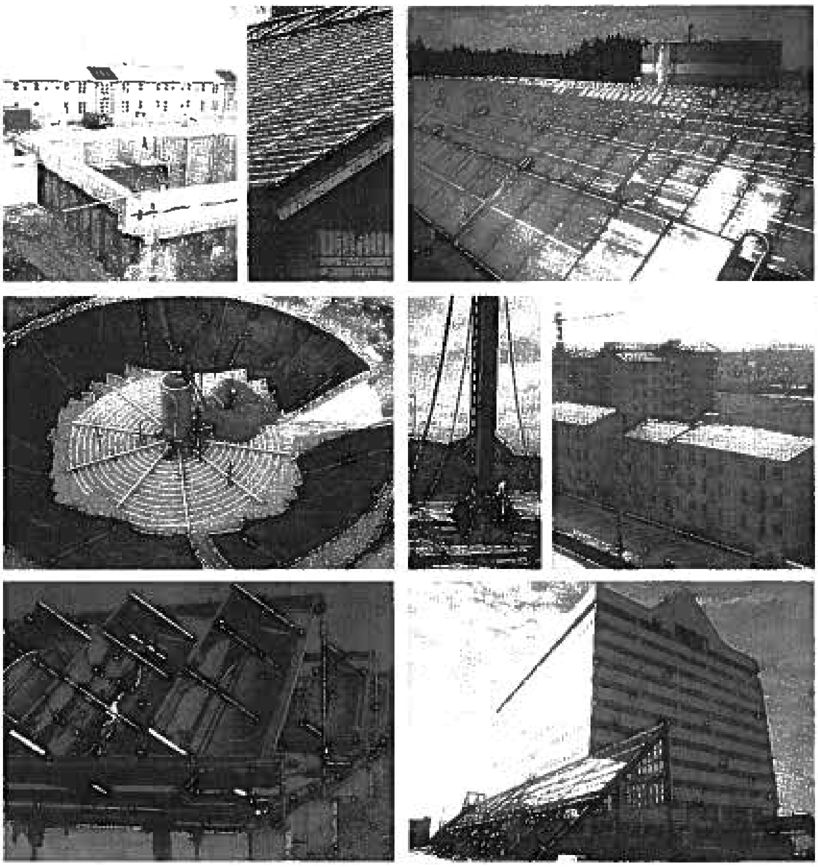
IEA
SOLAR R&D

INTERNATIONAL ENERGY AGENCY
solar heating and
cooling programme
task VII

central solar heating plants with seasonal storage – status report

june 1990



In the late 70's solar heating of buildings appeared to be an unrealistic proposition for northern countries: In wintertime, when heat is most needed, there is virtually no solar radiation to utilize. While long-term storage could make the heat available when needed, the economics of seasonal storage had been found to be unfavourable on a single house approach.

Nevertheless, there was reason to believe that long-term storage might make sense on a larger scale, and in 1979 an investigation was started to establish the feasibility and cost-effectiveness of central solar heating plants with seasonal storage (CSHPSS).

During the investigation a large amount of technical and economic data has been compiled, analythical tools have been developed and a great number of reports have been published. This report is the last in the series of IEA technical reports on this topic.

Installations of CSHPSS systems in seven countries are presented. Years of operational experience is analyzed, as well as experience from design and construction. The findings are generalized to aid future projects.

Earlier technical and economic information has been updated, and a general study of the feasibility and cost-effectiveness for various climates and applications is presented.

The conclusions are, that this technology is a realistic, non-polluting heat supply alternative for applications located between latitudes 40° and 65°. It may be used for existing buildings as well as for new, and could thus reduce the environmental pollution if used on a large scale.

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

International Energy Agency

The International Energy Agency, headquartered in Paris, was formed in November 1974 as an autonomous body within the framework of the Organization for Economic Cooperation and Development to establish cooperation in the area of energy policy. Twenty-one countries are presently members, with the Commission of the European Communities participating under a special arrangement.

Collaboration in the research, development and demonstration of new energy technologies to help reduce dependence on oil and to increase long-term energy security has been an important part of the Agency's programme. The IEA R&D activities are headed by the Committee on Research and Development (CRD) which is supported by a small Secretariat staff. In addition, four Working Parties (in Conservation, Fossil Fuels, Renewable Energy and Fusion) are charged with monitoring the various collaborative energy Agreements, identifying new areas for cooperation and advising the CRD on policy matters.

Solar Heating and Cooling Programme

One of the first collaborative R&D agreements was the IEA Solar Heating and Cooling Programme which was initiated in 1977 to conduct joint projects in active and passive solar technologies, primarly for building applications. The eighteen members of the Programme are:

Australia
Austria
Belgium
Canada
Denmark
European Community
Federal Republic of Germany
Finland
Italy
Japan
The Netherlands
New Zealand
Norway
Spain
Sweden
Switzerland
United Kingdom
United States

A total of sixteen projects or "Tasks" have been undertaken since the beginning of the Programme. The overall programme is managed by an Executive Committee composed of one representative from each of the member countries, while the leadership and management of the individual Tasks is the responsibility of Operating Agents. These Tasks and their respective Operating Agents are:

