IEA
SOLAR R&D

INTERNATIONAL ENERGY AGENCY

solar heating and cooling programme

task VII

central solar heating plants with seasonal storage

summary report of phases I and II

may 1986

INTRODUCTION TO THE INTERNATIONAL ENERGY AGENCY AND THE IEA SOLAR HEATING AND COOLING PROGRAMME

The International Energy Agency was formed in November 1974 to establish cooperation among a number of industrialized countries in the vital area of energy policy. It is an autonomous body within the framework of the Organization for Economic Cooperation and Development (OECD). Twenty-one countries are presently members, with the Commission of the European Communities also participating in the work of the IEA under a special arrangement.

One element of the IEA's programme involves cooperation in the research and development of alternative energy resources in order to reduce excessive dependence on oil. A number of new and improved energy technologies which have the potential of making significant contributions to global energy needs were identified for collaborative efforts. The IEA Committee on Energy Research and Development (CRD), supported by a small Secretariat staff, is the focus of IEA RD&D activities. Four Working Parties (in Conservation, Fossil Fuels, Renewable Energy, and Fusion) are charged with identifying new areas for cooperation and advising the CRD on policy matters in their respective technology areas.

Solar Heating and Cooling was one of the technologies selected for joint activities. During 1976–77, specific projects were identified in key areas of this field and a formal Implementing Agreement drawn up. The Agreement covers the obligations and rights of the Participants and outlines the scope of each project or "task" in annexes to the document. There are now eighteen signatories to the Agreement:

Australia	Italy
Austria	Japan
Belgium	Netherlands
Canada	New Zealand
Denmark	Norway
Commission of the European Communities	Spain
	Sweden
Federal Republic of Germany	Switzerland
	United Kingdom
Greece	United States

The overall programme is managed by an Executive Committee, while the management of the individual tasks is the responsibility of Operating Agents. The tasks of the IEA Solar Heating and Cooling Programme, their respective Operating Agents, and current status (ongoing or completed) are as follows:

Task I — Investigation of the Performance of Solar Heating and Cooling Systems – Technical University of Denmark (Completed).

Task II — Coordination of Research and Development on Solar Heating and Cooling – Solar Research Laboratory – GIRIN, Japan (Completed).

Task III — Performance Testing of Solar Collectors – University College, Cardiff, U.K. (Ongoing)

Task IV — Development of an Insolation Handbook and Instrument Package – U.S. Department of Energy (Completed).

Task VIII — Passive and Hybrid Solar Low Energy Buildings – U.S. Department of Energy (Ongoing).

Task IX — Solar Radiation and Pyranometry Studies – Canadian Atmospheric Environment Service (Ongoing).

Task X — Materials Research & Testing – Solar Research Laboratory, GIRIN, Japan (Ongoing).

Task VII – Central Solar Heating Plants with Seasonal Storage: Feasibility Study and Design

For northern countries, solar heating of buildings appears to be an unrealistic proposition: In wintertime, when heat is most needed, there is virtually no solar radiation to utilize. While long-term heat storage could make the energy available when needed, the economics of seasonal storage has been found to be unfavorable on a single house approach.

Nevertheless, there was reason to believe that longterm storage might make sense on larger scale. Task VII therefore was established in 1979 to investigate the feasibility and cost-effectiveness of central solar heating plants with seasonal storage (CSHPSS).

The work has been divided into three phases. During the first phase (1979–1983), the participants collected engineering, performance and cost data on the major component subsystems needed for system design. A parallel effort consisted of the development of MINSUN, a major computer program capable of simulation and optimization of various CSHPSS configurations. MINSUN and the subsystem data collected were used to prepare preliminary site-specific designs for each country.

During the second phase (1983–1985), the MINSUN design tool was used to make a more systematic evaluation of design concepts and to identify those which are most competitive with alternative systems for heating of buildings. Guidelines were also established for consistent documentation of monitoring and evaluation of operational systems.

The objective of Phase III (1986–1988) is to verify and expand on the results of the two previous phases by an exchange of information on the design, construction and operation of existing or new systems, and to perform a collaborative evaluation of this information.

This report documents work carried out during Phase I and Phase II of this Task.

central solar heating plants with seasonal storage

summary report of phases I and II

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This report is part of the work within the IEA Solar Heating and Cooling Programme
Task VII: Central Solar Heating Plants with Seasonal Storage

ACKNOWLEDGEMENTS

The initial concept for a collaborative task on central solar heating plants with seasonal storage emanated from a meeting in Ottawa in 1977 between Jack Wadsworth (CMHC, Canada) and Olof Eriksson (Council for Building Research, Sweden). A second meeting was held in Stockholm in April 1978 which explored bilateral interests in such a concept. After further discussions, a meeting was convened in Stockholm to consider and draft a proposed new annex under the IEA, Solar Heating and Cooling Programme. The resulting approved Annex VII elicited participation from ten countries.

Under the Task VII organization, the two phases were divided into sub-tasks, each with a Lead Country taking responsibility for planning, organizing, and documenting the work. Such responsibility often fell most heavily on one or two experts from the Lead Country. These primary contributors were:

Sub-Task I(a)	System Studies	Ron Biggs/Verne Chant
Sub-Task I(b)	Collectors	Charles Bankston
Sub-Task I(c)	Storage	Pierre Chuard/J.C.Hadorn
Sub-Task I(d)	Distribution	Tomas Bruce
Sub-Task I(e)	Preliminary Design	Arne Boysen
Sub-Task II(a)	MINSUN Enhancement	Verne Chant
Sub-Task II(b)	Evaluation of System Concepts	Charles Bankston
Sub-Task II(c)	Exchange of Data	Cees den Ouden/Johan Havinga

Overall Task management and reporting was the responsibility of the Task Operating Agent, Arne Boysen, for the Swedish Council for Building Research. The Operating Agent reported to an Executive Committee of representatives of the participating countries.

The authors acknowledge the special contribution made by all participants in the Task, many of whom have participated over the six-year period of Phases I and II. This contribution has been one of collaborative work toward a common goal for the benefit of all.

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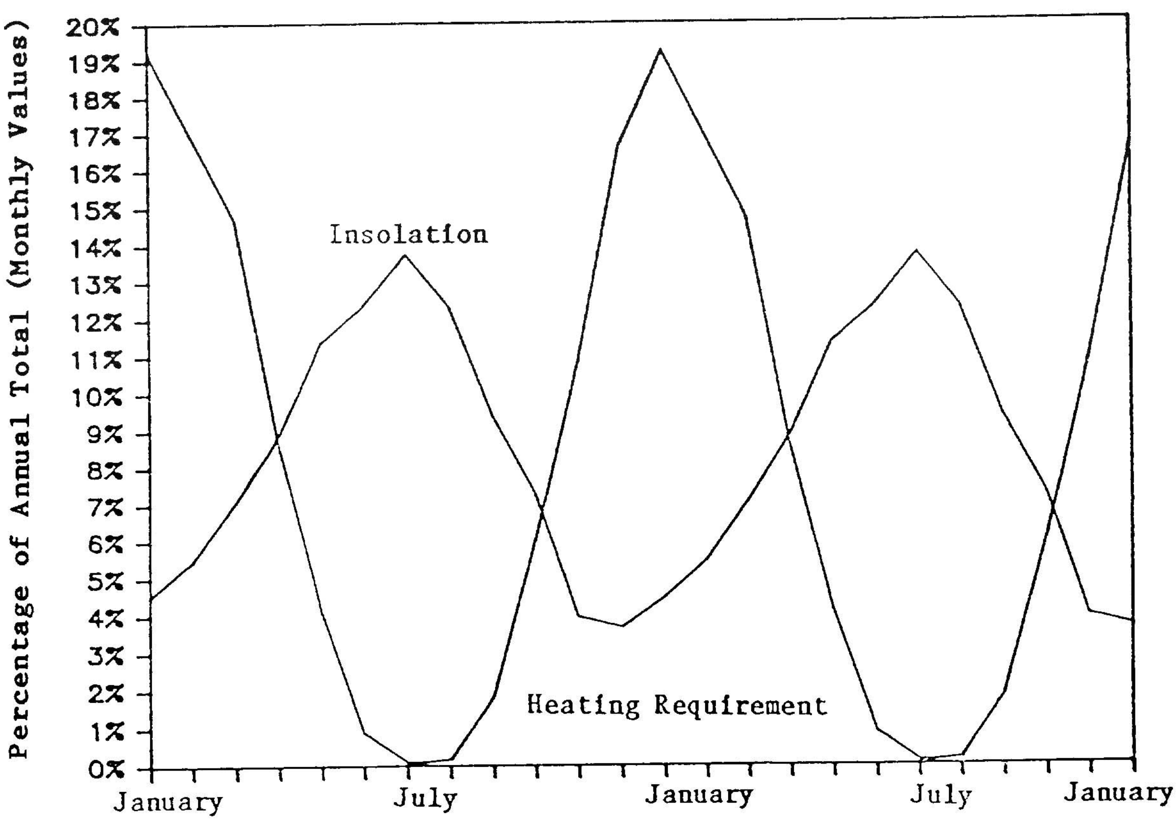
Figure 1.1 Seasonal Mismatch Between Heating Requirement and Solar Insolation for a Northern Climate



1 INTRODUCTION AND TASK ORGANIZATION

1.1 INTRODUCTION

In cold climates, space heating requirements are six months out of phase with solar insolation. This reality is depicted graphically in Figure 1.1. The purpose of the work of Task VII is to investigate the feasibility of matching the abundant summer time supply of solar energy with the winter time demand for heat. Seasonal thermal storage is the vehicle for accomplishing this matching. Because of the cost-effectiveness advantages of scale associated with seasonal storage, large centralized plants are of primary interest. This Task involves, therefore, central solar heating plants with seasonal storage (CSHPSS).

The work of Task VII addresses the following technical issues:

- sub-system (solar collectors, storage, distribution, heat pumps) selection and design,
- system configuration and design,
- system operational strategy, and
- cost

Other issues relating to the implementation of a CSHPSS plant, e.g. institutional questions, legal and jurisdictional questions, financing, etc. have not been addressed within this Task.

1.2 TASK ORGANIZATION

This section provides an overview of the international organization of Task VII. It is included for those who are unfamiliar with this task working environment. This section may be skipped by those who are interested primarily in the technical and econmic aspects of the task.

This Task has been organized under the IEA, Solar Heating and Cooling Programme (see inside front cover of this report for further background). Based on the objective and proposed workplan for Task VII, ten countries elected to participate in this Task: Austria, Canada, Commission of the European Communities, Denmark, the Federal Republic of Germany, the Netherlands, Sweden, the United Kingdom and the United States. All of these countries continued work into Phase II of Task VII (see below) except for Austria and the United Kingdom.

When Task VII was started in 1979, the workplan called for the development of a number of designs for solar heating plants with seasonal storage. These designs were to be developed in two phases. In the first phase, preliminary site-specific designs were to be developed by each country, based on model development and data analysis undertaken as part of the Task. In the second phase, these preliminary designs were to be further developed into detailed designs. It was expected that the level of detail would be sufficient for decisions to be taken to proceed with construction, if any country was prepared to go ahead.

The original workplan and sub-task structure was as follows:

PHASE I

Sub-Task I(a): System Studies and Optimization
- Lead Country: Canada

Sub-Task I(b): Solar Collection Sub-Systems
- Lead Country: U.S.A.

Sub-Task I(c): Heat Storage Sub-Systems
- Lead Country: Switzerland

Sub-Task I(d): Heat Distribution Sub-Systems
- Lead Country: Sweden

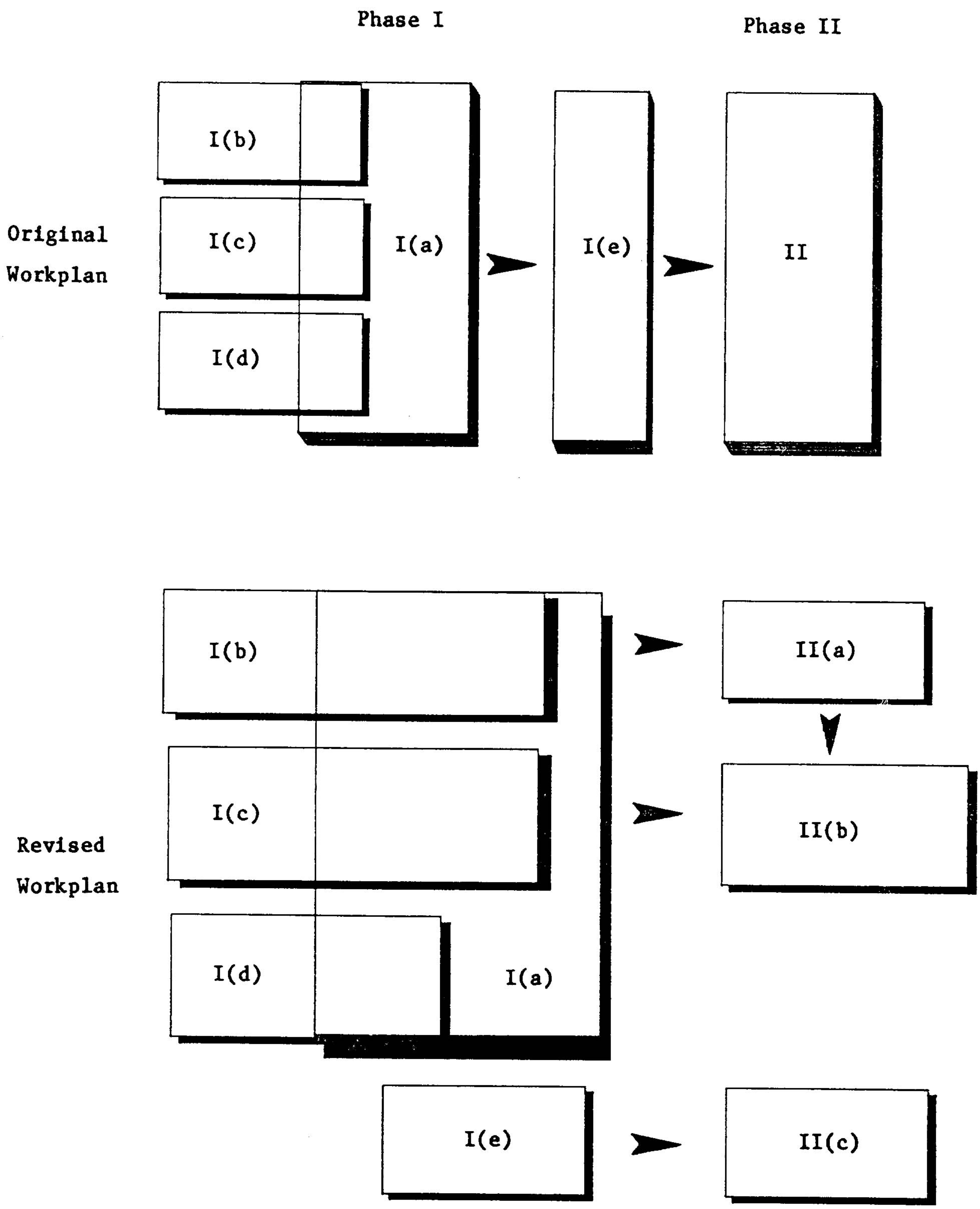
Sub-Task I(e): Preliminary Site-Specific Design
- Lead Country: Sweden

PHASE II

Detailed System Design

In reality, as illustrated in Figure 1.2, it was not possible to follow the original straightforward plan of work such that Sub-Task I(e) work would be based on the other Phase I results. It was found that R&D on the major sub-systems of a solar heating system with seasonal storage

Figure 1.2 Task Organization and Workplans



was still in a dynamic phase and not yet yielding definitive conclusions and design recommendations. Some of the designs presented in Sub-Task I(e), therefore, cover those systems already in operation and some are preliminary designs made without the aid of the design tools from Sub-Tasks I(a) - I(d). Towards the end of Phase I, it was decided that a most useful continuation of the task would be a systematic evaluation of most promising and realistic system concepts.

The revised Phase II comprised three sub-tasks

Sub-Task II(a): MINSUN Enhancements and Support
- Lead Country: Canada

Sub-Task II(b): Evaluation of System Concepts
- Lead Country: U.S.A.

Sub-Task II(c): Data Exchange
- Lead Country: The Netherlands

Under the revised workplan, the culmination of the analytic work of Phases I and II is embodied in Sub-Task II(b). These analytic results are summarized in Section 4 of this report and are documented in the Sub-Task II(b) report (T9)[1]. The models and analytic tools and procedures selected for use in Task VII and the further development of these tools are summarized in Section 3 of this report and are documented in the respective sub-task reports from Sub-Tasks I(a), I(b), I(c), I(d) and II(a) (T1 to T7). The Sub-Task I(e) report (T8) presents an overview of the site-specific designs, most of which are listed in Section 5 of this report. Sub-Task II(c) prepared the basis for an exchange of data and experience from CSHPSS systems in operation, which is the logical continuation of the work of Task VII. This sub-task work is documented in two working papers: Monitoring for Evaluation of CSHPSS Systems (W10) and A Set of Reporting Formats for CSHPSS (W11).

Section 2 of this report provides an introductory overview of CSHPSS system concepts and defines the scope of system configurations examined in Task VII.

