same initial cost as the reference conventional system, only a 15% reduction in efficiency under the same cost conditions was allowable in Hartford, where the benefit per kWh of shifting the electrical load off-peak is lower than for either St. Louis or Pittsburgh.

In general, the prospects for a complete replacement system in a retrofit scenario look poor. For each system evaluated in this scenario, the TES-augmented replacement system would have to be less expensive than its corresponding conventional unit, while achieving the same annual COP or a higher annual COP for the same cost.

The economic prospects for an add-on storage unit in a retrofit scenario appear much better. A TES add-on unit resulting in a system with the same annual COP as the reference conventional system (1.621 to 1.743, depending on building type and size) would be worth \$700 to \$1100 in St. Louis (depending on the building type and size). This means that up to \$700 to \$1100 could be spent on the storage unit and modifications to the conventional system and still be economically attractive. The annual COP requirement, on the other hand, applies to the entire resulting system, including chill generation,

storage, and delivery. System COP is still defined as the total chill provided to the residence divided by the total electric energy input to the system on an annual basis. In general, the trends and prospects for the retrofit/add-on scenario are similar to that described above for the new construction scenario.

The cost and performance requirements calculated for St. Louis, Hartford, and Pittsburgh were all based on electric rate structures that did not offer any up-front cash incentives or rebates to the residential homeowner. If such incentives or rebates were offered by the utilities, it would directly increase the cost requirement (for a given TES-augmented system COP) by the amount of the cash incentive or rebate.

Sensitivity analyses were conducted for alternative storage sizing, reference (conventional) system electric rate structure, and financing rate assumptions. Assuming the chill-generator and storage unit would be sized so that the chill-generator ran continuously (24 hours per day) on the peak cooling day of the year (rather than sizing storage to move all electric demand to the off-peak period) reduced the initial capital cost requirement by 15% or less for a given level of annual COP. Basing the reference (conventional) system's annual electric bill for cooling on the optional TOD rate (which yielded a higher annual electric bill for cooling than the flat rate) increased the initial capital cost requirements by up to 30% for a given level of annual COP. Finally, using 5.9% rather than 10% as the financing rate increased the initial capital cost requirements by up to 15% for a given level of annual COP.

It would be difficult to justify the selection of any specific combination of initial capital cost and annual COP as the singular requirement for residential cool storage without considering a target share of the residential market. Meeting the cost and performance requirements of cool storage in Hartford would practically allow targeting of the entire residential market. Meeting the requirements in St. Louis would allow targeting of a small fraction of the total market, but this may still be significant in terms of the number of units and impact on U.S. energy demand. This study has developed initial

capital cost and annual COP requirements for a broad range of conditions so that interpolation to other conditions could be made.

The current cost and performance requirements identified in this study would be very difficult to achieve. A previous study conducted for the Electric Power Research Institute (Asbury, Giese, and Looney 1986) concluded that a TES-augmented cooling system could probably be installed for a \$2000 premium above the cost of a conventional cooling system, but noted that very few utility rate structures provide the residential class with a sufficient level of financial incentives for shifting air conditioning demand to off-peak. The cost and performance requirements developed in this study confirm this dilemma. Based on the current characteristics of residential air conditioning equipment and rate structures, the allowable cost premium in St. Louis (the most attractive of the three sites evaluated in this study), was estimated to be only \$1000.

The cost premium for TES-augmented cooling systems must be lower than \$2000 and/or greater financial incentives will likely be required from utilities before cool storage becomes economically feasible for the residential homeowner. During the time frame this study was conducted (1987-1988), the availability of TOD rates for the residential class was rapidly increasing. Of particular importance, many Southern utilities (where cool storage technologies are expected to have the greatest potential) did not have TOD rates for the residential class at the beginning of the study, but were implementing this type of rate structure as the analytical portion of this study came to a close. The increased availability of TOD rates or other incentives for employing residential cool storage within Southern utilities would significantly change the results of this study. Follow-on efforts should be directed toward tracking the changes in residential rate structures and identifying future-oriented cost and performance requirements when the long-run characteristics of the structure for the residential rate class is more certain.

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