Task 1: Investigation of the Performance of Solar Heating and Cooling Systems - Denmark
Task 2: Coordination of Research and Development on Solar Heating and Cooling - Japan
Task 3: Performance Testing of Solar Collectors - United Kingdom
Task 4: Development of an Insolation Handbook and Instrument Package - United States
Task 5: Use of Existing Meteorological Information for Solar Energy Application - Sweden
Task 6: Performance of Solar Heating, Cooling, and Hot Water Systems Using Evacuated Collectors - United States
Task 7: Central Solar Heating Plants with Seasonal Storage - Sweden
Task 8: Passive and Hybrid Solar Low Energy Buildings - United States
Task 9: Solar Radiation and Pyranometry Studies - Federal Republic of Germany
Task 10: Material Research and Testing - Japan
Task 11: Passive and Hybrid Solar Commercial Buildings - Switzerland
Task 12: Building Energy Analysis and design Tools for Solar Applications - United States
Task 13: Advanced Solar Low Energy Buildings - Norway
Task 14: Advanced Active Solar Systems - Canada
Task 15: (in planning stage)
Task 16: (in planning stage)

Task VII - Central Solar Heating Plants with Seasonal Storage

For northern countries, solar heating of building would appear to be an unrealistic proposition: In winter, 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, seasonal storage has been found to be uneconomical for individual houses.

Nevertheless, it was thought that long-term storage might make sense on a larger scale. Task VII therefore was established in 1979 to investigate the feasibility and cost-effectiviness of central Solar Heating Plants with Seasonal Storage (CSHPSS).

The work has been divided into three phases. During Phase I (1979-83), 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 Phase II (1983-85), MINSUN was used to make a more systematic evaluation of design concepts and to identify those which are most competitive with alternative systems for building heating. Guide-lines were established for consistent documentation of monitoring and evaluation of operational systems.

The objective of Phase III (1986-89) was to correlate and expand on the result of the previous phases by an exchange of information on the design, construction and performance of existing or new systems, and to perform a collaborative evaluation of this information.

The following countries have participated in the three Phases of Task VII:

Austria	I		
Canada	I	II	III
CEC (JRC Ispra)	I	II	
Denmark	I	II	III
Federal Republic of Germany	I	II	III
Finland			III
Italy			III
The Netherlands	I	II	III
Sweden	I	II	III
Switzerland	I	II	III
United Kingdom	I		
United States	I	II	III

IEA Technical Report:

CENTRAL SOLAR HEATING PLANTS WITH SEASONAL STORAGE — STATUS REPORT

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Department of Building Services Engineering

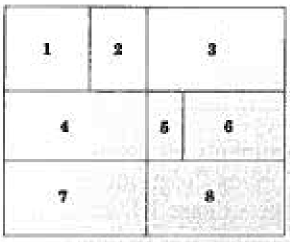
CHALMERS UNIVERSITY OF TECHNOLOGY

GÖTEBORG, Sweden

This report documents results of cooperative work performed under IEA Solar Heating and Cooling Programme, Task VII - Central Solar Heating Plants with Seasonal Storage - Phase III, and relates to research grant No. 850775-4 from the Swedish Council for Building Research to the Department of Building Services Engineering, Chalmers University of Technology, Göteborg.

Cover photos:

No.	Project
1.	Tubberupvaenge, Denmark
2.	Kullavik, Sweden
3.	Ingelstad Ib, Sweden
4.	Stuttgart University, FRG
5.	Groningen, Netherlands
6.	Treviglio, Italy
7.	Ingelstad Ia, Sweden
8.	Scarborough, Canada



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CONTENT

PREFACE

In many high latitude countries, the heating of buildings is a major component of the national energy balance, sometimes representing as much as half of the national energy budget. The primary source of energy for heating of buildings is fossil fuels. Thus, heating of buildings contributes substantially to the degradation of the global atmosphere through the emission of CO_2 and other greenhouse gasses, and to the depletion of our finite reserves of these fuels.

The severe climates of these countries determine that solar energy can make a major contribution to the heating of buildings only when combined with seasonal energy storage in CSHPSS. Plants with large seasonal storage are also one of the few effective ways to retrofit the existing building stock with solar heating. They offer a way to integrate solar energy with other renewable and waste heat energy sources.

The international effort within Task VII has established that CSHPSS are technically feasible, and economically competitive with fossil fuels, for large load applications of more than 50 GWh/a, or about 2 000 residential units. It is assumed that an established market for major CSHPSS components would be formed after the construction of about ten large plants. These initial plants would need subsidies or tax credits to cover approximately 20 per cent of their capital costs.

This conclusion has been accepted in Sweden, where implementation is now being given serious consideration by the Swedish Government. The climatic and economic conditions in most other countries that participate in Task VII are more favourable for the application of CSHPSS, but none have developed the necessary technology to the degree available in Sweden.

In order to foster the development of cost effective CSHPSS in other countries and to accelerate the more rapid diffusion of the technology in Sweden, it is important to develop seasonal storage systems that can be cost effective for smaller loads. Substantial progress has been achieved in Task VII in identifying promising technological approaches and in setting realistic and achievable cost goals for their development.

With the presentation of this report, Task VII has been completed. The Executive Committee for the IEA Solar Heating and Cooling Programme has however decided, that the possibility of further international collaboration should be investigated. A new Task (no. 15) is in preparation, and is expected to start in 1990.