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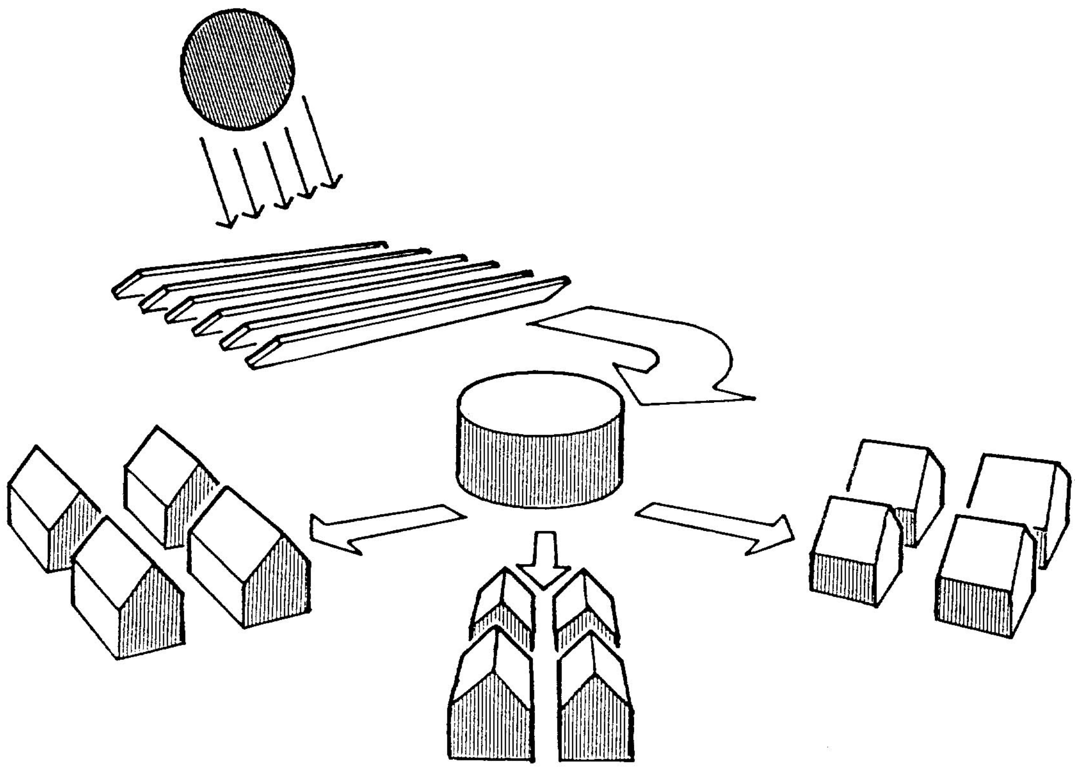
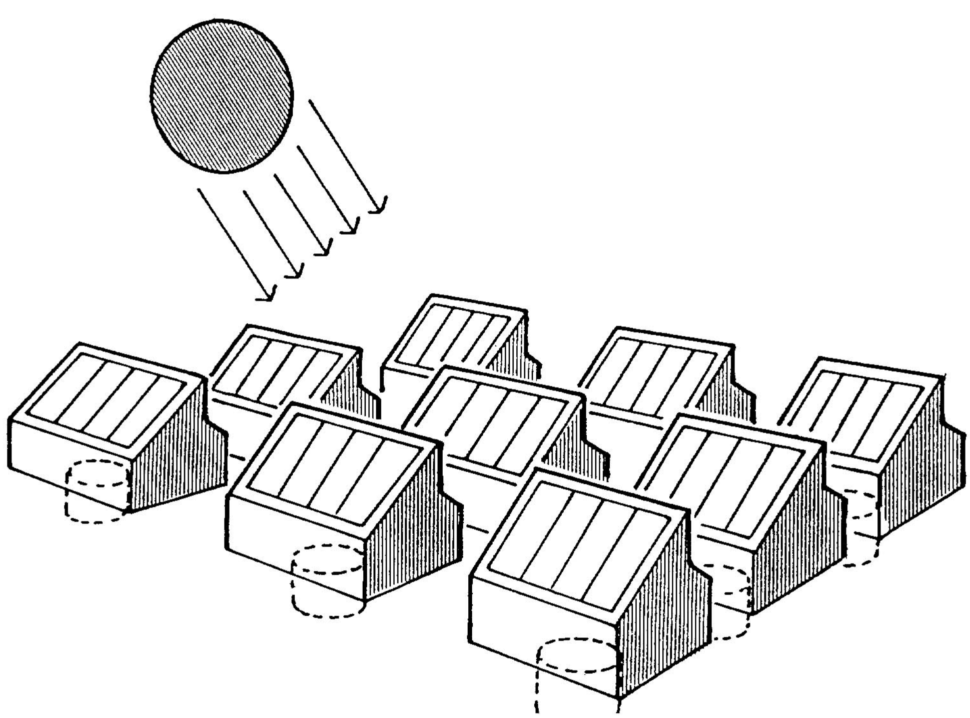
1. References are given in Appendix A: List of Task VII Documents.

Figure 2.1 Central vs. Distributed Configurations

Central Solar Heating Plant with Seasonal Storage



Distributed Solar and Storage



2 CSHPSS SYSTEM CONCEPTS

2.1 SYSTEM CONFIGURATIONS AND SUB-SYSTEM COMPONENTS

As stated above, the focus of Task VII was on central systems with seasonal storage. These two system characteristics go together for reasons of physics and economics. Seasonal storage is of interest in order to match the summer solar resource with the winter heat demand. Seasonal storage implies an annual cycle time period, i.e. long time constants. Heat loss from sensible heat storage systems is determined by the surface area of the storage geometry and the heat conduction properties adjacent to this surface area. Heat loss relative to heat storage is, therefore, inversely proportional to storage size as measured by a characteristic linear dimension. Relative heat loss is reduced as storage size is increased. Large storage implies centralized storage rather than distributed close to the load. This concept is illustrated in Figure 2.1

The basic system configuration analyzed in this task is illustrated in Figure 2.2 (overleaf). As illustrated there, the collector sub-system is generally connected directly to storage, although some cases of having the collectors deliver heat directly to the load were analyzed. The heat pump, if included, was placed centrally and utilized storage as a source of heat for the evaporator. This both extended the range of the storage and allowed both storage and collectors to operate at a lower temperature. A boiler which operated on auxiliary fuel was assumed to be used whenever the rest of the central plant could not otherwise meet the load demand.

In general, both solar collectors and thermal storage operate more efficiently at lower temperatures. There is an interesting trade-off, therefore, between low temperature solar and storage systems including a heat pump, and higher temperature systems which do not require heat pumps. To examine this trade-off, configurations with and without heat pumps have been examined.

Figure 2.2 Basic System Configuration for Analysis Purposes

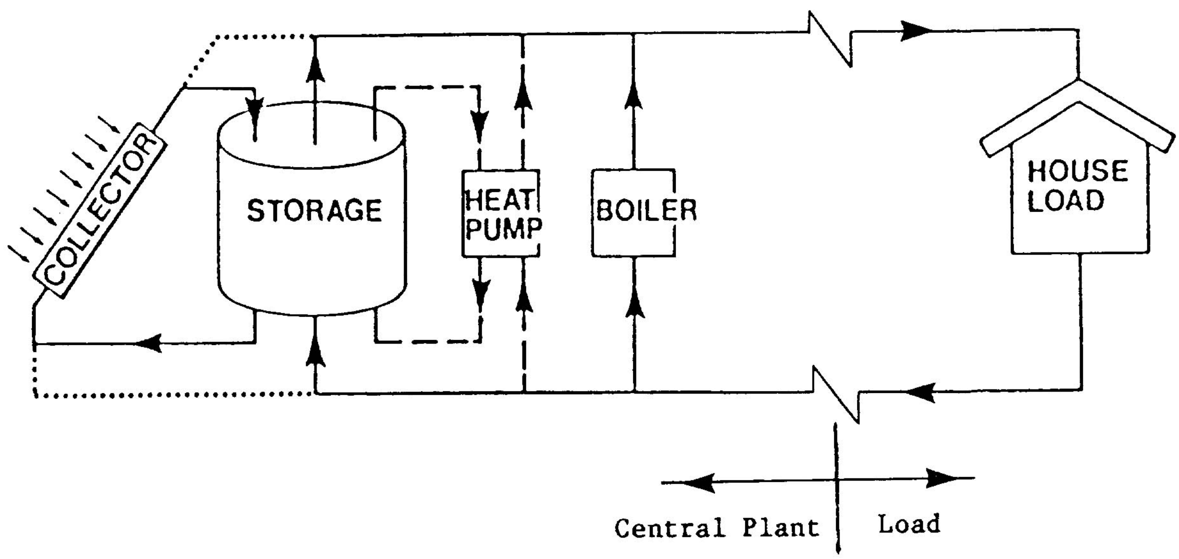
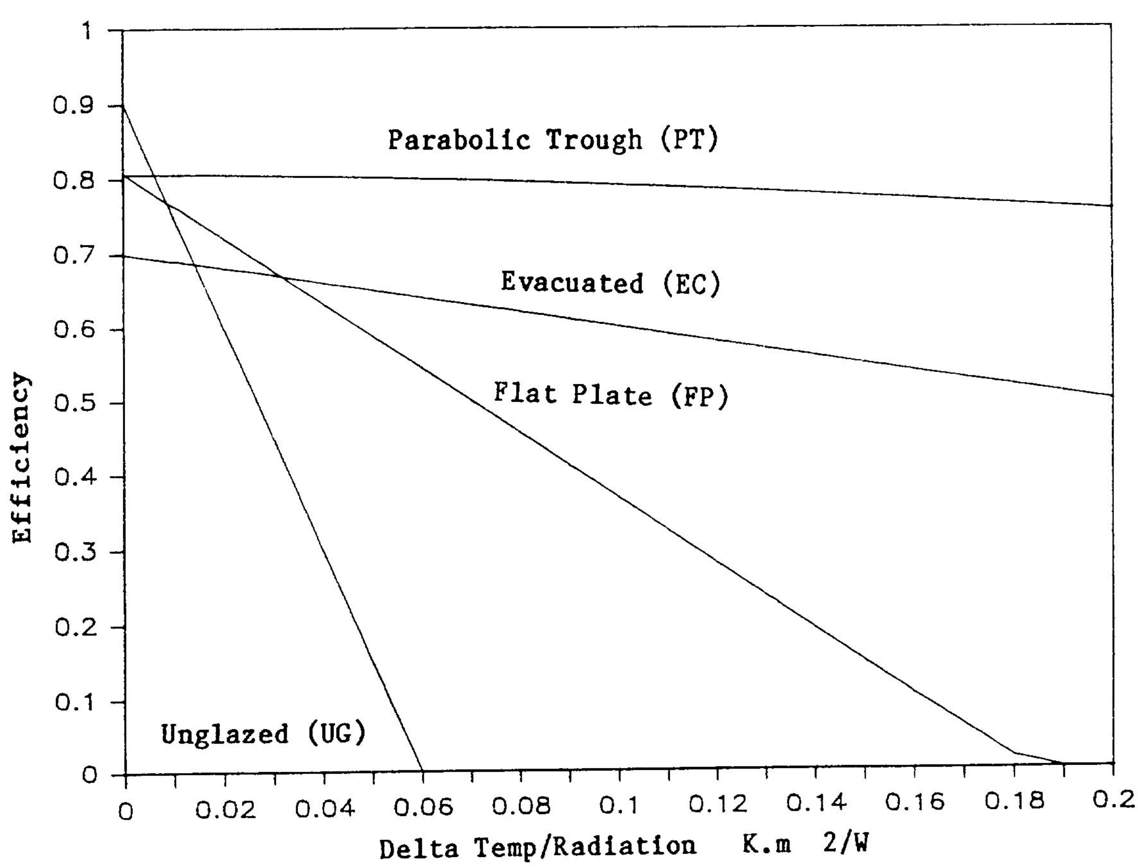


Figure 2.3 Instantaneous Efficiency Curves for Task VII Selected Collector Types



Each of the major sub-systems (collector, storage, distribution) is described below. Currently available technology and performance were assumed for all sub-systems.

2.1.1 Solar Collector Sub-Systems

Four collector types were included for analysis in Task VII. Of these four types, however, only two (flat plate and evacuated) were selected for detailed analyses of specific CSHPSS system configurations.

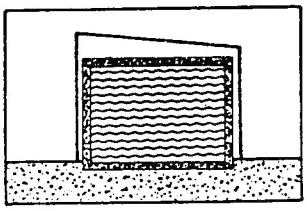
Flat plate collectors represent the most mature technology in all Task VII countries. This type of collector spans a wide spectrum from low-cost, unglazed absorbers to sophisticated, selective-coated, multi-layered glazed collectors. In the systems concept analyses, two categories of the flat plate collector type were examined: an unglazed, low-temperature (up to 50°C), low-cost collector, and a single-glazed, selective-coated, top performance collector (up to 100°C).

The evacuated-type collector included in Task VII analyses was a high-performance, stationary, concentrating collector. Although the assumed performance for such a collector had not been exhibited by a readily-available commercial product, such performance had been demonstrated in the laboratory as early as 1982. Such a collector can operate at very high temperatures, but in Task VII analyses, performance was examined only up to 150°C

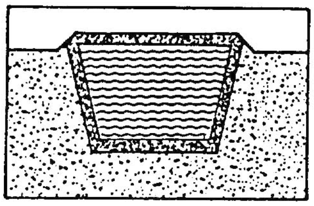
Parabolic trough-type collectors were included in Sub-Task I(b) (Solar Collection Sub-Systems) but were not included in the systems concept evaluations. The collector examined was suntracking with an East-West orientation. For the performance model, a hypothetical collector was selected - having an optical efficiency and heat loss characteristics equal to the 1985 goal set by the Sandia National Laboratory, U.S.A. These values had been demonstrated in laboratory tests before 1984.

The instantaneous efficiency curves for individual collector panels of the types listed above are shown in Figure 2.3.

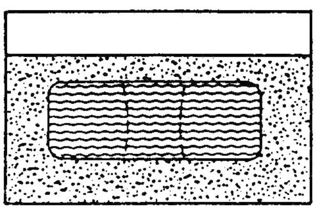
Figure 2.4 Storage Types



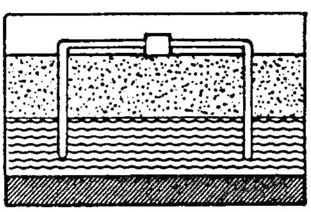
Water Tank



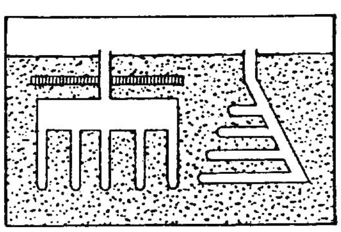
Water Pit



Water Cavern in Rock

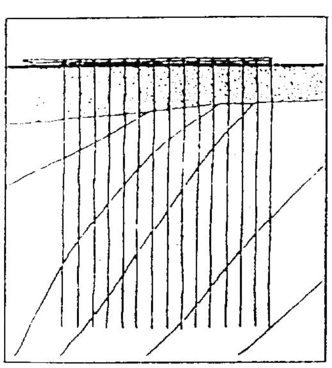


Aquifer



Earth with horizontal ducts, excavated

Earth with vertical ducts, drilled



Rock with ducts

Central receiver-type collectors were also included in I(b) but not in the systems concept evaluations. Although there are at least seven operational installations, the performance model used in Sub-Task I(b) was based on a detailed simulation of heliostat and receiver performance undertaken by Sandia National Laboratory.

For large applications, collector panels have to be arranged in large arrays. In Task VII, special attention was given to the performance of large collector arrays as compared to single panels. Very little information was found in the literature and in research reports, so Task VII participants initiated a special workshop[1] on this topic, which was held in the U.S.A., in June, 1984. Based on the available experience, on analysis, and on subjective assessment, performance reduction factors for large collector arrays were estimated and applied in the simulation models in Task VII.

2.1.2 Heat Storage Sub-Systems

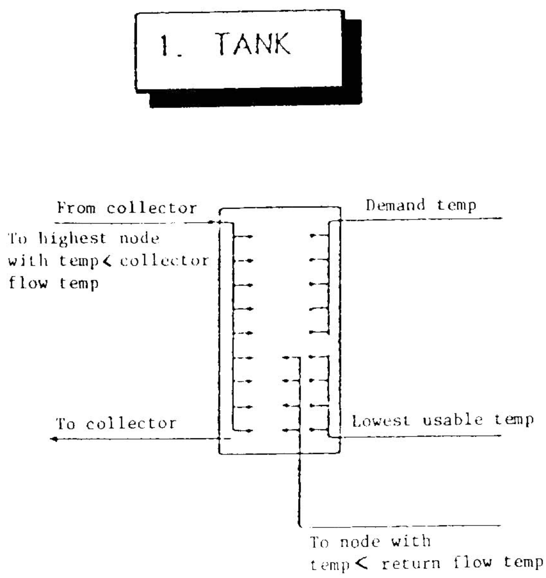
Heat storage is an essential part of CSHPSS systems. In Task VII, six storage types were selected for investigation: tank, pit, cavern, aquifer, and ducts in earth and rock. Figure 2.4 illustrates these six types which are described briefly below.

Tank storage is a well-known technique. It can be used almost everywhere, has low heat losses when properly insulated and is very flexible in operation. Structural considerations limit tank size to about 100,000 m^3, but several tanks may be used.

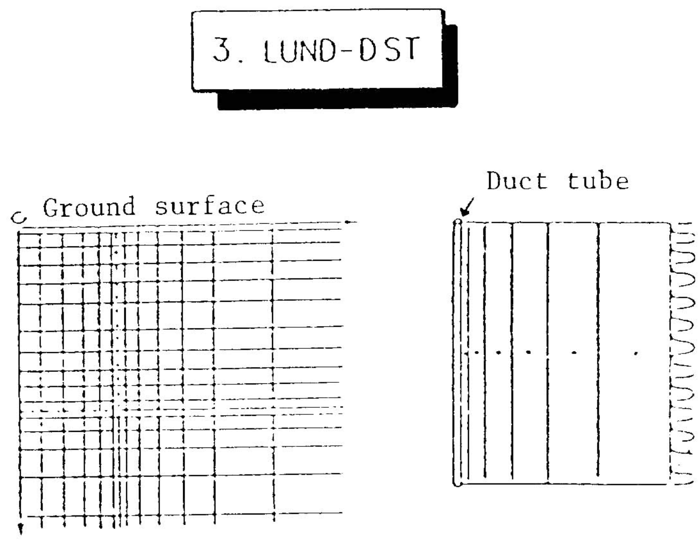
A water pit for heat storage is a partially excavated, lined pit in earth. Waterproofing is of paramount importance; it must retain watertightness and strength for many years at elevated temperatures. The liner ensures that the chemical composition of the storage water remains unchanged. This storage type has a higher lid surface to volume ratio than other storage types. The lid and embankments are, therefore, usually insulated. Extra heat is required during the first years of operation to warm up the insulated mass of soil.

1. Design and Performance of Large Solar Thermal Collector Arrays,

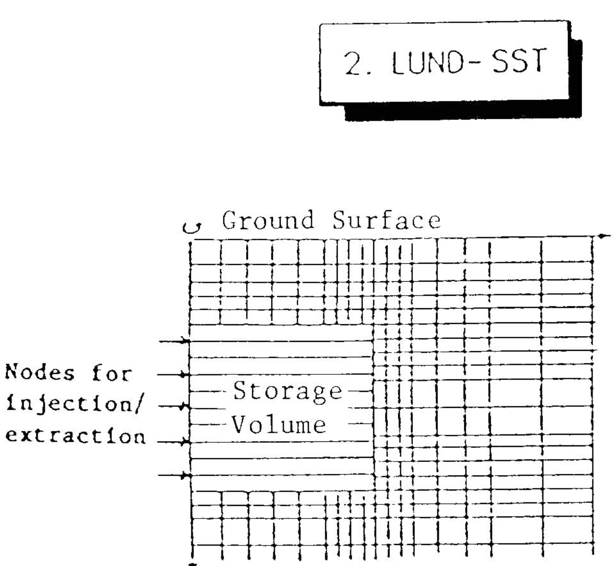
Figure 2.5 Storage Models



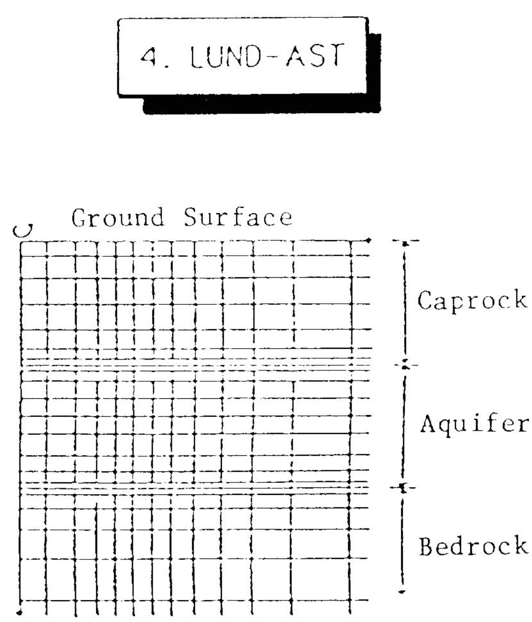
Tank Model



Duct Storage Model



Pit and Cavern Model



Aquifer Model

Ideal geological conditions for pit storage are ease of excavation, stable soil, and absence of ground water.

Heat storage in rock caverns is an example of an established technique being applied to a new area. In crystalline rock, excavation of large caverns is straightforward. Caverns are built without heat-insulating liners, and the surrounding rock participates in the temperature variations and heat storage. Considerable amounts of heat are needed during the first years of operation to warm up this mass.

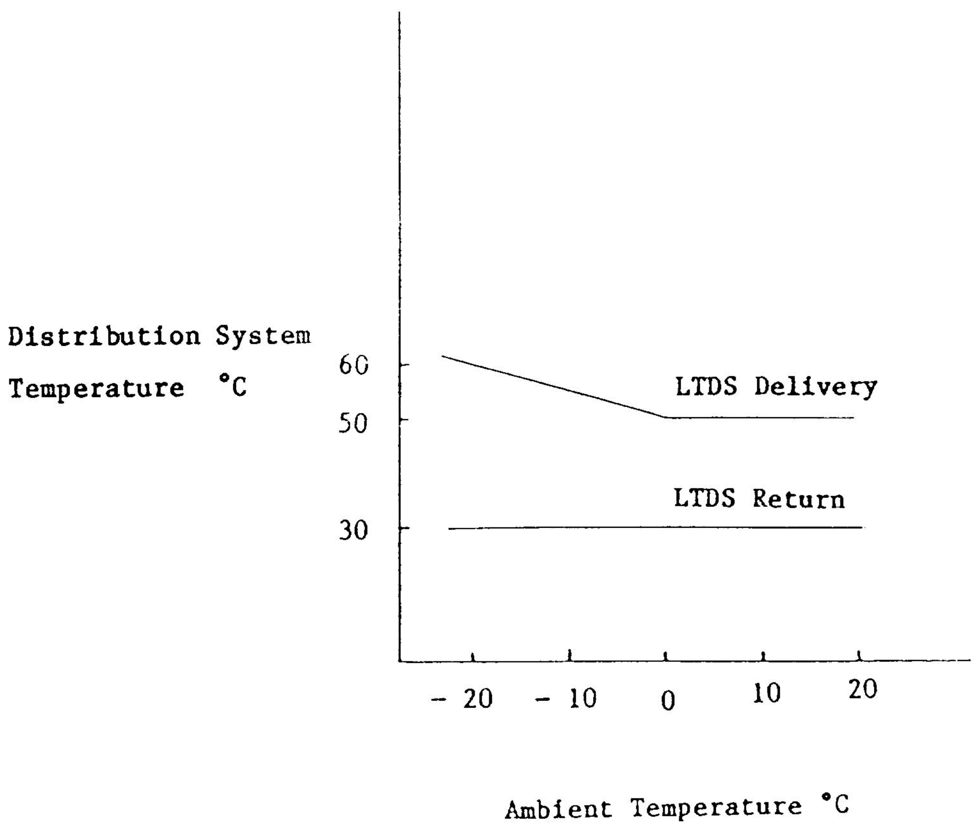
An aquifer is an underground formation containing water. Heat storage in aquifers is accomplished by transferring water to and from the aquifer through wells. Such use of aquifers has been demonstrated successfully, but a number of problems still need to be addressed. Much larger heat transfer can be accomplished with an aquifer compared with earth or rock storage systems which depend on heat exchangers underground.

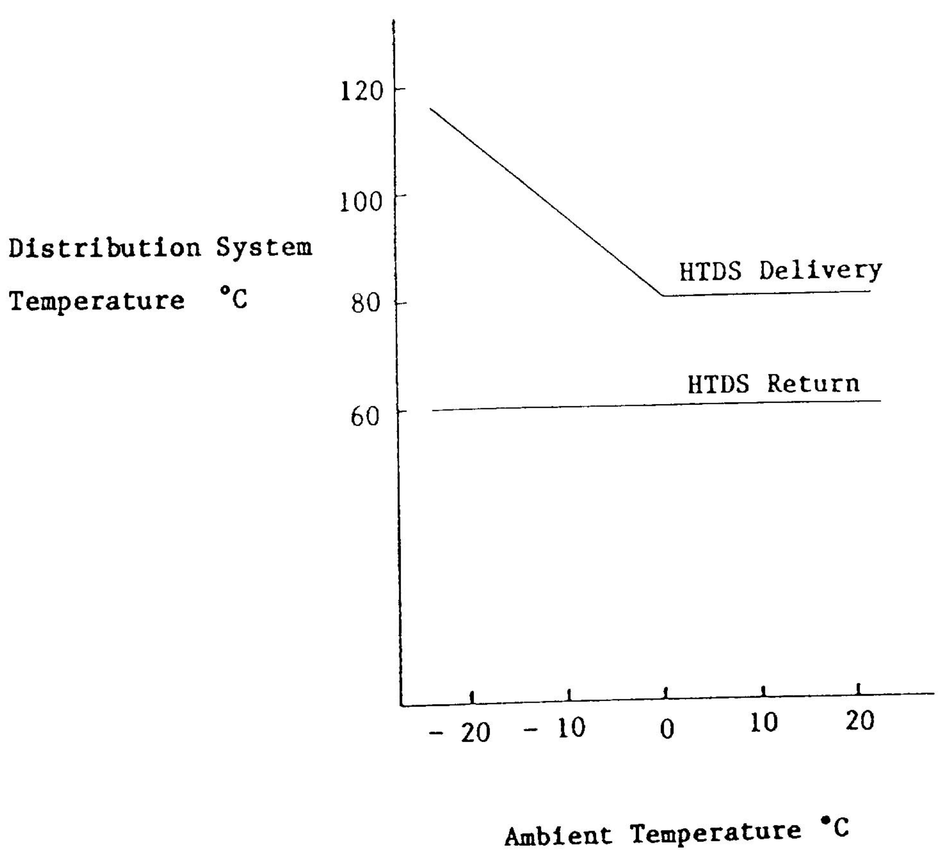
An earth storage is a layer of subsoil containing a heat exchanger. The heat exchanger is usually formed by tubes, placed either vertically (via drilling) or horizontally (via excavation). Insulation is usually installed on the top and often around the perimeter, if the volume has been excavated. Ideally, the earth should be saturated, but high permeability and ground water movements can cause high heat losses. Low storage temperatures are common; there is very limited experience with temperatures higher than 40°C.

Rock storage is similar to earth storage with vertical tubes. Construction of a rock storage utilizes well-known drilling techniques. The heat carrying fluid, normally water, is circulated through bore-holes in the rock, in open or closed circulation systems. Short-term buffer storage is often incorporated to reduce heat transfer peaks. Deep wells allow storage temperatures above 100°C.

Computer models were used to simulate the thermal behavior of the different storage types. In addition to the water tank model which was part of the original MINSUN program, models were required for all these storage types. Simulation models for each storage type were collected, tested and evaluated. These models were classified into three families

Figure 2.6 Low and High Temperature Distribution System Profiles





namely: one for water tank, pit and cavern storage systems, one for aquifer systems, and one for duct storage systems in earth and rock. For the first family, seven models were investigated, eight for the second and five for aquifers. The evaluation resulted in the selection of three models, all originating from the Lund Institute of Technology, as illustrated in Figure 2.5. Computer codes for these three models were modified for use within MINSUN, the program developed in Task VII (see section 3.2).

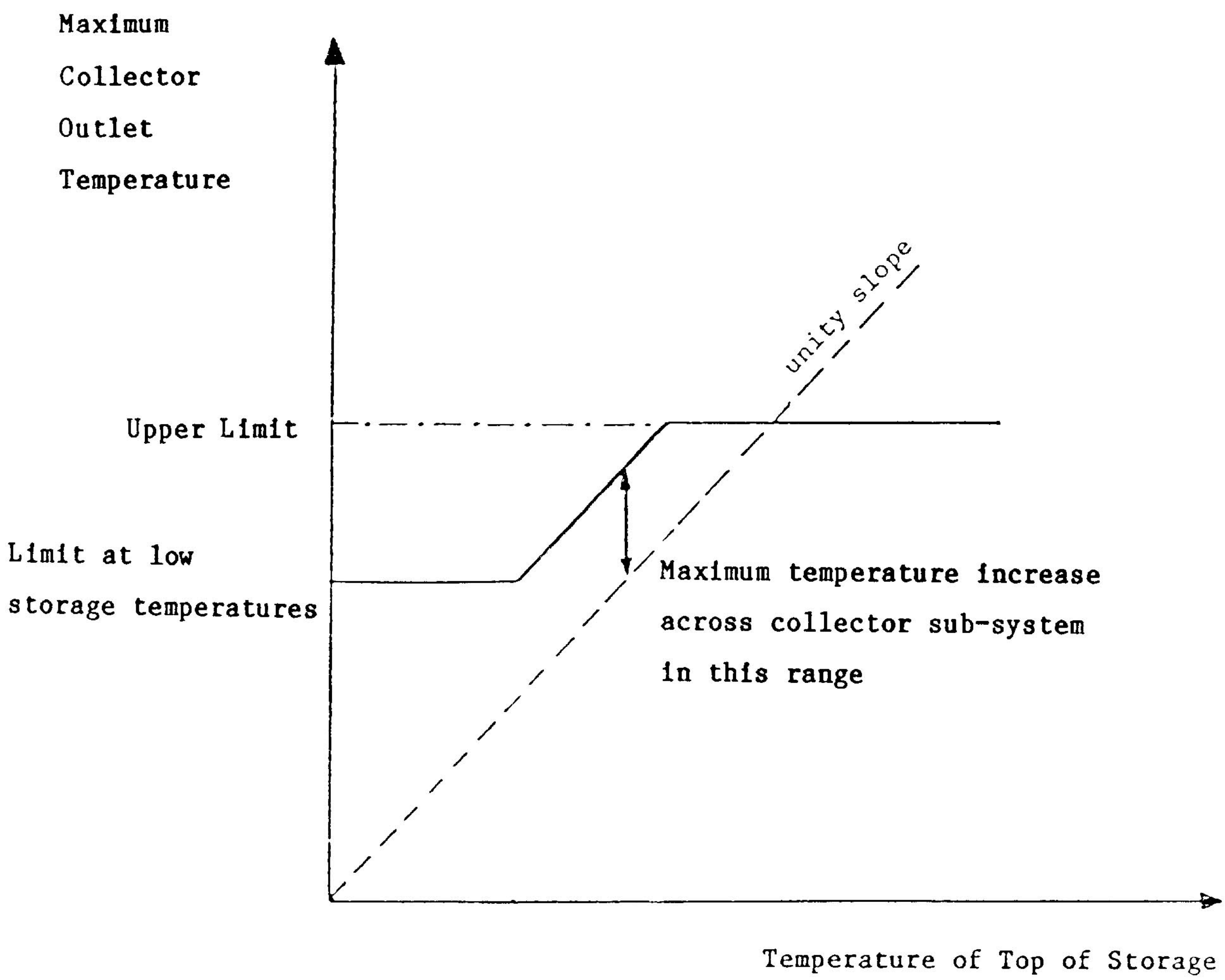
2.1.3 Heat Distribution Sub-Systems

In CSHPSS systems, heat distribution uses the same technology as a district heating system. For CSHPSS systems, however, distribution temperatures at the low end (up to 60°C) of current practice are preferred because collectors and storage are more efficient at lower temperatures. Several of the participating countries have operational experience with these systems. As part of Sub-Task I(d), a report was prepared summarizing experiences in the participating countries, including identification of computer codes for design and analysis (T7).

In the systems concept evaluations undertaken in this Task, two distribution temperature regimes have been examined. The low temperature distribution system (LTDS) is defined to be as low as possible consistent with the demand load and would apply to newly built systems using solar. The high temperature distribution system (HTDS) is more consistent with existing distribution systems and, therefore, would be more appropriate in retro-fit applications. Figure 2.6 illustrates these two temperature regimes.

In CSHPSS systems, there are two heat transfer systems. In the collector to storage loop, the total annual energy involved has to be collected during sunshine hours in about one half of the year. The peak energy transfer rate and the variability of energy transfer is greater in this collector-to-storage loop than in the central-plant-to-load loop. These considerations favour the location of the storage close to the collector field and as close to the load centre as possible.

Figure 2.7 Variable Flow Collector Control Strategy



2.2 SYSTEM OPERATING STRATEGIES

The basic system configuration considered in Task VII is illustrated in Figure 2.2. Except for a few specific cases, direct energy flow from the collector field to the load was not considered. System operating strategies were thus simplified, since the collector/storage operation could be separated from the storage/heat pump/boiler/load operation. This separation of operating strategies between the two loops does not deny the interaction of the two strategies and the overall cost-effectiveness of the various combinations of strategies. During the analysis, basic parameters of the operating strategies were varied, and the most cost-effective parameter values were selected.

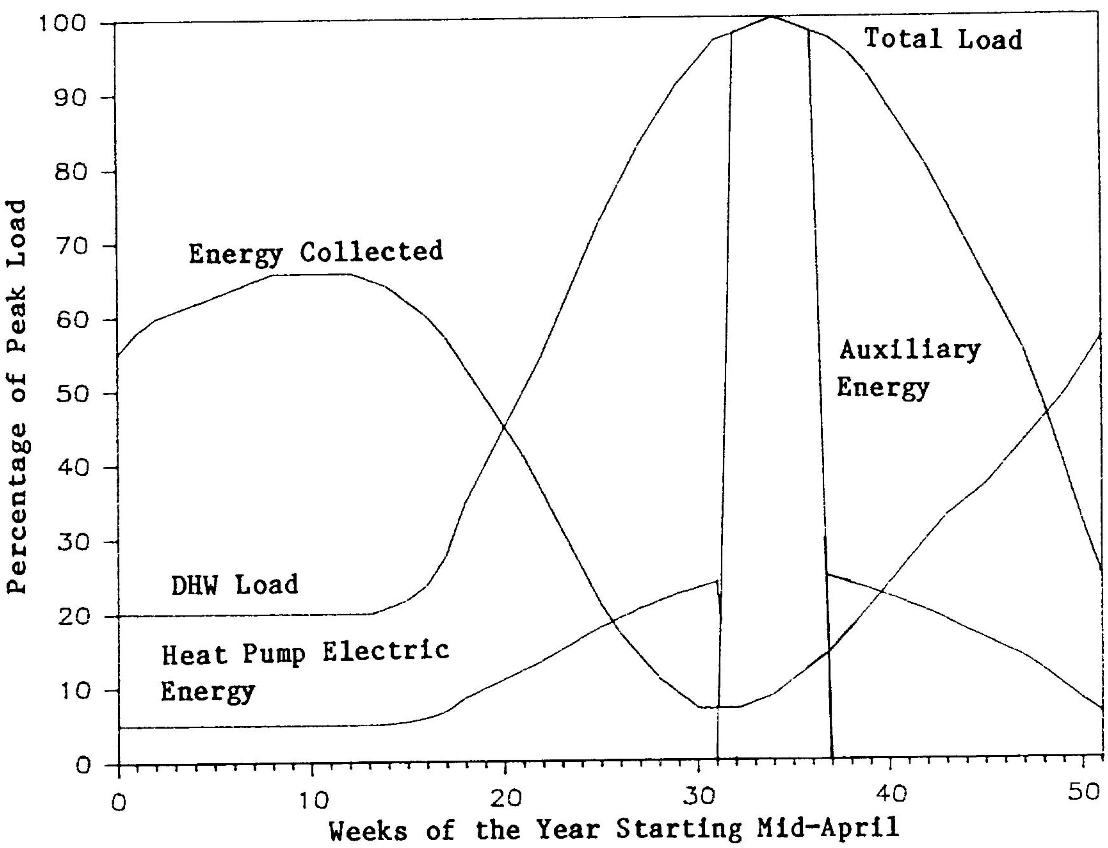
Operating strategies for the collector/storage loop were different for the different storage types (and were different in parameter values for the different collector types). For the stratified water storage types (tank, cavern, and pit, if stratified), collector inlet temperature was the lowest temperature from storage. Both variable flow and fixed flow were modelled. Variable flow (between pre-set minimum and maximum limits) was set to attain if possible, a specified outlet temperature dependent on the maximum temperature in storage (see Figure 2.7). Collector outlet was then returned to the stratified storage at a layer just lower in temperature.

For the aquifer storage, collector inlet temperature was determined by the cool-well water temperature. Generally, collector outlet temperature was set to a constant value (using variable flow) for injection into the warm well.

For duct storage systems, collector inlet temperature was determined by the storage extraction temperature which gradually increases over the charging period. Generally, a pre-set temperature increase across the collector field (within limits) determined flow rate and re-injection temperature.

In all storage types, cost-effective operating temperatures for configurations with heat pumps were lower than for configurations without heat pumps.

Figure 2.8 Typical Annual Profile of Energy Flows for a System with a Heat Pump



Operating strategies for the storage/heat pump/boiler/load loop were similar for all storage types but differed whether a heat pump was included or not. In Task VII analyses, the load was determined by actual weather conditions for the location and a specified requirement for DHW. This load requirement determined the temperatures, flows and losses in the distribution system. The load as seen by the central heating plant was, therefore, calculated and pre-determined. The heating plant was then required to meet this load on a daily average basis.

For configurations without a heat pump, the operating strategy was simply to meet as much load from storage as possible (on each day). If the temperature or amount of energy available from storage was insufficient, the boiler made up the difference.

For configurations with a heat pump, the strategy was modified such that the first choice was to meet the load directly from storage. If this was not possible, the second choice was to meet the load using the heat pump, with storage as heat source for the evaporator. If the heat pump could not handle the entire load (because storage was at too low a temperature), the operating strategy would not use the heat pump at all. In that case, the boiler (third choice) would be used to satisfy the load. Figure 2.8 shows a typical annual profile of energy flows for a configuration that includes a heat pump. In this figure, the daily fluctuation has been smoothed for presentation purposes.