ACKNOWLEDGEMENTS

This document is the result of international cooperative work within Task VII of the IEA SHCP. Each participating country has carried out and documented evaluations of existing installations in their countries according to common guide-lines. The participants have also analyzed the results from computer simulations of generic and other systems. The findings and conclusions in this document present the collective opinion of the experts participating in the Task, having first compiled and reviewed national reports.

All of the participants have been incredibly supportive through their comments and suggestions during the study and the preparation of this document. Our thanks are due to all the national participants and their experts, who have made significant contributions to this work, and especially Edward Morofsky and Verne Chant, who have revised the English in the report, and Pierre Jaboyedoff, who has compiled the results into a consistent whole.

The author's participation in this Task was made possible by support from the Swedish Council for Building Research. The author and all participants also wish to acknowledge the support and encouragement of the Task Operating Agent, Arne Boysen of Sweden.

EXECUTIVE SUMMARY

The following headlines are identical with the chapter headings of the full report.

Introduction

Task VII of the IEA SHCP was established in 1979 to investigate the feasibility and cost-effectiveness of Central Solar Heating Plants with Seasonal Storage (CSHPSS, pronounced as "chips"). The objectives of Phase III (1986-89) were to verify and expand on the results of the previous phases by an exchange of information on design, construction and performance of existing or new systems, and to perform a collaborative evaluation of this information. The Introduction chapter describes the evaluation approach together with a summary of present activities and plans in the participating countries.

Evaluation of existing plants

In general, the agreement between calculations performed in recent years and measured performance is good, showing that the pre-design tools (e.g., the computer model MINSUN) are now reliable. Our present knowledge forms a stable basis for appropriate models and parameters.

Design tools and thermal performance simulation models have been validated by comparing design, simulated and measured performance for several existing installations. Every participating country has evaluated its existing plants using a common procedure. System configurations and design data are described together with major thermal performance evaluation results from seven existing installations. National evaluation summaries are included as appendices.

Lessons from plants in operation

A new installation designed and built with present knowledge, would perform much better than most existing plants. Simpler system designs and control strategies would be used. It is often possible to apply conventional heating technology, but a very careful thermal design is essential in order to achieve efficient performance. A solar heating plant requires, therefore, more advanced thermal design methods than a conventional boiler plant, and it is essential that the temperature level in the connected heat distribution system should be as low as possible.

Solar collector sub-systems must be carefully designed and operated for CSHPSS. A collector field design with suitable characteristics has been used in several Swedish projects. For plants with annual heat loads above approximately 15 GWh, water-filled uninsulated rock caverns are suitable for heat storage. Construction of rock caverns is an established technology where rock conditions are favourable. For smaller plants, suitable storage would be insulated water-filled pits and ground storages with vertical ducts or pipes, but these types need to be further developed in detail.

Planning, design, construction and operational performance from eleven existing installations have been compiled. This information should assist designers of future installations.

New projects

A new generation of pilot-plants has been initiated in Denmark and Sweden. Four pilot CSHPSS with insulated water-filled pit storages are presented. Three of these projects have ground-mounted collectors and the other has roof-integrated collectors. A comprehensive design study for a large CSHPSS, supplying the requirements of a Swedish town, with a heat load of 56 GWh/a, is also presented.

Generic systems study

The analytical work in Phase III has been concentrated on two generic system configurations that were found to be of major interest among the participating countries. These system configurations comprise high temperature flat plate solar collectors and high temperature water or ground storages. A third system configuration presented is a solar assisted heat pump system with unglazed collectors and a low temperature aquifer storage. This system was considered to be one of the most promising CSHPSS system during Phase II.

Economic analyses of the systems have been based on investment cost levels in the participating countries. All generic systems supply heat at a cost equal to or below 50 US$/MWh for almost all climates and load sizes using estimated future costs, 5 % real interest rate and 25 years depreciation time. Each of the three generic systems has been simulated with MINSUN for four climates and three load sizes. Updated cost and performance data as compared to Phase II have been used together with the experience gained from the national evaluations concerning system design and validations of MINSUN.

Major Findings

International co-operation has been invaluable in the evaluation of projects, and the exchange of information in the international forum of the IEA has greatly improved design know-how on a national level.

The system aspects of CSHPSS are now better understood and design tools have been developed and confidence has been gained in their use. Designing a CSHPSS heating system requires, however, expertise from many fields not related to conventional heating plants.

Conclusions and recommendations

Technical feasibility of CSHPSS has been well established and the understanding of the design and construction of plants and their major components has reached the level where selective introduction may be economically feasible. If the external costs of global pollution produced by burning fossil fuels were taken into account, CSHPSS would already be cost effective for many applications.

Rational manufacturing techniques for large ground mounted, as well as roof-integrated solar collectors, do exist and it should be possible to bring the cost down to 130 US$/m^2 through larger scale production.

The key issue for further development of CSHPSS, in order to be cost-effective in all countries, is further development of the storage technology. Specifically there is a need for internationally coordinated R&D on high temperature storages.

Development of simple and general design tools, to be used by designers and consultants in feasibility studies, is also an important issue.

1 INTRODUCTION

1.1 The work within Task VII

The general objective of Task VII has been to establish the technical and economic feasibility of Central Solar Heating Plants with Seasonal Storage (CSHPSS), and to promote and assist in the establishment of this technology in the participants' countries.