Figure 3.1 (a) Actual Cost Profile

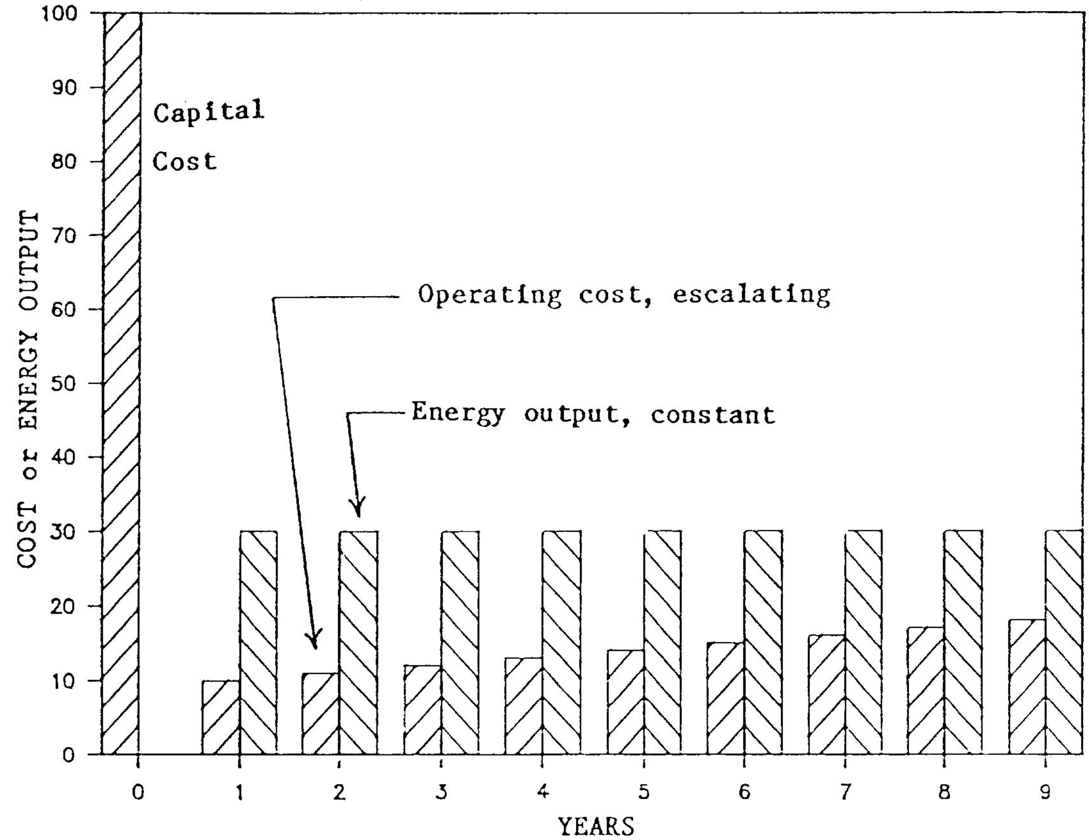
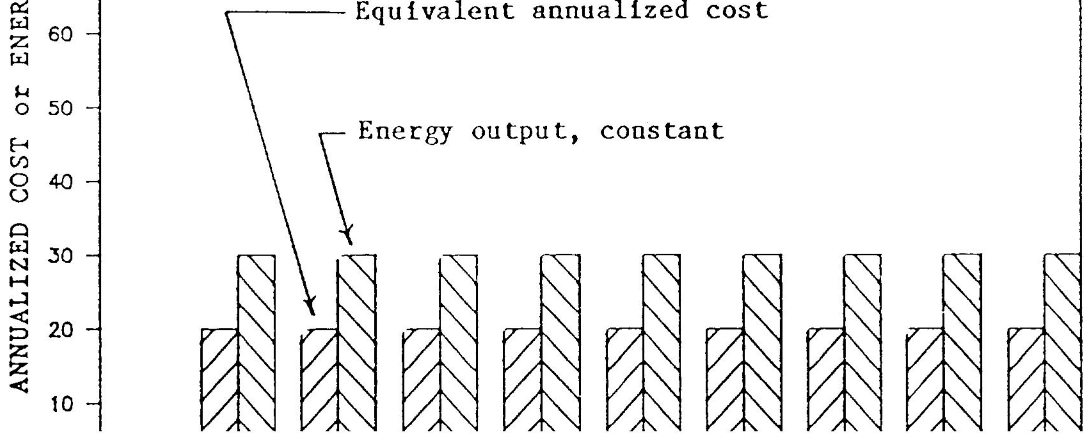


Figure 3.1 (b) Annualized Cost Profile



3 ANALYTIC APPROACH AND TOOLS IN TASK VII

3.1 ECONOMIC EVALUATION CONSIDERATIONS

Task VII has dealt with the technical and economic feasibility of CSHPSS systems. Examination of system performance from an economic or cost-effective point-of-view requires the specification of a framework for determining costs and for undertaking analyses.

The framework adopted for assessing costs included:

- the specification of equipment that was state-of-the-art but commercially available in 1985;
- the establishment of costs in U.S. dollars for all sub-systems that would be used in the common analyses among all participants;
- costs would apply to 1985 but were based on data collected among all participant countries during Phase I (1980-83) with currency conversion based on 1980 rates;
- energy costs for electricity and auxiliary fuel were left unspecified and analyses would be applicable to a wide range of such costs; and
- operating and maintenance costs other than operating energy costs were considered to be capitalized and included in the total investment costs.

The framework for economic analysis was based on present value theory. Real (non-inflationary) costs occurring at different times were reduced to the equivalent amount in the year of construction by applying the appropriate discounting factor. This amount in the year of construction was then converted to an equivalent stream of equal annual amounts over the expected lifetime of the plant using the same discount rate. Figure 3.1 illustrates this annualization of costs concept.

This equivalent annualized cost can be usefully expressed per unit of energy output. In this way, the amount per unit of energy ($/MWh) can be interpreted as an energy price, in constant dollars, which, if collected on each unit of energy produced, would exactly recover the total cost of

3.2 ANALYTIC PROCEDURE

The criteria considered for determining a suitable procedure for Task VII analyses were:

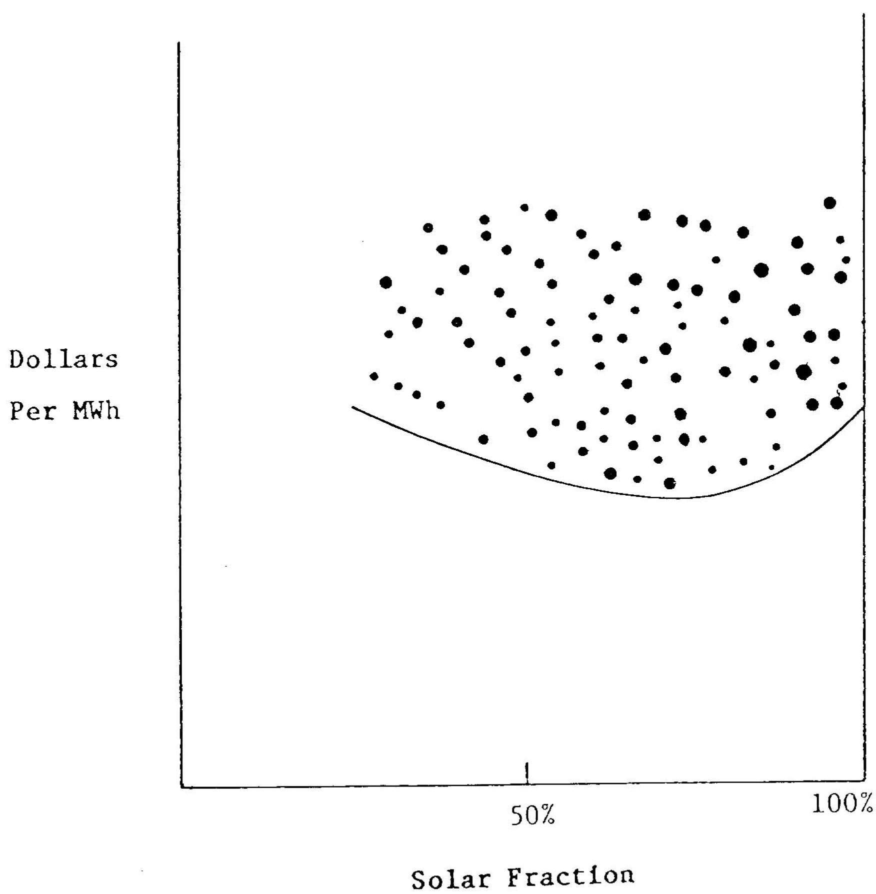
- the applicability of the results to a wide range of fuel and electricity prices;
- the use of solar-only costs so that sensitivities are not masked by conventional system costs;
- the need to rank a large number of system configurations with different cost structures with respect to cost effectiveness;
- the need to compare CSHPSS economic performance with conventional systems.

The following procedure was applied for each reference case (see section 4.1) for which "optimal" designs were identified:

- a "reasonable" system configuration, based on a series of preliminary model simulations, was specified as a starting point;
- design parameter values and component definitions were varied over a wide, but appropriate, range;
- solar component cost and solar system useful heat output were calculated for each simulation run and the results were plotted on a graph of unit solar cost versus solar fraction;
- those system configurations and design parameters which have the lowest solar cost for each solar fraction were identified;
- marginal cost analysis was performed to determine the optimal system solar fractions for the range of auxiliary fuel prices of interest.

Solar capital cost was defined as the collector sub-system cost, plus storage sub-system, plus collector-to-storage transmission pipes plus heat pump, if any. Auxiliary fuel and electricity costs were not included. The rationale for including heap pump capital cost was that the solar system design is enhanced by having the heat pump in the system (collectors and storage operate at lower temperatures); thus, this cost

Figure 3.2 Unit Solar Cost versus Solar Fraction



energy cost was excluded because this energy is delivered to the load and the cost of this energy is dependent on assumptions about energy prices and location.

Unit solar cost was defined as the annualized solar cost of the system divided by the annual solar heat output of the system. The solar heat output was defined as that provided by the storage sub-system to the heat pump or to the load directly.

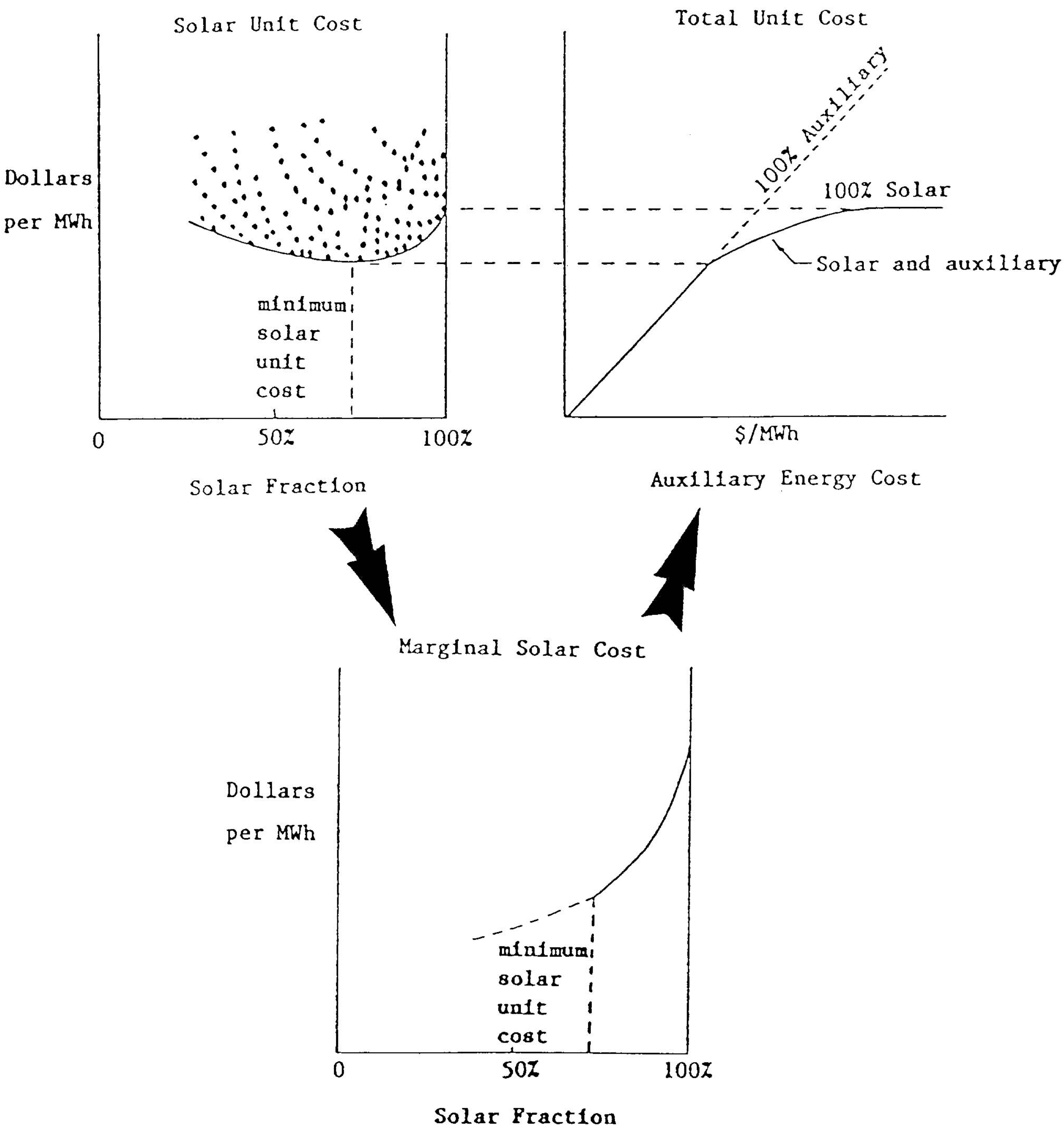
To determine the least cost solar designs for a given load and set of common parameters, the unit solar cost and fractional solar output were plotted on a single graph. By plotting all relevant simulations on one graph, the least cost design for various solar fractions could be identified even though the designs may be for different sub-system types (e.g., different collector types), storage system parameters, or control strategies. Figure 3.2 illustrates the graphical representation for unit solar cost versus solar fraction.

The envelope of minimum-cost points can be used to compare one type of system with another (e.g., to compare aquifer storage systems with duct storage systems). The optimum system solar fraction, and therefore system design and size of sub-systems, depends on the cost of auxiliary energy.

Since auxiliary energy may be either fuel or electricity or some combination, the total unit cost of energy from a particular solar system will depend upon the respective price, efficiencies, and requirements for fuel and electricity. To simplify this comparison, we made the assumption that the effective cost of supplying heat from the fuel source and electric source were equal. This assumption is convenient and simplifies the analysis, presentation, and discussion of the optimization procedure; however, it is not essential. The procedure can be adapted for any range of auxiliary energy costs.

If the minimum unit solar cost is less than the auxiliary fuel cost, the optimum system design will be for a larger solar fraction than that at the minimum unit solar cost. The solar fraction should be increased

Figure 3.3 Solar Unit Cost and Total Unit Cost



It is useful to examine how the system (i.e. solar plus auxiliary) unit energy cost varies with the auxiliary energy cost. The central plant unit energy cost is the annual levelized solar system cost plus the levelized auxiliary energy cost divided by total annual load. As outlined above, the optimum system design and size can be identified given the cost of auxiliary fuel. Generally, this design was for less than 100 percent solar.

For all values of auxiliary energy cost below a certain point, the optimal system designs would be non-solar. Central plant energy costs are less than fuel costs at auxiliary energy cost levels above a certain point. That point is determined by the minimum of the unit solar cost curve. The relationship between central plant energy cost and auxiliary cost was determined by selecting the appropriate solar system configuration and solar fraction based on the system expansion curves and marginal solar cost. Figure 3.3 illustrates this procedure.

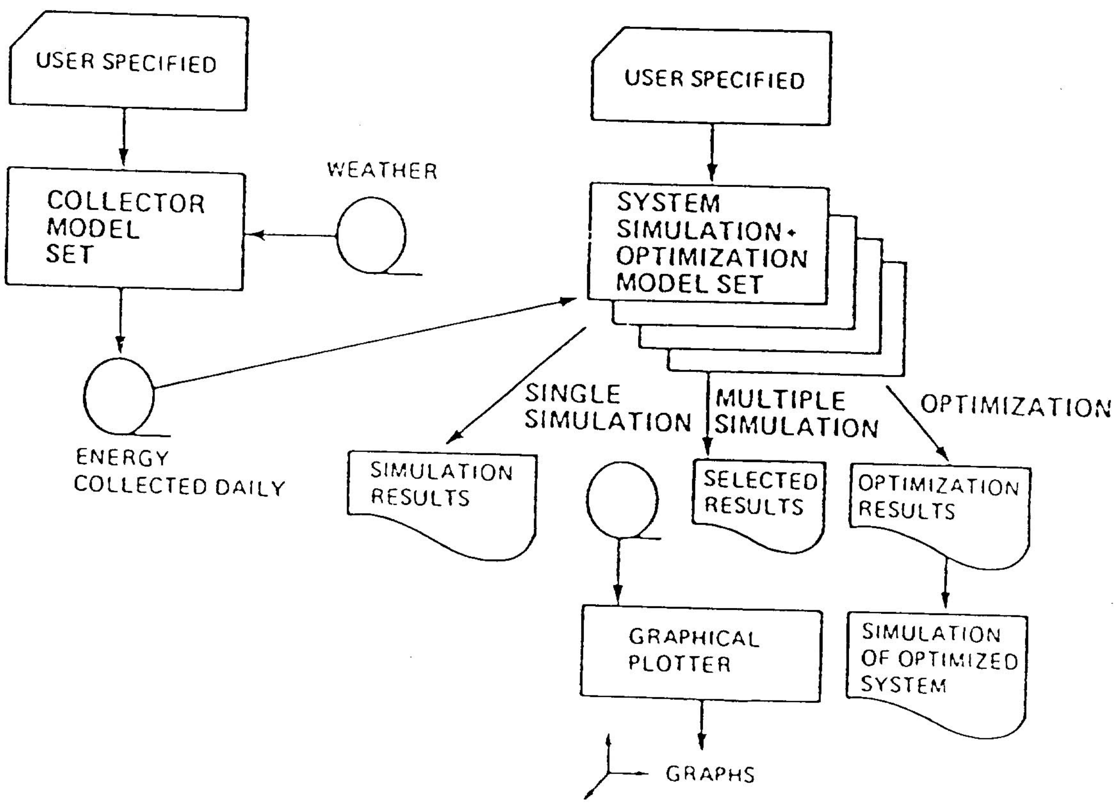
3.3 ANALYTIC TOOLS

Two computer program system models were used in Task VII. The MINSUN programs, originally developed at Studsvik in Sweden, were significantly modified and extended by the participants of Task VII (T1 and T2). These programs provide CSHPSS simulation, economic analysis, and optimization. MINSUN continues to be used by Task participants in ongoing work. Most recently, it has been converted to run on an IBM PC micro-computer which makes it more readily available for other users. The second computer program system model used in Task VII was the well-known TRNSYS program[1] (Version 11.1). TRNSYS provided detailed simulation and sub-system examination.

A MINSUN model of each system is made up of the components illustrated in Figure 3.4 (overleaf): solar collectors, thermal storage, heat pumps, auxiliary heaters, a network of connecting pipes, and residential heat

1. TRNSYS - A Transient System Simulation Program, Solar Energy Laboratory, University of Wisconsin-Madison, Madison, Wisconsin, U.S.A.