The work of Phase I has concentrated on the development of design tools for the principal system components, and computer codes for optimising the system design. Cost data for all components have been collected and analyzed. Each participating country presented a CSHPSS system design. Some of these were conceptual, while others were designs of existing systems or systems in the construction stage. This work has been presented in a number of previous reports (see the List of Task VII Technical Reports).

Phase II identified the most promising system concepts, and developed guidelines and reporting formats for the presentation of experience and data from systems in operation.

Some system configurations were operating, some were in the construction phase, and others were in the design phase. Direct comparisons among these heterogeneous systems were not possible. However, some comparisons among operating subsystems with similar characteristics were made and the simulation tool MINSUN was used to extend the performance and economics of the designs to other sizes and climates. In this manner, some general conclusions on system design and operation were made.

A parametric study was published as an IEA Technical Report (Bankston, 1986), and the guidelines (Havinga and Wijsman, 1986a) and reporting format (Havinga and Wijsman, 1986b) were distributed as working documents for the use of participants.

The objective of Phase III was to exchange information, experience and data on the design, construction and operation of national CSHPSS projects, and to evaluate this information co-operatively.

The evaluated systems are of various designs and sizes, and are located in differing climatic regions, but all of them have been in operation for at least several years. The main evaluation effort has been on the national level but the evaluations have been carried through following common evaluation guidelines.

The evaluation of individual systems was based on comparisons of the thermal performance of the designed system, the actual constructed system, and a re-optimized system. Re-optimized systems incorporate design or operation changes based on experience gained during monitoring and evaluation of the actual system.

The original work plan was extended to include two other major features:

- the compilation and analysis of experience from system design, construction, and operation; and
- simulation studies for three generic CSHPSS systems incorporating re-optimized designs, using updated cost data and weather data for four locations.

The compilation and analysis of experience resulted in general recommendations to assist future designers to improve the quality and performance of CSHPSS. The simulation studies provided results on the current feasibility and cost-effectiveness of three generic CSHPSS concepts.

Improvements were made in the MINSUN code during the course of Phase III. These improvements have been documented in a revised manual (Mazzarella, 1989) and a new version (5.2) for PC is available, although this was not part of the formal agreement for Phase III.

1.2 Evaluation of existing plants

The purpose of the evaluation was to assess the technology, the design principles or tools, the system concept, and subsystem components, and to compile information on general design, construction, thermal performance, and operational experience.

The analysis of national experience has involved collaboration among the experts from the participating countries. They have shared their experience freely and without constraints. They have been open to ideas from their colleagues, and the report has thus become an instrument in creating a common basis of knowledge and understanding.

1.2.1 Material for evaluation.

According to the Annex VII Agreement each participating country was to contribute information from at least one CSHPSS in their country. Sweden decided to contribute data from several projects.

The Swedish program included a number of CSHPSS projects, the first in operation since 1978. The projects demonstrated different system and subsystem concepts, and promoted a general development of the technology.

Other countries in Task VII did not all have similar, broad-based R&D programs. Most had one project to enter in the Phase III evaluation, often developed before the international collaboration was established.

The projects of Phase III of Task VII were originally designed to meet national needs and were not co-ordinated internationally. The variety of the objectives in the national programs is illustrated in Table 1.1.

Table 1.1 **Objectives of Task VII National Programs**

Country/Subject		CDN	CH	DK	FRG	I	NL	SF	S	USA
Thermal performance evaluations										
Collector				♦	♦		♦		♦	
Heat store	Aquifer	♦			♦					
	Ground		♦		♦	♦	♦	♦		
	Water			♦				♦	♦	
System analysis										
System concepts			♦	♦	♦		♦	♦		♦
Control	Optimize	♦	♦		♦	♦		♦	♦	
	Simplify	♦				♦		♦	♦	
Modelling	Validate		♦		♦	♦	♦			
	Simplify							♦		

Note:	CDN	Canada
	CH	Switzerland
	DK	Denmark
	FRG	Federal Republic of Germany
	I	Italy
	NL	The Netherlands
	SF	Finland
	S	Sweden
	USA	United States of America

The status of existing and planned projects differed as well. For most existing plants, national reports were produced within the Phase III period. Some more recent projects were in a preliminary stage and did not provide operational data during Phase III.

Table 1.2 lists all plants in operation and covered within this report. These are the plants that have been internationally evaluated within a collaborative work during Phase III of Task VII. Installations in **bold** are covered in the performance evaluations in Chapter 2, **Evaluation of existing plants.** All installations are covered in the experience analysis in Chapter 3, **Lessons from Plants in operation.**

Table 1.2 CSHPSS evaluated in this report

Country	Installation
Canada	Scarborough
Finland	**Kerava**
FRG	**Stuttgart University**
Italy	**Treviglio**
The Netherlands	**Groningen**
Sweden	**Ingelstad** Kullavik Lambohov **Lyckebo** Sunclay
Switzerland	**Vaulruz**

A short description of all installations, except Kerava, can be found in the Summary report from Phase I and Phase II (Boysen and Chant, 1986). Finland joined task VII in Phase III.

1.2.2 Thermal performance analysis

For the thermal performance analysis, standard monitoring methodologies were applied by the participants. The performance predictions were primarily made with the help of MINSUN, developed and documented in Phase I and Phase II. The reporting format for the system design has been developed in Phase II, but was essentially a format originally developed in Task I of the SHCP. The presentation of the thermal performance was also based on the methodology used in the 2nd Workshop on Solar Assisted Heat Pumps with Ground Coupled Storage (van Hattem, 1985).

The project evaluation was intended to proceed as follows:

- The project design and performance, as well as weather data, were documented for each site.

- The performance of each project was simulated using actual weather and load characteristics, and the results were compared to the measured results from the same project.

- The operational strategy was optimised for each site, using different weather conditions.

- The system design, and sometimes the operation strategy, were re-designed and re-optimized.

This evaluation procedure had several aims. It provided each participant with site specific data from different countries, to be used in the analysis of different system concepts. It served to validate the design tools used by each country. It served to achieve better performance of the existing systems. And finally, it provided some information on the universal applicability of system concepts.

Obviously these steps apply only to existing systems, and these thermal performance analyses using local weather data are compiled in Chapter 2, **Evaluation of existing plants**. For new systems, the evaluation was limited to simulations of the designed systems using weather data for other sites.

However, due to limitations in national research programs and the characteristics of certain installations, it has not been possible to follow this evaluation procedure in all project evaluations.

1.2.3 The experience analysis.

A compilation of experience with CSHPSS systems was perpared based on national project reports and other sources in each country. From these reports, significant experiences were identified together with a brief note of the implications. Analysis of detailed local factors was left to national evaluations, while the Task VII experts concentrated upon identifying general conclusions from this material.

Observations are organized so as to demonstrate where in the system they took place and at which stage of the project. The system components are the solar collectors, the heat store and the heating plant, and the project stages are listed as design, construction and operation.

Observations have often led directly to recommendations concerning the correct application of technology, use of materials, operation of systems and subsystems, or management of projects. Actions or recommendations have been noted, and these lists have then become the source for the general conclusions in this report. These experiences are compiled in Chapter 3, **Lessons from plants in operation**.

1.3 Analysis of generic systems

The analysis of generic systems in Phase III was organized to present a more detailed picture of some promising generic systems with high solar fractions identyfied from the work in Phase II. The analysis included four types of climate zones, to give a better understanding of how the climate would affect the design of a system. Up-dated cost information was compiled. To achieve the best cost-effectiveness of CSHPSS, the lowest cost for each component was used in the analysis, even though this figure represented the situation in just one country.

Descriptions of the generic systems, the assumptions and the result are presented in Chapter 5, **Generic systems analysis.** The methodology used to find the optima for the various cases was the same as in Phase II, and is presented in detail in another report (Bankston, 1986).

1.4 CSHPSS - An emerging technology

When Task VII began in 1980 the application of the CSHPSS concept was new. A few systems had been built, most of them in Sweden. Now systems are in operation in a number of countries, as indicated in Table 1.3.

Since the initiation of Task VII, confidence in the technology has grown. The benefits of large scale solar systems are now recognized and heating of buildings with large solar energy fractions has also been demonstrated in northern climates. The main problems now are economy and financing, but this is a general problem for all solar heating applications. Now that environmental benefits are being seriously considered, the implementation of CSHPSS systems should be easier to justify.

The confidence in the CSHPSS technology has come so far that a comprehensive design study of a large solar heating plant of 56 GWh/a load has been completed for the town of Kungälv in Sweden. Construction of the plant is planned to begin in the 1990's, if financing can be arranged.

1.4.1 CSHPSS related projects

Table 1.3 includes some projects which, properly speaking, are not solar projects. They use other energy sources in systems with large heat storage facilities. Know-how from such systems is useful for the CSHPSS technology which explains their inclusion in the table. The data shown for each project are design values.

Most of the projects have the components characteristic of CSHPSS systems: solar collectors, large heat stores, and hydronic heat distribution systems. The solar fraction of the supplied heat varies greatly. In only a few cases these fractions are optimal.