Figure 3.4 The MINSUN Set of Computer Programs



load. The program utilizes hourly data on solar radiation and ambient temperature to estimate energy collection and space heating requirements respectively. The estimated energy collected based on a typical solar panel performance model was adjusted by an array performance reduction factor to account for various operating losses. Once these daily variances are accounted for, the remainder of the model simulation utilizes a daily time step. Due to the interactions among sub-system components (e.g. collector sub-system with storage sub-system), the model solution often requires iterative calculations to estimate certain daily values.

The MINSUN program was used to simulate the thermal behaviour of a central solar heating system and to determine the optimum size of some of the components in the system. MINSUN can be used to perform a thermal simulation for a given, fixed configuration. MINSUN can also be used to perform several simulations in a single run while systematically varying the parameters defining the system.

Any system design variables can be varied during multiple simulation runs. Key variables usually include collector area, storage volume, storage height to diameter ratio, storage insulation thickness, number of bore-holes or ducts, specific heat transfer parameters of the heat pump, control set-point temperatures, etc.

4 TECHNICAL AND ECONOMIC EVALUATION OF SYSTEM CONCEPTS

4.1 SELECTION OF SYSTEM CONFIGURATIONS FOR EVALUATION

The sub-system components of a CSHPSS can be configured in an enormous number of ways to form systems for central heating plants. Considering the options within the major sub-systems, such as the storage type, the collector type, the distribution temperature, heat pump or not, and the load, and limiting the many possible arrangements of these sub-systems, there are about 500 configurations that should be considered. In addition, the economic viability of any of the system configurations depends upon its location (latitude and climate), its economic environment, and the manner in which the system and the load are controlled. Even a small subset of these variables would require that each system be evaluated under about 50 different sets of conditions, thus bringing the total number of evaluations to 25,000. Such an undertaking was obviously not feasible within the constraints of the resources available. A ranking and selection was, therefore, undertaken, which was based on results from Phase I and on the knowledge and judgement of the Task VII participants.

The primary system configuration cases that were selected for detailed analysis were:

Storage Type:

Water Storage	- including insulated and uninsulated tanks, pits and caverns
Earth and Rock	- including all forms of duct accessed storage in non-aqueous media
Aquifer	- including natural and man-made aquifers for low and high temperature storage

Collector Type:

Unglazed (UG) - unglazed, low-temperature collectors (up to 50°C)

Flat Plate (FP) - stationary non-concentrating collectors intended mainly for medium temperature operation (up to 100°C)

Evacuated (EC) - stationary, concentrating, evacuated collectors; capable of high performance at elevated temperatures (up to 150°C)

Distribution System:

Low Temperature - minimum delivery temperature of 50°C (LTDS) increased to 60°C at -20°C ambient and return temperature of 30°C. Referred to as (60/50/30). See Figure 2.6.

High Temperature - minimum delivery temperature of 80°C (HTDS) increased to 115° at -20°C ambient and return temperature of 60°C. Referred to as (115/80/60). See Figure 2.6.

Energy Conditioning:

Heat Pump - in series with load and auxiliary heating when needed

No Heat Pump - only auxiliary heating when needed

Load:

Small - 3.6 TJ (1,000 MWh) per year or approximately 50 houses

Large - 360 TJ (100,000 MWh) per year or approximately 5,000 houses

The load was characterized as space heating (dependent on weather) and DHW. The fraction of DHW was set nominally at 20% but was varied to zero and to 50% to test sensitivity to load seasonality.

Location:

Severe Continental - Madison, Wisconsin, U.S.A.

Northern Maritime - Copenhagen, Denmark

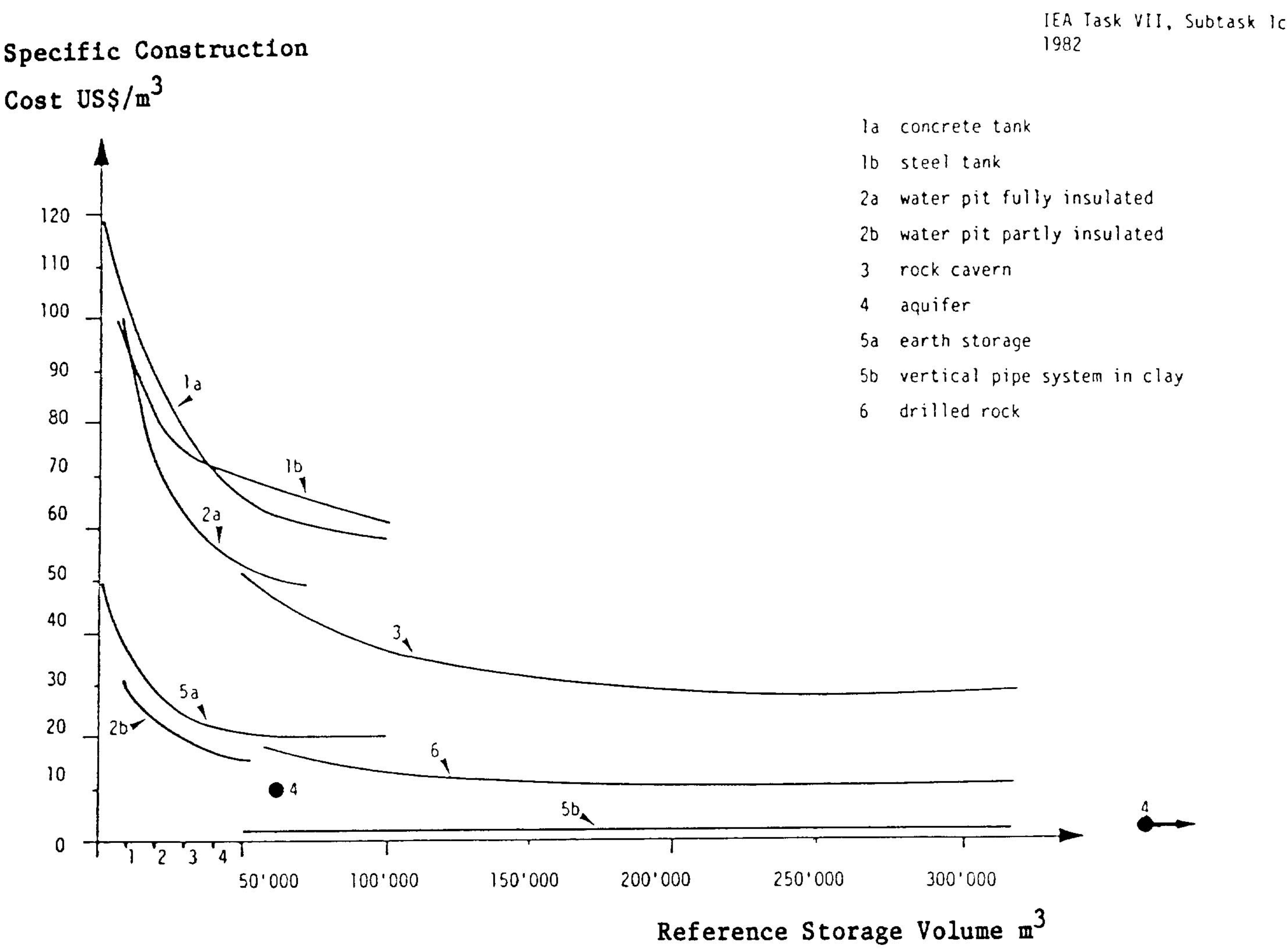
4.2 SPECIFICATION OF TECHNICAL AND ECONOMIC PARAMETERS

For the systems concept evaluation work carried out collectively within Task VII, a common set of technical and economic parameters was used. As required by the MINSUN set of programs, a system specification requires more than 100 technical parameters and approximately 30 economic parameters. The values selected for each storage type, collector type, etc. are given in the references (T9, W1, W2, W3). The key parameter values are specified below. In the national systems studies which are reported in the Sub-Task II(b) report (T9), parameter values appropriate for each national context were employed.

Collector Sub-System:

- instantaneous collector panel specifications as illustrated in Figure 2.3 (page 10) plus incident angle modifiers.
- large array energy reduction factors of 0.7 for unglazed and evacuated and 0.66 for flat plate collectors.
- operating strategy as illustrated in Figure 2.7 (page 18), dependent on storage type and with optimized parameters.
- costs for large arrays, all-inclusive, 140, 245 and 350 U.S. dollars per m^2 for unglazed, flat plate and evacuated, respectively.

Figure 4.1 Characteristic Storage Costs using Assumed Cost Parameter Values



(From Technical Report T 5)

Storage Sub-System:

- for earth and rock coupled storage types, common parameter values were used for thermal conductivity and specific heat as shown in Table 4.1 below.
- characteristic storage costs using assumed common parameters are illustrated in Figure 4.1; actual storage costs are site dependent and vary widely.

Heat Pump:

- a simple, theoretical model of an electric heat pump has been used in MINSUN which is not specific to a particular heat pump type or refrigerant; its performance is related to the Carnot efficiency as specified by operational temperatures.
- cost is based on maximum power flows through the evaporator and condenser and maximum power required by the compressor.

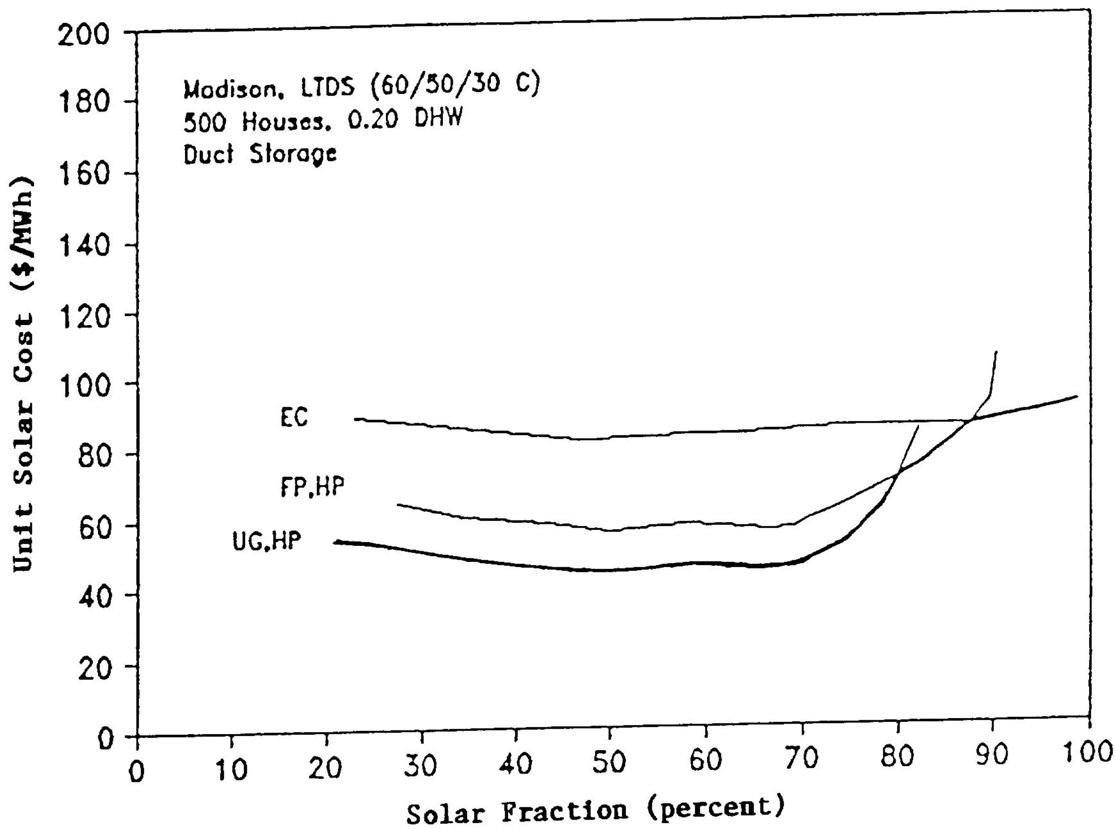
Distribution Sub-System:

- thermal losses are based on standard models and practice.
- distribution system costs have not been included in systems concept evaluations.

Table 4.1: Assumed Properties of Earth and Rock Storage Media

	Units	Pit	Cavern	Aquifer	Duct
Thermal Conductivity	W/m.K	2.0	3.5	2.0 Horiz. 2.75 Vert.	2.0
Specific Heat	MJ/m^3K	2.0	2.0	2.5	2.5

Figure 4.2 Example of Composite Expansion Path for Several Collector Types



LTDS = Low Temperature Distribution System

EC Evacuated Collectors

FP Flat Plate Collectors

HP Heat Pump

UG Unglazed Collectors

Load:

- space heating load dependent upon outdoor hourly temperature, set-point and internal gains.
- DHW load specified as 4.0 MWh per house per year.

Economic Analysis:

- economic life time equals 20 years.
- real discount rate equals five percent per year.
- fuel and electricity costs escalate at two percent per year (above general inflation).

4.3 SUMMARY OF RESULTS

This section presents the main results for the reference case for the Madison climate for the two distribution system temperatures (low, LTDS and high, HTDS). Comparable results for Copenhagen are available in the Sub-Task II(b) report (T9).

Madison, LTDS

To illustrate the construction of the composite expansion diagrams, Figure 4.2 shows results for a duct storage system using the low temperature heat distribution to 500 houses (36 TJ load) with 20% DHW. The diagram was constructed by superimposing expansion paths generated for several generic configurations--i.e. systems with and without heat pumps and with various collector arrays. The least expensive system at each solar fraction is emphasized by a heavy line, which represents the expansion path for all systems employing a particular (duct) storage technology. The collector type and the presence of a heat pump in the system are indicated in the diagram.

Figure 4.2 indicates that unglazed collectors are more cost effective than flat plate collectors when used with a heat pump, even in the severe Madison climate. However, in order to obtain solar fractions above about 80 percent, conventional flat plate collectors are required with heat

Figure 4.3 Composite Expansion Diagram - Low Temperature Distribution

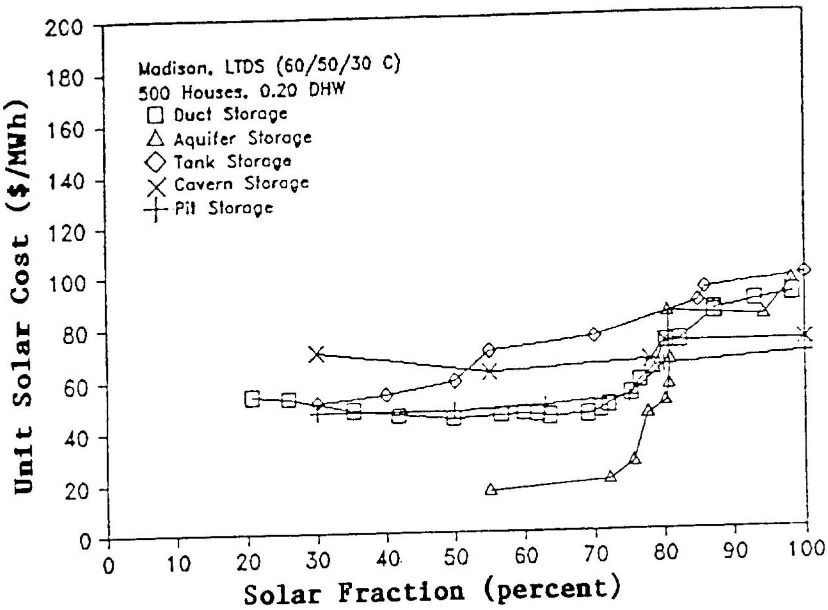
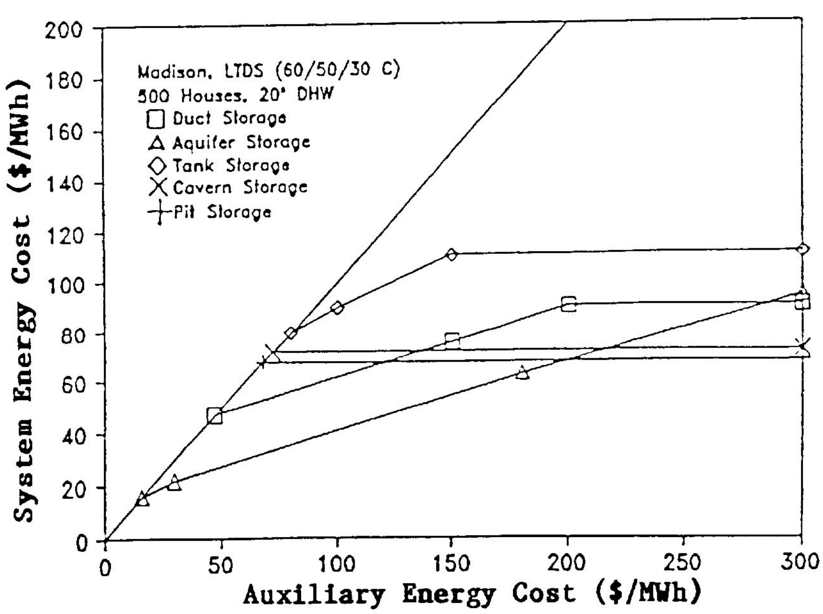


Figure 4.4 CSHPSS Energy Cost versus Auxiliary Energy Cost - Low Temperature Distribution



A composite expansion diagram showing the expansion paths for the best systems for each storage technology is presented in Figure 4.3. The aquifer, duct, and tank storage expansion curves all represent systems with heat pumps at solar fractions below 75 to 90 percent. From this figure one may conclude that aquifer or duct systems with heat pumps offer the lowest solar costs at low solar fractions, but that to achieve high solar fractions and a higher degree of energy independence, it is best to employ a stratified pit or cavern storage system coupled directly to the load.

The overall optimal system selection depends upon cost of fuel and electricity. To simplify presentation of the results in Figure 4.4, all system types are compared subject to the restriction of equal effective costs for auxiliary fuel and electrical energy. The cost of operation of a plant with no solar energy is shown as the straight line of unit slope and zero intercept. Each of the solar system curves is terminated at the point where it intersects the nonsolar system line, since the solar system would not be economically attractive if auxiliary energy was lower in cost. Figure 4.4 shows that if auxiliary energy cost is above 20 $/MWh there is some solar system that is more economical, and that if conventional energy costs more than 80 $/MWh any of the solar systems shown would be economical.

Costs shown in Figure 4.4 do not include distribution costs and are, therefore, only comparable with the costs of other energy forms available at central heating plants.

Madison, HTDS

Composite expansion diagrams for the Madison high temperature distribution system shown in Figure 4.5 have the same general features as Figure 4.3 but the relative costs for different systems have changed significantly. The direct systems (without heat pumps) are now the least expensive over most of the range of interest. Unglazed collectors are not viable at these temperatures. Heat pump systems are relatively more expensive and relatively more limited in solar fractions. Note also that the stratified temperature storage systems (tank, pit and cavern) do not exhibit the sharp cost increases shown by the aquifer and duct systems as

Figure 4.5 Composite Expansion Diagram - High Temperature Distribution

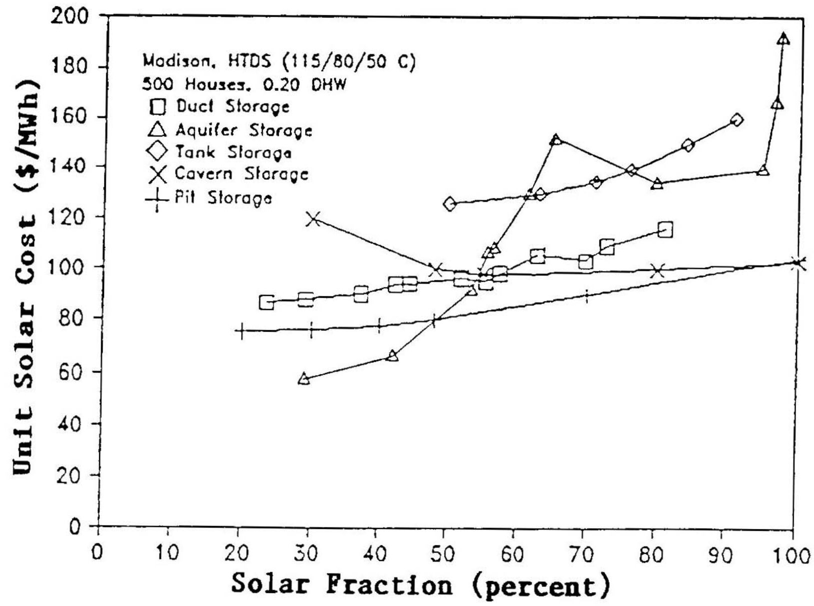
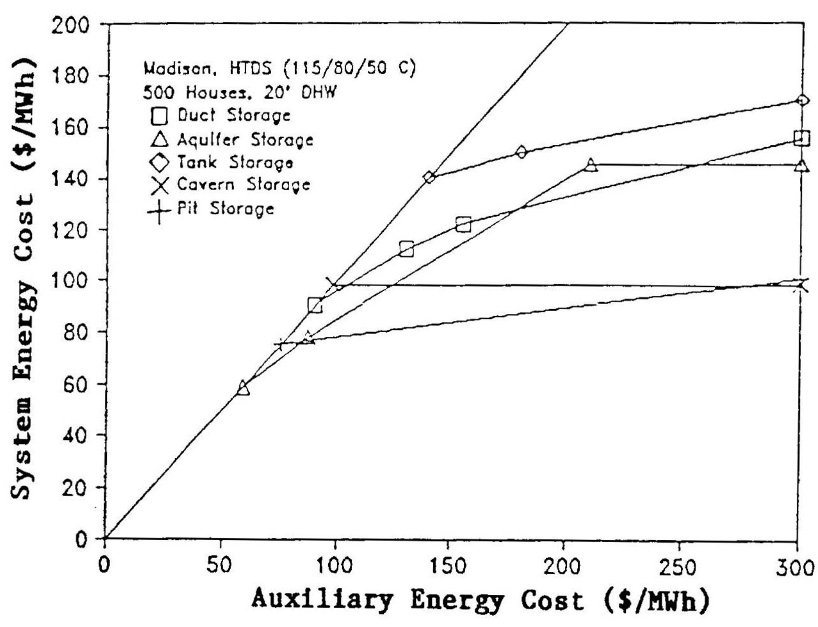


Figure 4.6 CSHPSS Energy Cost versus Auxiliary Energy Cost - High Temperature Distribution



the solar fraction approaches unity. This is because stratification allows the store to meet the load temperature requirements even when its stored energy is quite low.

The economic viability of high temperature distribution systems shown in Figure 4.6 indicates that these systems become competitive at higher auxiliary fuel prices than the low temperature distribution systems, but the direct systems offer the greatest cost savings for all auxiliary energy costs greater than 100 $/MWh.

As a result of the thousands of calculations that were performed by the analysis teams in developing the expansion curves, the sensitivities of the solar cost function to design variables have been determined. Detailed results may be found in the references, but the general findings are summarized in Table 4.2. For reference, cost of a 3.6 TJ cavern system is about 100 percent greater than the 36 TJ system, and the variation of DHW fraction from 20 percent to 0 and 50 percent changes the cost of most reference systems by plus five to ten percent and minus five percent respectively.

Sensitivities to storage parameters such as insulation thickness, number, spacing and depth of boreholes, depth of aquifers, etc. were usually small (less than ten percent) for maximum variations of independent variables.

TABLE 4.2 Cost Sensitivities

	Small Load	**Fraction DHW**	**Area of Collectors**	**Volume of Storage**	**Storage Parameters**
Aquifer	medium	medium	high	medium	low
Duct	low	medium	high	low	medium
Tank	low	medium	high	medium	medium
Pit	low	medium	high	low	low
Cavern	high	medium	high	high	low

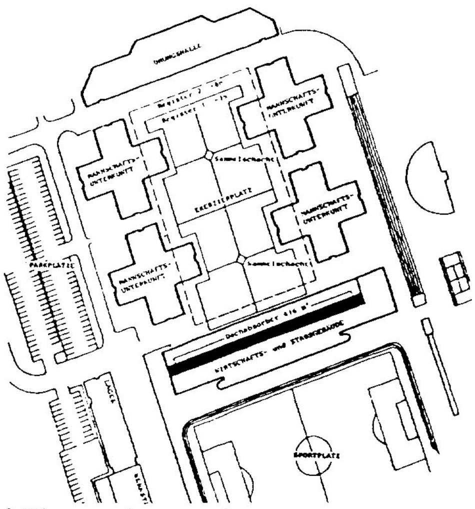
5 OVERVIEW OF KEY PROJECTS IN SOME IEA COUNTRIES

CSHPSS systems are not yet being applied on a commercial basis in any of the Task VII participant countries. In most of these countries, however, there are R&D programs in support of the CSHPSS concept. Depending on the degree of advancement of these programs, and on the relative cost-effectiveness of various CSHPSS concepts and applications in particular countries, there are a large number of experimental or demonstration-type projects among the Task VII countries. Some of these projects have been the focus of the Sub-Task I(e) national designs; others have developed without involvement in this Task.

On the following pages, and on a fold-out, comparative, summary data table at the end of this section, 17 of these projects have been described. Although the space in this report was too limited to provide very much information on each project, it does provide an overview of the kind of projects and activity ongoing in this field. In the fold-out table, the data reported are from either design studies or actual performance, depending on the time schedule of each project. For each project, there is a contact person identified so that further information can be obtained on any specific project.

5.1 AUSTRIA

5.1.1 Kranebitten Project

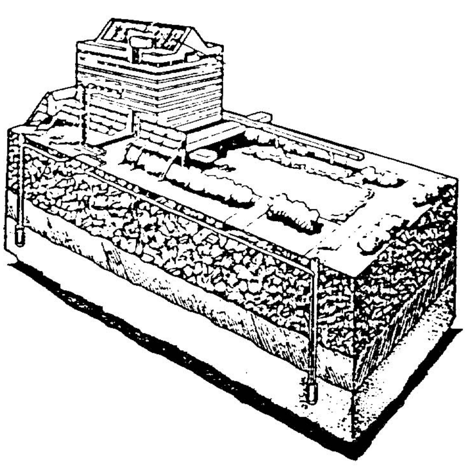

Building - general arrangement

Novelty: Using a heat pump, the earth seasonal store operates both above and below the freezing point.

Purpose: To demonstrate the use of earth storage and low temperature ground source heat pump for space and water heating purposes.

5.2 CANADA

5.2.1 Scarborough Government of Canada Building



Novelty: The aquifer and building energy systems can be configured in many ways for research and development purposes. The aquifer can be used for either cooling or heating (or, perhaps, both in the same annual cycle).

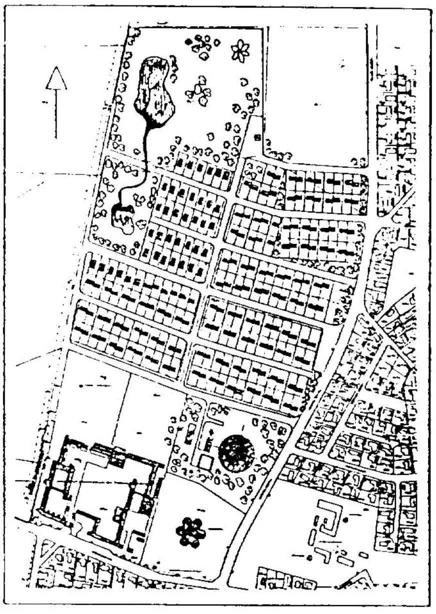
Purpose: To study the operation of aquifer thermal energy storage and to demonstrate the application of such seasonal storage for energy management in a large commercial building.

Status: The building is complete, occupied and operational. The aquifer monitoring system was in place in Fall 1985 for initial charging of aquifer with cooling in the Winter 1985-86.

Contact: Dr. E.L. Morofsky, Chief Energy Technology, Public Works Canada, Sir Charles Tupper Bldg, Room C-456, Ottawa, Canada K1A 0M2.

5.3 DENMARK

5.3.1 Hjortekaer Study



Novelty: Heat storage is a 49,400 m^3 excavated uninsulated pyramidical pit. The temperature in the storage has a maximum of about 40°C and a minimum of about 10°C.

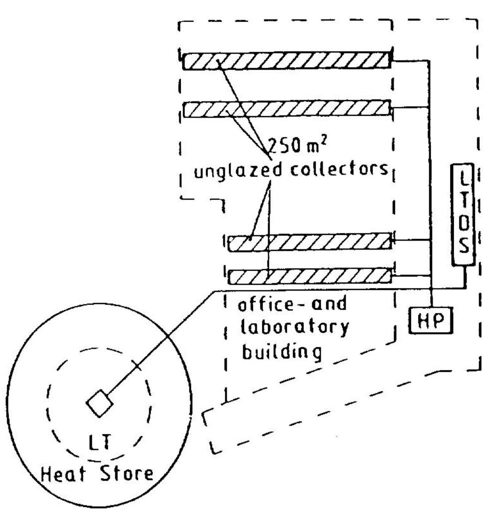
Purpose: The objective is to make calculations and system design of a CSHPSS project with a high solar fraction. The design is such that at least 80% of the energy demand for DHW and space heating is covered by solar energy, and the remainder by electricity for the heat pump. An oil-fired hot water boiler is connected as a reserve and peak load heat facility. The total life-cycle costs for the system are calculated with the present value method and show an energy price almost identical with the price of electricity.

Status: The project is only a theoretical study and it will probably not be built.

Contact: Preben Hansen, The Technical University of Denmark, The Thermal Insulation Laboratory, Building 118, DK-2800 Lyngby, Denmark.

5.4 FEDERAL REPUBLIC OF GERMANY

5.4.1 Stuttgart University Project



Novelty: The first solar-assisted long-term storage project in Germany. Two different storage concepts are combined: an artificial aquifer with horizontal drain tubes within vertical flow, and plastic (VPE) coils in eight horizontal layers at various depths. With the aid of VPE-coils, latent heat capacity of water in the gravel bed will be used. (35% water).

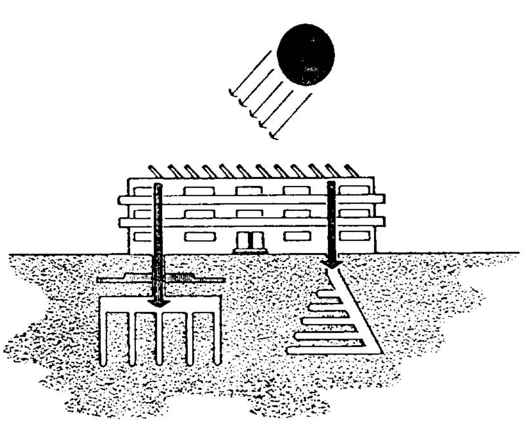
Purpose: To study the operation of two different long-term thermal energy storage concepts and demonstrate the application of such seasonal storage, combined with unglazed collectors and a heat pump, for DHW and space heating. The detailed thermal and hydraulic behavior for these two storage concepts will be investigated with the use of models in the laboratory.

Status: The building was occupied in 1984. The unglazed collectors and the heat pump have been in operation since summer 1985. The storage construction was finished in November 1985 and the monitoring of the system started in December 1985.

Contact: Norbert Fisch, University of Stuttgart, Pfaffenwaldring 6, 7000 Stuttgart - 80, FRG.

5.5 ITALY

5.5.1 Cooperativa "San Pietro" in Treviglio (30 km east from Milan)



Novelty: First large scale solar heating plant with seasonal storage in Italy. Inexpensive roof integrated collectors distributed over the five apartment buildings, including 102 apartments.

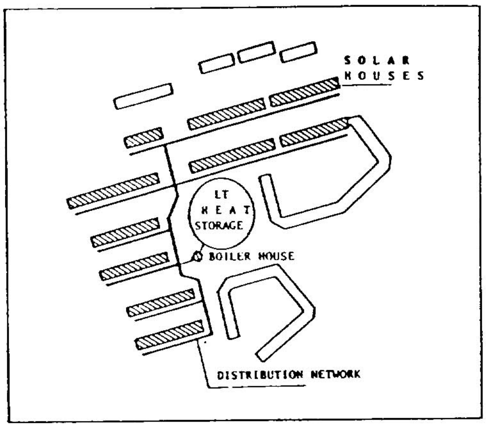
Purpose: The solar heating plant is a private initiative of the building company and the home owners. The main purpose is to avoid the use of oil for the heating. Though the plant was not designed for research purposes its performance is monitored and analysed.

Status: The installation is in operation since summer 1982.

Contact: Livio Mazzarella, Politecnico di Milano, Dipartimento di Energetica, Piazza L. da Vinci 32, I-20133 Milano.

5.6 THE NETHERLANDS

5.6.1 Groningen



SITE PLAN

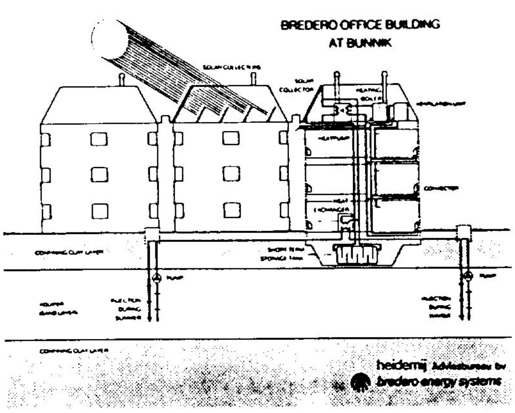
Novelty: Unique construction technique developed for placing heat exchanger coils in the earth store. The store includes a small water tank for use as a daily buffer.

Purpose: The objective of this study is to gather practical experience with the design, construction and operation of a large scale seasonal heat storage system. The solar fraction of this system for 96 houses was designed to be 65%.

Status: In operation at the end of 1984. Monitoring will continue for 2 to 3 years.

Contact: Aad Wijsman or Johan Havinga at Technisch Physische Dienst, TNO/TH, P.O. Box 155, 2600 AD Delft, The Netherlands.

5.6.2 Bunnik Aquifer Project



Novelty: First aquifer pilot project in the Netherlands.

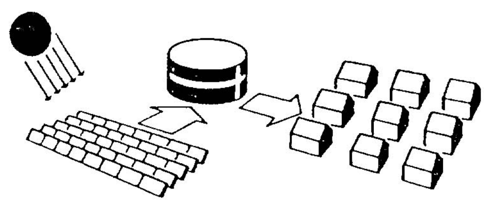
Purpose: To examine the feasibility of the combined application of the use of solar energy and seasonal storage on an aquifer for space heating in an office building.

Status: Installation completed in May 1985. Monitoring is currently underway and will be completed near the end of 1986.

Contact: R. van der Bruggen, Bredero Energy Systems, P.O. Box 24, NL-3980 CA, Bunnik, The Netherlands.

5.7 SWEDEN

5.7.1 Ingelstad Project



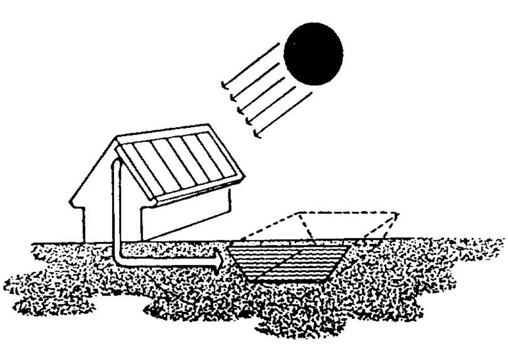
Novelty: First large-scale solar heating plant in Sweden adopted for part time heat generation and supply in a small district heating system with a central, oil fired boiler. The first Parabolic Trough (PTC) collector array and the first big concrete tank for hot water storage in Sweden.

Purpose: The solar heating plant was built primarily to evaluate the performance of high temperature solar collectors for plants without heat pumps and to demonstrate the performance of an above ground storage tank with respect to the choice of materials and design features. The design objective was to meet 50% of the annual heat demand of 52 ordinary single family homes.

Status: The PTC-design was evaluated and reported. PTCs were replaced by flat plate collectors in 1984. The plant is still in operation and assessment is on-going.

Contact: J-O Dalenbäck, Chalmers Tekniska Högskola, Installationsteknik, 412 96 Göteborg.

5.7.2 Lambohov Project

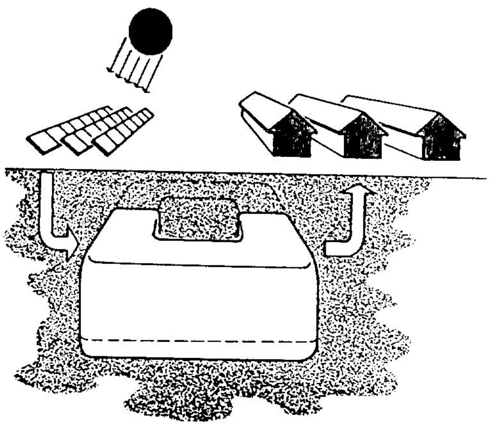


Novelty: Designed for low temperature operation incorporating a heat pump; first large-scale roof integrated array in Sweden and first large-scale pit store.

Purpose: The solar heating plant in Lambohov was built primarily to evaluate the performance of medium temperature solar collectors for plants with heat pumps and to demonstrate the erection and operation of pit store with respect to the choice of materials and design featues. The design objective was to meet 100% of the annual heating requirements of 55 terraced houses with a solar energy coverage of 85%.

Status: Put into operation in 1980. Comprehensive measurements of system performance were made during

5.7.3 Lyckebo Project



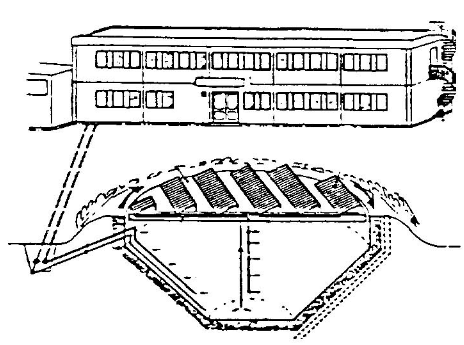
Novelty: Very large rock cavern storage. Low temperature distribution (maximum 70°C).