Table 1.3 List of CSHPSS related projects

LOCATION				LOAD CHARACTERISTICS				DESIGN	
	Country	Site/Name	Lat (°)	Year of first operation	Load Type	Building area (m^2)	Annual load (MWh)	Nominal design Supply/ Return (°C)	Fraction Solar/HP/Aux (%)
1	A	Kranebitten	47	82	Military barracks	65 000	1 370		66/-/-
2	CDN	Scarborough	44	85	Office Building	30 000	1 800		
3	DK	Lyngby	56	83	Heat exch. R&D				
4	DK	Tubberupvaenge	56	1)	92 Resid. units	6 900	1 020	55/35	74/11 ng/15 ng
5	SF	Kerava	60	83	44 Resid. units	3 760	550	60/45	75/- el/- el
6	F	Tolouse-Blagna	43	80					
7	F	Aulnay-Sous-Boi	49	83	225 Resid. units	2 475		50/25	66/24/10
8	F	Saint Quentin	49	86	School Building	2 500			
9	F	Cormontreuil	49	86	Function Hall	5 200			
10	FRG	Stuttgart	48	86	Office Building R&D	1 375	150	50/40	74/26 el/0
11	I	Treviglio	46	82	Apartm. Buildings	9 200	960	35/25	76/24 el/0
12	I	Torino	46	1)	Office Building				
13	CEC	JRC Ispra	46	81	Simulated R&D				
14	Japan	Yonezawa	38	82	Snowmelt + Building				
15	NL	Groningen	53	84	96 Resid. units	9 600	1 165	43/33	63/0/37
16	NL	Bunnik	52	85	Office Building	10 000	660	50/40	35/42 ng/11$^{3)}$
17	S	Studsvik	58	78-84	Office Building	200	17	30/22	100/0/0
18	S	Ingelstad Ia	56	79-84	52 Resid. units	6 500	1 160	80/50	50/0/50 oil
19	S	Lambohov	58	80	55 Resid. units	7 000	900	55/25	85/15 el/0
20	S	Kungsb./Sunclay	57	81	School	15 000	1 500	55/45	60/40 oil/0
21	S	Härryda/Sunpeat	57	82	School	7 000	750	55/45	70/25 el/5 oil
22	S	Kullavik	57	83	Apartm. Buildings	3 500	310	55/45	60/25 el/15 oil
23	S	Lyckebo	60	83	550 Resid. units	45 000	8 500	70/55	100$^{4)}$/0/0
24	S	Ingelstad Ib	56	84-87	52 Resid. units	6 500	920	80/50	50/0/50 oil
25	S	Kronhjorten	56	87	Office Building	2 500	170	55/45	65/0/ 35 oil
26	S	Ingelstad Ic	56	88	52 Resid.units	6 500	920	80/50	70/0/30 oil
27	S	Malung	61	1)	Apartm. Buildings	20 000	2 200	90/60	10$^{5)}$/-/90 el
28	S	Särö	57	1)	Apartm. Buildings	5 000	400	55/45	65/0/35 wood
29	S	Kungälv	57	2)	Mixed urban	350 000	56 000	100/60	75/0/25 ng
30	CH	Cort.-Neuchatel	47	81	12 Resid. units		190	60/-	40/-/-
31	CH	Lavigny-Vaud	47	81					
32	CH	Vaulruz	47	83	Office/Garage	3 200	341	50/-	46/19 el/35 oil
33	CH	Geneva/Meyrin	47	1)	Office/Industry	30 000	1 000		
34	USA	Hatfield	42	83	School	4 025	293	90/60	
35	USA	Massachusetts		2)	University dorm.				

1) Project in the final design or construction phase
2) Feasibility studies and preliminary design
3) 12 % waste heat
4) 85 % simulated by electric boiler
5) Pilot plant - Storage used short-term
el = electricity and ng = natural gas

Most of these projects were evaluated within national solar development plans. Some of them were demonstration projects with R&D aspects. For others, the R&D aspect was predominant. These projects are indicated by "R&D" in the column for load type.

1.4.2 Present national activities and plans

The activities and results of Task VII have already had a significant influence on the national plans for future research, development and demonstration of the technologies concerned with CSHPSS. Following is a brief description of the attitudes and plans for each country as contributed by the Task VII Experts from each participating country. It is hoped that these descriptions will facilitate an understanding of the variety of responses that result from differing national policies, prices and outlooks.

Canada

Large-scale combined heating and cooling systems are being implemented and research continues on the heat-pumped ice field in-ground concept. Based on Task VII results, a survey is planned to assess the potential for CSHPSS in Canada. Industrial cooperation with Sweden on large-scale CSHPSS applications is possible. Environment is the number one issue for Canadians. Cooperation is proceeding with the USA on a CSHPSS feasibility study and with Sweden on the "Heating and Cooling Consultant" expert system.

Denmark

The present CSHPSS R&D in Denmark comprises support for the Tubberupvaenge II, a grant to design and build an experimental duct storage and run a simulated solar operation of this storage, and the construction of an experimental artificial aquifer. The Tubberupvaenge project (with a water pit) is being constructed. Operation is expected in 1989. A borehole project at the Technical University is going ahead with simulated solar. Old water pit design will be converted to water and gravel filled pit. Application to extend CSHPSS computer program has been approved. Dynamic PC model for heat transfer in boreholes is part of the extention.

The Danish R&D in CSHPSS also includes a grant to allow continued further development of simulation programs for design and operation of solar plants with seasonal storage. Grants are anticipated to further study pit design and construction. A 1 000 m^2 collector array in a district heating system may be monitored. Applications for a predesign study of a solar system for a village is being considered. Studies to possibly create further collector arrays in the return lines of district heating systems are underway. The present political decision to create 20 to 30 new cogeneration plants in smaller communities may lead to the application of pits for storage if the present problems of design and construction can be solved. A buried concrete tank storage for district heating system is under construction using a new protective coating. All solar plants in Denmark are granted a subsidy of 30 % of the construction cost.

Federal Republic of Germany

The interest for small district heating networks with low cost distribution systems is growing at present. The Stuttgart University (ITW) has started a project with site specific CSHPSS studies for several locations in the FRG. Emphasis are on construction and cost estimation of a solar heating system for at least 200 residential houses (units). A bilateral cooperation between Swedish and German experts is planned.

Funding, for a further four years study (1989-92), has been approved for the Stuttgart University Project, including short-term storage operation and combined seasonal heating and cooling.

A small scale solar assisted heat pump system (100 MWh/a) with a duct store has been completed near Munich and will be monitored for two years. The collector and storage investment costs are low. The specific investment cost for the unglazed collectors (100 m^2) is 12 US\$/m^2 and the specific investment cost for the duct store (2 850 m^3) is 3 US\$/m^3.

Finland

No new CSHPSS projects are contemplated, though some major seasonal storage projects are planned. There is an ongoing investigation to convert a 190 000 m^3 rock cavern gasoline storage into a high temperature storage. University studies will continue on specific CSHPSS questions, modelling and perhaps a predesign. The new 5 year Advanced Energy Systems Program has begun with up to 100 million FMK, which includes solar and storage. A photovoltaic grid connected plant is to be built. A significant industry involvement is expected in the R&D projects.

Italy

A small CSHPSS is under construction at Torino ENEL (Ente Nazionale Energia Elettrica). It supplies both heating and cooling energy utilizing a buried water tank storage and solar collectors. It will be monitored. A request for a feasibility study of a CSHPSS with a large pit storage has been submitted to the Lombardia Regional energy department. The new Italian energy plan may call for a new effort to develop renewable energy resources.

The Netherlands

The main problem for CSHPSS in The Netherlands is cost-effectiveness. No real CSHPSS are in sight at the moment. However, several projects related to CSHPSS are in the design phase, under construction or in operation. The present national interest is for cold storage in aquifers for building space cooling and industrial process cooling. One cold storage project (Printing Hall Perscombinatie, Amsterdam) is in operation and several others are in the phase of predesign, e.g. one project at Amsterdam Schiphol Airport. An aquifer test facility is in operation in Delft since April 1989, and several experiments will be carried out on hydraulic, thermal, chemical and biological aspects of both heat and cold storage. A cogeneration plant with heat storage in an aquifer is under construction at the University of Utrecht.

Sweden

The SAS office building outside Stockholm is now operating with a combined aquifer storage for both heating and cooling. Triangel Centre in Malmö (sand aquifer) and GLG Centre near Stockholm (borehole in rock) will soon be in operation with combined heating and cooling. Small CSHPSS projects in Malung, Särö, and Kronhjorten are being constructed.

A large CSHPSS (56 GWh/a) in Kungälv is being designed with construction funding requested from the Swedish government. To provide continuity for a CSHPSS industry, 25 projects of Kungälv-size will be needed in the future. A survey is underway to find possible locations. Expansion of the Lyckebo project is under discussion, and there is a proposal to increase the Nykvarn array from 4 000 m^2 to 8 000 m^2 to meet 15 % of load. The Falkenberg project is being constructed. A collector array of 5 500 m^2 is used, together with wood chips, in a small district heating plant. There is general community support for these projects. Financing is the main obstacle.

According to a new research plan for 1990-93 CSHPSS with high temperature storage in clay has a certain priority concerning experimental efforts in full-scale plants. Priority is also given to insulated water-filled pit storages, but further development of the water-sealing is needed in prototypes before efforts in full-scale plants are launched.

Switzerland

One small CSHPSS project is under design and should be built by 1990 near Lucerne. It aims at a high solar fraction (95 %). The design includes a water storage tank and is without a heat pump. A project located at Meyrin, near Geneva, includes a low temperature duct storage of 20 000 cubic meters, 1 000 m^2 of collectors, and a heat pump. It will soon be put into operation. A few other potential projects are presently under consideration.

United States of America

The Franklin School project is presently a competition between CSHPSS and a ground source heat pump. There has been some Canadian assistance and funding for the feasibility study. A decision is expected within several months. A feasibility and design study (2 years) for solar heating using seasonal storage on or near the University of Massachusetts at Amherst is underway. No decision or project construction until 1990/91. There are possible projects in Arizona for solar cooling or combined heating and cooling of entire communities.

There are encouraging long term prospects for combined thermal and electric applications. State and Federal building projects might capitalize on growing interest in renewables. University of Wisconsin is implementing SST into TRNSYS. Validation is being done with Swedish project data. Swedish and American cooperation could provide a front end for TRNSYS. Parabolic trough collectors, manufactured by Luz are being produced in large volume (500 000 m^2 annually) at low cost (135 US$/$m^2$ installed) for massive power production facilities in California. Perhaps this collector type should be reexamined for CSHPSS applications.

Encouraging results have been obtained from the U.S. aquifer thermal energy storage experiment at the University of Minnesota. Thermal energy recovery in excess of 60 % has been achieved with storage cycles of 60 day charge, 60 day hold, and 60 day discharge and an injection temperature of 110 °C. In addition, the ion-exchange water treatment system has performed very well in a fully automatic mode.

2 EVALUATION OF EXISTING PLANTS

2.1 National Evaluation summaries

Plants have been evaluated, and design tools and thermal performance simulation models have been validated, by comparing design, simulated and measured performance for the existing installations. In recent years, the agreement between predictions based on these models and measured performance is good. The conclusion is that the reliability of and confidence in design tools (e.g. MINSUN) has increased. The main reason is an increased knowledge about real performance, which makes it easier to develop and apply appropriate models and parameters.

2.1.1 Introduction

All participating countries having an existing installation in operation have made evaluations of their installation according to common guide-lines. These national evaluations are documented in national reports, and summarized in appendices in this document.

The national evaluations are concentrated on description, documentation of monitored results, evaluation and re-design of one project. It has not been possible to make any general conclusions about new generic system configurations or system designs within each national evaluation, as most of the countries only have one existing installation. This has instead been done co-operatively and documented in Chapter 5, **Generic systems study**.