Purpose: The main objective of the Lyckebo project 80 km north of Stockholm is to demonstrate a large scale district heating system based wholly on solar energy. In the first phase of the project, 85% of the solar collector field is simulated by an electric boiler. The system is designed to supply 550 dwellings (single- and multi-family houses) in a new residential area with their total need of energy for space heating and domestic hot water. A maximum supply temperature of 70°C in winter and 50°C in summer is ordinarily used, but storage of 95°C water from the high performance FP collectors will be tested.

Status: The system was put in operation in September 1983. The first full annual cycle was from April 1984 to March 1985. Reports from operation and evaluation are available, and have also been given at international conferences during 1985. The evaluation will continue during 1986.

Contact: Ingvar Wallander, Upsala Kraftvärme AB, Box 125, 751 04 UPSALA. Christer Brunström, Swedish State Power Board Alvkarleby Laboratory, 810 71, ALVKARLEBY.

5.7.4 Studsvik



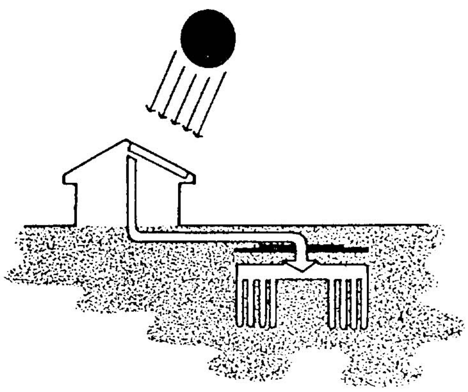
Novelty: 100% solar heating at high northern latiude. Rotating collector array on top of heat storage earth pit.

Purpose: The project at Studsvik was the first experimental plant with seasonal heat storage in Sweden. This prototype plant was too small to be economical, but large enough as a research project to demonstrate the ideas for a 100% solar heating system with a potential to become economically competitive even at high latitudes.

Status: The plant was first operational in 1979, and 100% solar heating was achieved during two years of continuous operation. It is now under reconstruction, using the experience gained from five years of operation.

Contact: Heimo Zinko, Studsvik Energiteknik AB, New Energy Technology Division, 611 82 NYKOPING.

5.7.5 Kullavik Project



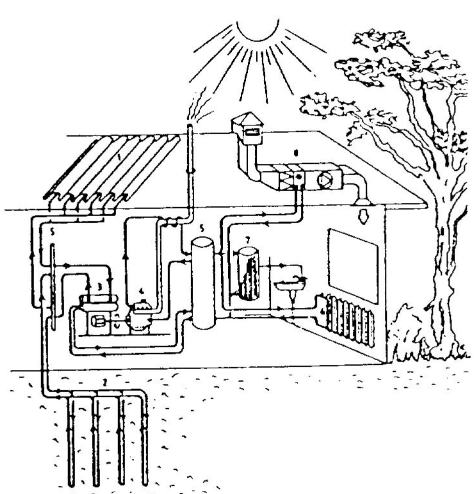
Novelty: Different temperature zones in a ground storage. High temperature storage in soft clay (60°C).

Purpose: The solar heating system in Kullavik was built as an experimental installation, to analyze two different temperature zones in a ground storage. The design objective was to meet 70% of the annual heat requirements with solar energy in cooperation with a heat pump.

Status: The project has been in operation since 1983 without serious problems. Measurements are being done by Chalmers University of Technology.

Contact: Stefan Olsson A.B. Andersson & Hultmark, Box 24135, S-40022 Göteborg, Sweden

5.7.6 Sunclay



Novelty: First seasonal ground heat storage ever built.

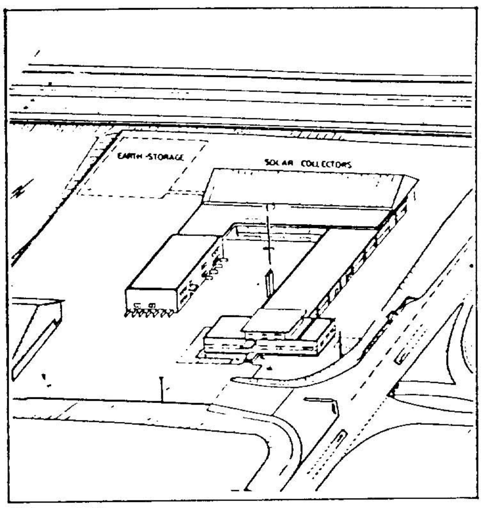
Purpose: The project Sunclay was built to develop and demonstrate low temperature solar collectors, diesel-driven heat pumps and a big seasonal ground heat storage in clay. The design objective was to meet 50% of the annual heating requirements of a 15.000 m^2 school.

Status: The system has been running since 1980 without any serious problems.

Contact: Göran Hultmark, A.B. Andersson & Hultmark. Box 24135, S-40022 Göteborg, Sweden

5.8 SWITZERLAND

5.8.1 The Vaulruz Project


Site Plan

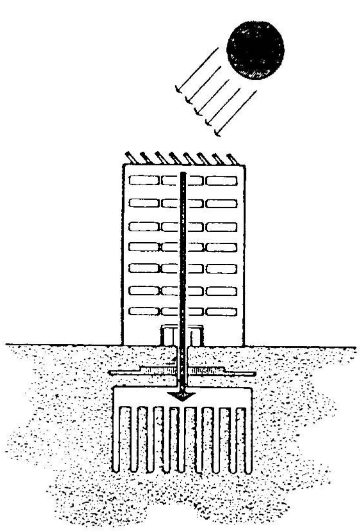
Novelty: The uniqueness of the project is the earth storage intended to be as seasonal as possible within the contraints of the site.

Purpose: The purpose of the project is to reduce as much as possible the oil consumption for heating the administration building (approx. 700 m^2 of the floor area) and the garages (approx. 2,000 m^2 of floor area) of a highway maintenance center, by using solar energy and electricity produced in the Vaulruz area by hydropower plants.

Status: The design started in 1977 and the total installation was completed in March 1983. The whole system is rather heavily monitored since that date and the monitoring should go on until 1987.

Contact: J.C. Hadorn, Sorane SA, Chatelard 52, CH - 1018 Lausanne

5.8.2 Project in Meyrin - Geneva



Novelty: The main novelty in the project is the fact that the seasonal storage is located beneath the building.

Purpose: The purpose of the project is to reduce significantly the primary energy consumption of a commercial and industrial private building (5 storeys, 17,000 m^2 of floor area).

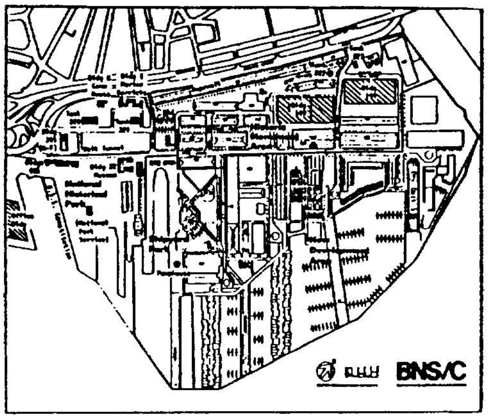
Passive Solar Energy should cover 10 to 15% of the space heating load, waste wood from a carpentry inside the building about 8%, and internal gains (people, light and appliances) should meet about 20% of the load.

The rest (about 1,000 MWh) is to be done as much as possible by active solar with a constraint on land occupation.

Status: The storage has been completed in Spring 1985 and the

5.9 UNITED STATES OF AMERICA

5.9.1 Charlestown Study



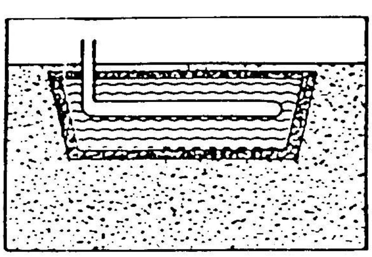
Novelty: Project is situated in the National Historic Park portion of the Charlestown Navy Yard. Tank storage utilizes existing underground concrete tanks which were originally built for petroleum and water storage for the Navy Yard.

Purpose: To demonstrate the application of solar energy with seasonal storage in a public, tourist location. The CSHPSS would serve the space heating load and the small hot water demand.

Status: Awaiting approvals for continuation of design and implementation.

Contact: Dwayne Breger, Charles A. Bankston Inc., 5039 Cathedral Ave. NW, Washington D.C. 20016 (202) 363-6693.

5.9.2 Smith Academy School



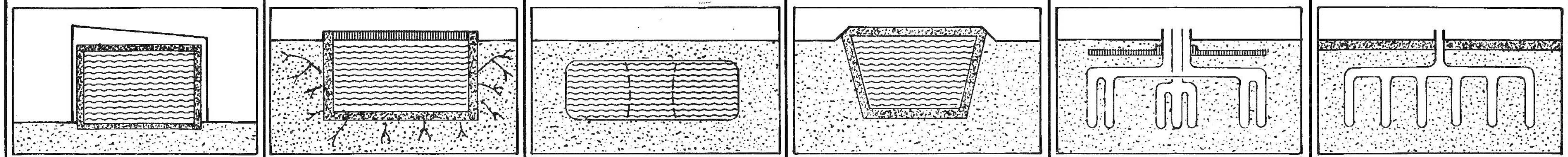
Novelty: Project utilizes an insulated earth storage system with single horizontal layer of "solar roll" pipes as a heat exchanger to serve the space heating load of a school building. The storage and solar systems were built as a retro-fit application using standard construction techniques.

Purpose: This project was built for experimental investigation purposes.

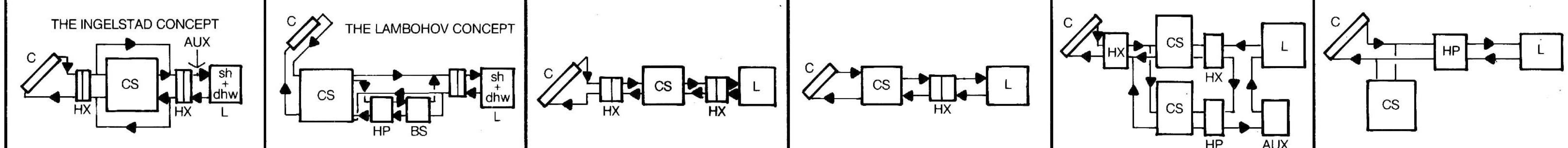
Contact: J. Krupczak, Jr., Department of Mechanical Engineering University of Massachusetts, Amherst, MA 01003

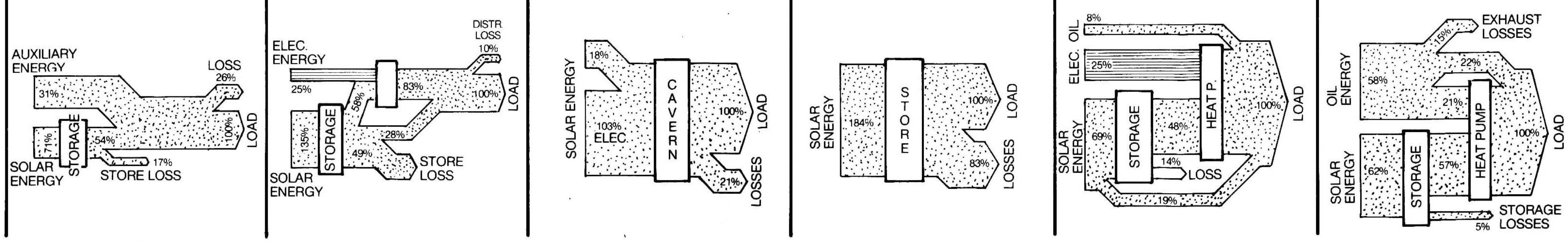
SWEDEN

- PROJECT
- STORAGE SUBSYSTEM
  - TYPE
  - SIZE — ▢ - 10.000 M^3; ▢ - 100.000 M^3
  - TEMPERATURE (VOL. AVG.) — T_C - WHEN FULLY CHARGED; T_D - WHEN FULLY DISCHARGED
- COLLECTOR SUBSYSTEM
  - TYPE
  - SIZE — ▢ - 1000 SQ.M.
  - TEMPERATURE (OPERATING RANGE)
  - LOCATION
- SYSTEM CONCEPT
  - CS - CENTRAL STORAGE
  - BS - BUFFER STORAGE (DIURNAL)
  - HP - HEAT PUMP
  - C - SOLAR COLLECTORS
  - L - LOAD
  - AUX - AUXILIARY HEAT SUPPLY
  - B - BOILER
  - HX - HEAT EXCHANGER
- CLIMATE
  - DEGREE-DAYS
  - SOLAR RADIATION — ANNUAL GLOBAL SOLAR ENERGY ON 1 SQ. M. HORIZONTAL SURFACE (kwh/M^2-yr)
- LOAD
  - ANNUAL BUILDING DEMAND (Mwh) — ▤ HEATING; ▨ COOLING; ▢ DOMESTIC HOT WATER
  - BUILDING FLOOR AREA — ▢ - RESIDENTIAL, 1000 SQ. M; ▨ - COMMERCIAL, 1000 SQ. M.
- ENERGY FLOW — PERCENTAGES BASED ON TOTAL BUILDING LOAD - 100 PERCENT



PROJECT	INGELSTAD	LAMBOHOV	LYCKEBO	STUDSVIK	KULLAVIK	SUNCLAY
STORAGE TYPE	CONCRETE TANK	ROCK PIT	ROCK CAVERN	INSULATED PIT	VERTICAL EARTH COIL	VERTICAL EARTH COIL
STORAGE SIZE	5.000 M^3	10.000 M^3	100.000 M^3	640 M^3	2000 M^3	87.000 M^3
COLLECTOR TYPE	42° FLAT-PLATE/ HIGH TEMPERATURE LARGE MODULES	FLAT-PLATE/ ROOF INTEGR. W SELEC. SURF.	FLAT PLATE	25° CONCENTRATING, ROTATING	27° FLAT-PLATE/ROOF INTEGR.	23% FLAT-PLATE/UNGLAZED
COLLECTOR SIZE	1425 M^2	2800 M^2	4320 M^2 (+ electric simulation)	120 M^2	540 M^2	1500 M^2
LOCATION	CENTRALIZED/FIELD	DISTRIBUTED/BUILDINGS	CENTRALIZED/FIELD	CENTRALIZED/FLOATING	DISTRIBUTED/BUILDING	DISTRIBUTED/BUILDING
DEGREE-DAYS	3850 (BASE: 17°C)	3850 (BASE: 17°C)	4000	3900	3600 (BASE: 20°C)	3600 (BASE: 20°C)
BUILDING FLOOR AREA	6500 M^2	7000 M^2	45,000 M^2	500 M^2	3200 M^2	15000 M^2

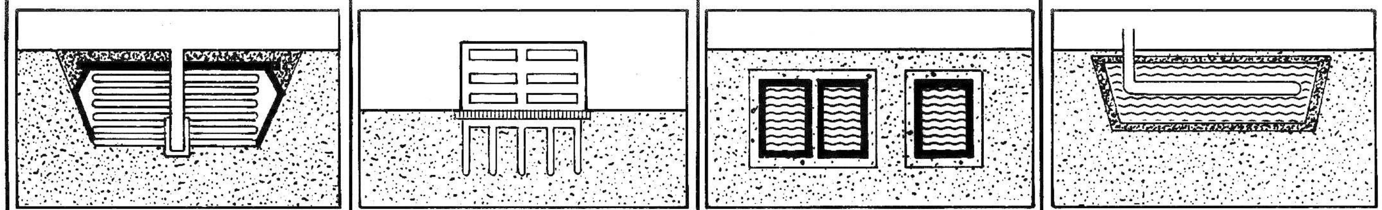


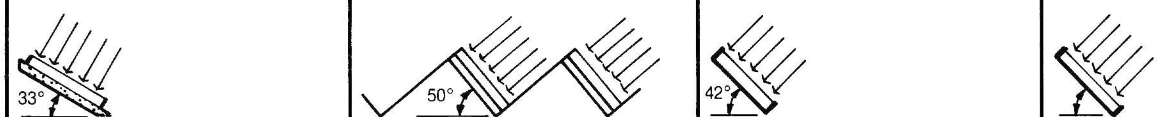


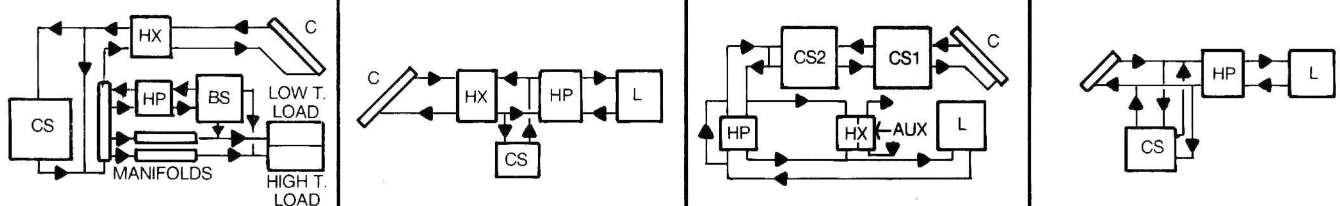
	SWITZERLAND		UNITED STATES	
• PROJECT	VAULRUZ	MEYRIN-GENEVA	CHARLESTOWN	SMITH ACADEMY SCHOOL
• STORAGE SUBSYSTEM				
• TYPE	HORIZONTAL EARTH COIL	VERTICAL EARTH COIL	CONCRETE TANKS	INSULATED PIT
• SIZE	5.500 M³	20.000 M³	5.700 M³	2000 M³
• TEMPERATURE (VOL. AVG.)				
• COLLECTOR SUBSYSTEM				
• TYPE	FLAT-PLATE/ROOF INTEGR.	FLAT PLATE/ROOF INTEGR.	FLAT-PLATE W SELEC. SURF.	
• SIZE	520 M².	550 M²	2.300 M²	170 M²
• TEMPERATURE (OPERATING RANGE)				
• LOCATION	CENTRALIZED/BUILDING	CENTRALIZED/BUILDING	CENTRALIZED/BUILDINGS	CENTRALIZED/BUILDING
• SYSTEM CONCEPT				
• CLIMATE				
• DEGREE-DAYS	3890 (BASE: 18°C)	3000 (BASE: 20°C)	3209 (BASE: 18°C)	3650
• SOLAR RADIATION				
• LOAD				
• ANNUAL BUILDING DEMAND				
• BUILDING FLOOR AREA	3200 M²	17000 M²	10.500 M²	5000 M²
• ENERGY FLOW				

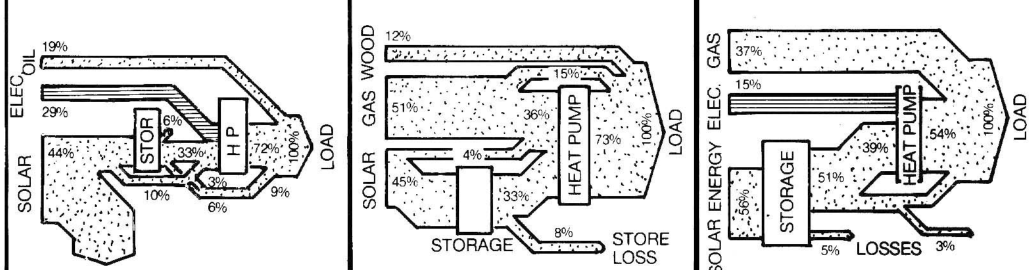
Legend:

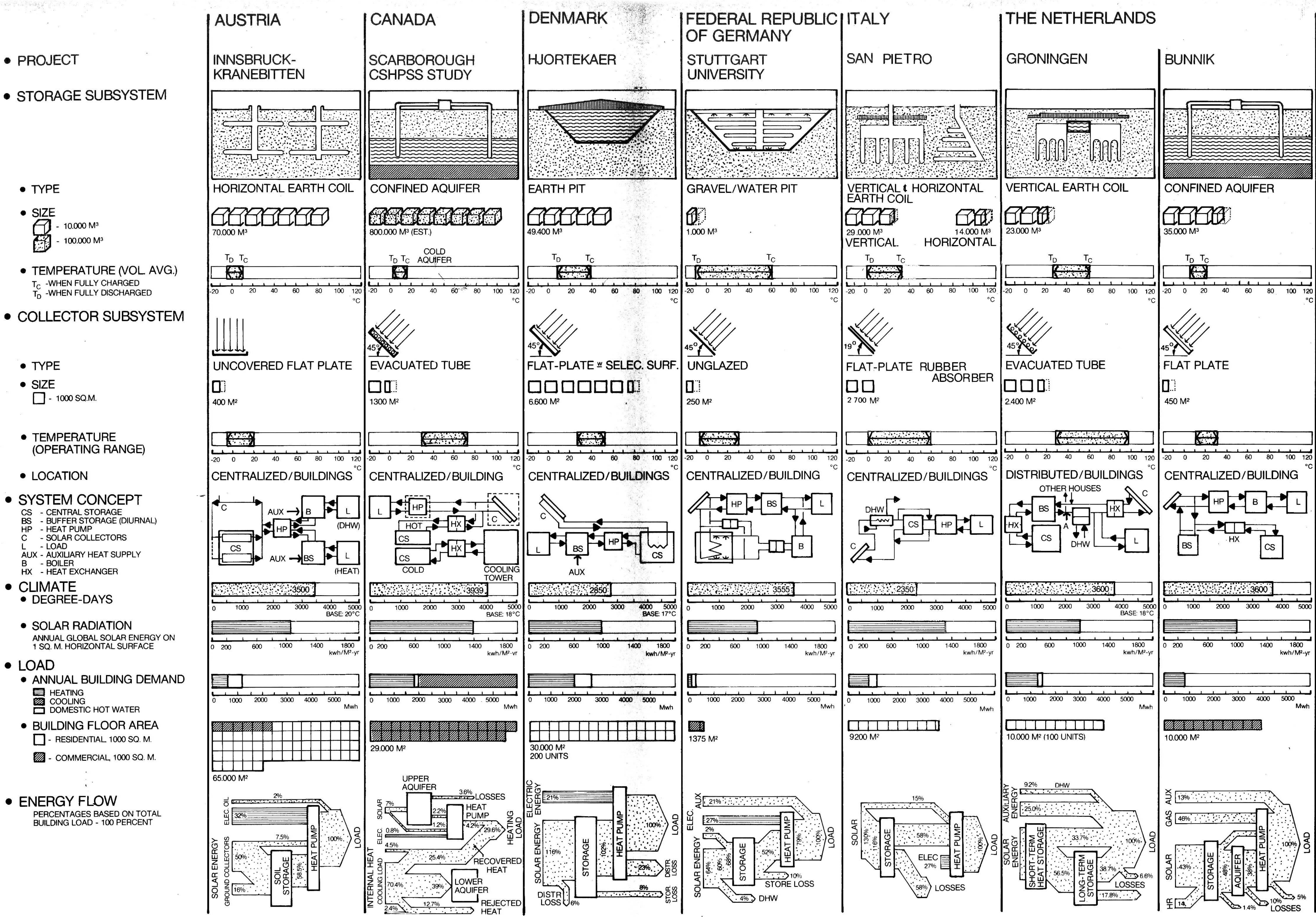
- SIZE (storage): - 10.000 M³; - 100.000 M³
- TEMPERATURE (VOL. AVG.): T_C - WHEN FULLY CHARGED; T_D - WHEN FULLY DISCHARGED (scale -20 to 120 °C)
- SIZE (collector): - 1000 SQ.M.
- SYSTEM CONCEPT: CS - CENTRAL STORAGE; BS - BUFFER STORAGE (DIURNAL); HP - HEAT PUMP; C - SOLAR COLLECTORS; L - LOAD; AUX - AUXILIARY HEAT SUPPLY; B - BOILER; HX - HEAT EXCHANGER
- DEGREE-DAYS: scale 0–4000
- SOLAR RADIATION: ANNUAL GLOBAL SOLAR ENERGY ON 1 SQ. M. HORIZONTAL SURFACE (scale 0–1800 kwh/M²-yr)
- ANNUAL BUILDING DEMAND: HEATING; COOLING; DOMESTIC HOT WATER (scale 0–5000 Mwh)
- BUILDING FLOOR AREA: - RESIDENTIAL, 1000 SQ. M; - COMMERCIAL, 1000 SQ. M.
- ENERGY FLOW: PERCENTAGES BASED ON TOTAL BUILDING LOAD - 100 PERCENT











AUSTRIA
CANADA
DENMARK
FEDERAL REPUBLIC OF GERMANY
ITALY
THE NETHERLANDS
• PROJECT
INNSBRUCK-KRANEBITTEN
SCARBOROUGH CSHPSS STUDY
HJORTEKAER
STUTTGART UNIVERSITY
SAN PIETRO
GRONINGEN
BUNNIK
• STORAGE SUBSYSTEM
• TYPE
HORIZONTAL EARTH COIL
CONFINED AQUIFER
EARTH PIT
GRAVEL/WATER PIT
VERTICAL & HORIZONTAL EARTH COIL
VERTICAL EARTH COIL
CONFINED AQUIFER
• SIZE
- 10.000 M³
- 100.000 M³
70.000 M³
800.000 M³ (EST.)
49.400 M³
1.000 M³
29.000 M³ VERTICAL
14.000 M³ HORIZONTAL
23.000 M³
35.000 M³
• TEMPERATURE (VOL. AVG.)
T_C -WHEN FULLY CHARGED
T_D -WHEN FULLY DISCHARGED
T_D T_C
COLD AQUIFER
-20 0 20 40 60 80 100 120 °C
• COLLECTOR SUBSYSTEM
45°
19°
• TYPE
UNCOVERED FLAT PLATE
EVACUATED TUBE
FLAT-PLATE w SELEC. SURF.
UNGLAZED
FLAT-PLATE RUBBER ABSORBER
EVACUATED TUBE
FLAT PLATE
• SIZE
- 1000 SQ.M.
400 M²
1300 M²
6.600 M²
250 M²
2 700 M²
2.400 M²
450 M²
• TEMPERATURE (OPERATING RANGE)
• LOCATION
CENTRALIZED/BUILDINGS
CENTRALIZED/BUILDING
CENTRALIZED/BUILDINGS
CENTRALIZED/BUILDING
CENTRALIZED/BUILDINGS
DISTRIBUTED/BUILDINGS
CENTRALIZED/BUILDING
• SYSTEM CONCEPT
CS - CENTRAL STORAGE
BS - BUFFER STORAGE (DIURNAL)
HP - HEAT PUMP
C - SOLAR COLLECTORS
L - LOAD
AUX - AUXILIARY HEAT SUPPLY
B - BOILER
HX - HEAT EXCHANGER
AUX B L (DHW) HP CS AUX BS L (HEAT)
L HP HOT CS HX C CS HX COLD COOLING TOWER
C L BS HP CS AUX
HP BS L B
DHW CS HP L C
OTHER HOUSES BS HX HX C A CS DHW L
HP B L BS HX CS
• CLIMATE
• DEGREE-DAYS
3500
3939
2850
3555
2350
3600
3600
0 1000 2000 3000 4000 5000
BASE: 20°C
BASE: 18°C
BASE: 17°C
BASE: 18°C
• SOLAR RADIATION
ANNUAL GLOBAL SOLAR ENERGY ON 1 SQ. M. HORIZONTAL SURFACE
0 200 600 1000 1400 1800 kwh/M²-yr
• LOAD
• ANNUAL BUILDING DEMAND
HEATING
COOLING
DOMESTIC HOT WATER
0 1000 2000 3000 4000 5000 Mwh
• BUILDING FLOOR AREA
- RESIDENTIAL 1000 SQ. M.
- COMMERCIAL 1000 SQ. M.
65.000 M²
29.000 M²
30.000 M² 200 UNITS
1375 M²
9200 M²
10.000 M² (100 UNITS)
10.000 M²
• ENERGY FLOW
PERCENTAGES BASED ON TOTAL BUILDING LOAD - 100 PERCENT
ELEC OIL 2% 32% 7.5% SOLAR ENERGY GROUND COLLECTORS 50% 16% SOIL STORAGE 58.5% HEAT PUMP 100% LOAD
UPPER AQUIFER 3.6% LOSSES SOLAR 7% 2.2% HEAT PUMP 1.2% 4.2% 29.6% HEATING LOAD ELEC 0.8% 4.5% 25.4% RECOVERED HEAT INTERNAL HEAT COOLING LOAD 70.4% 39% LOWER AQUIFER 12.7% 2.4% REJECTED HEAT
ELECTRIC ENERGY 21% SOLAR ENERGY 116% STORAGE 102% HEAT PUMP 100% LOAD 23% DISTR LOSS 8% STOR LOSS DISTR LOSS 6%
ELEC. AUX 21% 27% 2% SOLAR ENERGY 64% 60% 68% STORAGE 52% HEAT PUMP 79% 100% LOAD 10% STORE LOSS 4% DHW
15% SOLAR 130% 116% STORAGE 58% ELEC 27% HEAT PUMP 100% LOAD 58% LOSSES
AUXILIARY ENERGY 9.2% DHW 25.0% SOLAR ENERGY SHORT-TERM HEAT STORAGE 33.7% 56.5% LONG-TERM STORAGE 38.7% 17.8% 100% LOAD 6.6% LOSSES
GAS AUX 13% 46% SOLAR 43% STORAGE AQUIFER 48% 38% HEAT PUMP 100% LOAD HR 1% 1.4% 10% LOSSES 5%

6.0 FINDINGS FROM PHASES I AND II AND RECOMMENDATIONS

6.1 FINDINGS

6.1.1 From Phase I

It is possible to undertake collaborative research in an international environment and meet common goals with limited resources. The successful achievement of the common objective of the international work depends, to a large extent, upon the resources and results of national programs.

The Phase I work resulted in the selection and development of common tools for simulation and economic analysis of CSHPSS systems. Cost data were collected from each participating country. Common values for technical and economic parameters were selected for the collaborative analytical work in the task.

Based on the results and accomplishments of Phase I, a revised workplan was recommended and accepted for Phase II.

6.1.2 From Reference System Studies in Phase II

The key results from the Phase II system studies are outlined below. Although the scope of these studies was broad, it was necessary to introduce a number of limitations in order to met the objectives of the study within the resources of the task. The most important restrictions are:

- a limited number of configurations were analyzed,
- control strategies for each storage type were fixed,
- cost and performance data were standardized in order to make the analytical task manageable and the results broadly relevant. Cost and performance data can differ considerably, however, from country to country (due to different states of development of technology).

- effective cost of auxiliary energy is a variable in these studies, but all forms (oil, gas and electricity) of auxiliary energy were assumed to have the same effective cost,

- system cost and performance results exclude the distribution network since the influence of that part of the studied systems will be the same for all configurations. Comparisons with alternative, on-site heating systems, however, must include the distribution network.

The findings of the system studies are enumerated below.

1. Rankings of system configurations on the basis of cost depend primarily on the distribution temperature and on the cost of auxiliary energy and are less sensitive to the climate, total load, and DHW fraction.

2. For low-temperature distribution, these rankings favour systems including unglazed solar collectors and heat pumps, and for high-temperature distribution, systems including evacuated collectors without heat pumps are favoured.

3. Low-temperature distribution, together with systems with heat pumps offer the lowest solar unit costs -- as low as $20/MWh when a suitable aquifer is available -- and can meet about 75 percent of the load from solar.

4. Low-temperature distribution, together with systems without heat pumps are more costly -- about 60-70 $/MWh -- but can meet 100% of the load from solar.

5. The most cost-effective plants for use with high-temperature distribution systems employ temperature stratification of the storage volume and use evacuated collectors. The minimum solar cost of these systems is 90-100 $/MWh.

6. All systems show economies of scale because of diminishing unit storage costs and heat losses, and show improved cost effectiveness for increasing domestic hot water (DHW) fractions because of higher load in summer. Rock cavern systems exhibit the greatest size dependence and duct systems the least.

7. Collector costs dominate all but the low-solar-fraction, low-temperature systems with heat pumps. The collector sub-system cost is often twice as large as the storage sub-system cost.

6.1.3 From National Studies

Country and site-specific studies were performed using the system configuration and storage technology deemed most appropriate for each site. These studies used the same methodology employed in the reference system studies but substituted national data, where appropriate, for the performance, cost, and economic parameters. The results of these studies are presented in reference T9. Selected findings from these studies are listed below.

- Commission of the European Communities

  The CEC study employed the reference case parameter set for duct storage except for weather data which was taken for a site near Ispra in northern Italy. The results are very similar to those obtained in the reference system for Copenhagen--except that performance is somewhat higher and costs are somewhat lower because of the 17 percent greater annual insolation at Ispra.

- The Netherlands

  Duct storage systems were studied. Systems with heat pumps, especially the gas-driven heat pumps, were found the most cost-effective. It was found that the cost for a system with heat pumps including heat pump fuel cost was not much greater than conventional energy cost and was not very sensitive to collector unit cost; for the system without heat pumps, however, the systems cost is very sensitive to the collector unit cost.

- Sweden

Results in Sweden show that the development of thermal energy storage in water and of collector technology has reached a level at which systems without heat pumps are competitive with heat pump systems for all solar fractions. These systems are already nearly competitive with conventional energy systems.

- United States of America

The performance and cost of the optimized drilled rock storage systems analyzed in the U.S. study were not much different from those of the reference studies or other national evaluations. Because of the high cost of oil and electricity in the New England region of the U.S., however CSHPSS systems have costs that are already attractive.

The U.S. study showed that, even without the tax incentives which are currently available, the system unit energy costs for optimized CSHPSS systems are below electricity prices and on a par with oil.

6.2 CONCLUSIONS

- CSHPSS systems can meet a large fraction of the space and water heating load for buildings even in harsh northern climates, and they are already cost effective in some locations.

- solar costs as low as 20 $/MWh are possible where appropriate aquifers are available if a heat pump and low-temperature distribution system can be used.

- large solar fractions, more than 80%, can be achieved by systems without heat pumps using stratified energy storage and high performance collectors. Costs for these systems are about 60-70 $/MWh for low-temperature distribution systems and 90-100 $/MWh for high-temperature distribution systems.

6.3 RECOMMENDATIONS

Based on the findings from Phase I and II of Task VII, it was recommended that the following activities be included in the continuation of the IEA collaborative effort on CSHPSS systems.

- generally favourable findings of the study for the economic viability of CSHPSS systems should be widely reported within IEA and the solar community,

- existing and planned CSHPSS systems should be instrumented, monitored, analyzed and evaluated to verify the method, models, data, and findings of the analyses and to provide a foundation for extension and improvement of the analyses,

- cost data for the various CSHPSS sub-systems should be updated and developed in more detail. Costs for the various storage concepts analyzed in these studies may decrease as more experience is gained. Collector sub-system costs are expected to decrease with increasing production volume and the use of large panels,

- analytical work should continue to explore promising new configurations, to support further design and system development, to verify preliminary findings, and to validate the analytical methods used,

- the analytical tools and procedures developed for the system analysis and parametric study should be in the evaluation of operating systems. These tools and procedures should be used to re-optimize the design of existing plants using current knowledge and data, and to simulate the performance and to analyze economics of these plants in other locations and economic environments.

6.4 CONTINUING WORK

An agreement for continuing work in a third phase of this Task has been prepared and approved. Most of the participants in Phase II plus a few new participants will be part of this new Phase III. The major activities in Phase III are outlined below.

The objective of Phase III is to test in practice the results of Phases I and II by an exchange of information, experience and data from the design, construction and operation of CSHPSS, and to evaluate this information cooperatively.

Each participating country will offer at least one project for co-operative analysis and evaluation in this task. The analysis is envisioned to include:

- uniform documentation of design and performance data, and other information for further analysis and evaluation,
- re-optimization of system design based on system performance results and up-dated costs,
- examination of the range of technical and economical applicability of the new designs at different locations, etc.

The results of Phase III will be:

- evaluation of specific projects or designs, documented in national and IEA reports,
- evaluation of generalized configurations leading to guidelines for design, construction and operation of CSHPSS,
- guidelines for project documentation suitable for international comparison and evaluation studies.

For these large projects, the design, construction and monitoring work

APPENDIX A: LIST OF TASK VII DOCUMENTS

Technical Reports

T1 Tools for Design and Analysis, Verne G. Chant and Ronald C. Biggs, December, 1983, National Research Council, Canada, (available as CENSOL1 from Technical Information Office, Solar Energy Program, National Research Council, Ottawa, Canada, K1A 0R6).

T2 The MINSUN Simulation and Optimization Program: Application and User's Guide, Edited by Verne G. Chant and Rune Hakansson, September, 1985, National Research Council, Canada, (available as CENSOL3 from Technical Information Office, Solar Energy Program, National Research Council, Ottawa, Canada, K1A 0R6).

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(with identification of sub-task(s) of major involvement)

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BOYSEN

CENTRAL SOLAR HEATING

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BOYSEN

CENTRAL SOLAR HEATING PLANTS WITH SEASONAL STORAGE.

The purpose of Task VII - Central Solar Plants with Seasonal Storage - is to investigate the feasibility and the cost-effectiveness of large systems with a capacity for storing solar energy from summer to be used in winter.

This report gives an overview of the work in the two first phases of the Task, with references to IEA Technical Reports as well as national reports. The methodology for the economic evaluation is presented in some detail, and main results are indicated from the analysis of the economics of various system concepts.

The findings and conclusions of these studies, which are detailed in Chapter 6, show that large solar fractions can be achieved at a competitive energy price, when conditions are favourable.

Technical data from existing plants in the following 9 countries are given:

AUSTRIA

CANADA

DENMARK

FEDERAL REPUBLIC OF GERMANY

ITALY

NETHERLANDS

SWEDEN

SWITZERLAND

UNITED STATES OF AMERICA

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