However, a summary of the Swedish research program for solar heating systems with seasonal heat stores is included (Appendix F). Existing plants are described, and the essential basis for new designs using the experience from and research related to existing plants is given. Based on today's knowledge in Sweden, these solar heating systems should be designed and rated to provide a solar fraction of approximately 75 % of the heat requirement of the load. They should be realized using flat plate collectors in large modules - mounted on ground or integrated in the roof - with a basically simple system design. Smaller systems, intended to supply heat to some hundreds of users, require the use of thermally insulated heat stores. Larger systems, intended to supply heat to some thousands of users, can utilize water-filled uninsulated rock caverns.

Similar new system configurations, based on the evaluation of the national project, are also suggested in some national evaluations, such as high temperature flat plate (HT FP) collectors in combination with ground storage (Switzerland) and HT FP collectors in combination with water and gravel-filled pits (FRG).

Furthermore, the national evaluation summary from the Netherlands includes a re-design and evaluation study for three different system concepts based on a seasonal ground storage as the one in Groningen.

2.1.2 System configurations

The solar heating installations described cover a wide range of applications and include a lot of different subsystems which are summarized in Table 2.1 and 2.2. Collector, heat storage and load type in these installations are described in Table 2.1. Design data for the same installations are presented in Table 2.2.

The common feature in the installations is that they are intended to cover a large part (50-100%) of the connected load by using solar thermal collectors in combination with a seasonal storage.

The installations are described in more detail in order to create a better understanding of the applicability of the evaluation results, both concerning thermal performance and experience analysis.

The total collector area in these installations is almost 20 000 m^2, varying from 200 m^2 to 4 300 m^2, which means that the largest one is twenty times the smallest one. The total amount of annual solar heat from the collectors in these eleven installations is of the order of 6 GWh, which is equal to the yield in some thousands of conventional solar DHW-systems.

The annual heat loads, including space heating, Domestic Hot Water (DHW) and distribution heat losses, vary from 150 to 8 500 MWh, which means that the largest one is about sixty times the smallest one. Seven of eleven **heat loads** are residential building loads including DHW and the others are commercial building loads.

- 1 group of single family houses
- 6 groups of row and/or multifamily houses
- 2 office buildings
- 1 school building
- 1 administration and garage building

The applied **space heating systems** cover many design approaches with low temperature requirements.

- 1 floor heating system
- 6 air heating systems
- 7 radiator systems

Table 2.1 **Collector, heat store and load**

Installation	Collector	Heat store	Load
Groningen[1)] 1984	Evac.tube roof mounted	Ground/vert pipes	96 row houses
Ingelstad[1)2)] 1979/84	Conc/Flat plate on ground	Water/insulated concrete tank above ground	52 single fam houses
Kerava 1983	Flat plate roof/wall integ	Water/rockpit + Rock/ducts	44 row houses
Kullavik 1983	Flat plate roof integ	Ground (clay)/ vert pipes	40 apartments
Lambohov 1980	Flat plate roof integ	Water/insulated rock pit	55 row houses
Lyckebo[1)] 1983	Flat plate on ground	Water/rock cavern	550 residential units
Scarborough 1985	Evac.tube on roof	Aquifer	30 000 m^2 office building
Stuttgart 1986	Flat plate[3)] roof mounted	Man-made aquifer/gravel-water pit	1 375 m^2 office building
Sunclay 1981	Flat plate[3)] roof integ	Ground (clay)/ vert pipes	15 000 m^2 school building
Treviglio 1982	Flat plate roof integ	Ground/ hor-vert pipes	100 apartments
Vaulruz 1983	Flat plate roof integ	Ground/ hor pipes	3 200 m^2 maintenance buildings + garage

[1)] No heat pump.
[2)] Concentrating collectors replaced with flat plate in 1984.
[3)] Absorbers (un-glazed collectors).

Legend:
evac = evacuated
integ = integrated
hor = horizontal
conc = concentrating
fam = family
vert = vertical

Table 2.2 **Design data**

Installation	Collector area (m^2)	Store volume (m^3)	[1]Solar fraction (%)	Suppl. energy (type)	Heat load (MWh/a)
Groningen	2 400	23 000	63	gas	1 165
Ingelstad[2]	co 1 320 fp 1 425 fp 2 425	5 000 5 000 5 000	50 50 70	oil oil oil	1 160 920 920
Kerava	1 100	water 1 500 rock 11 000	75	el HP + el res	550
Kullavik	490	8 100	60	el HP + oil	310
Lambohov	2 700	10 000	85	el HP	900
Lyckebo	[3]28 800	105 000	100	el res	8 500
Scarborough[4]	700	(800 000)	-	el HP + el res	1 800
Stuttgart	210	1 050	74	el HP + distr heat	150
Sunclay	1 500	87 000	60	diesel HP	1 500
Treviglio	525 1 260 555	hor 14 000 vert 15 000 vert 14 000	75	el HP + gas	275 415 270
Vaulruz	520	3 300	46	el HP + oil	340

[1] Solar fraction = (heat load - suppl energy) / heat load * 100

[2] Concentrating collectors replaced with flat plate in 1984, flat plate collector array increased with 1 000 m^2 in 1987.

[3] 4 320 m^2 (15%) are built, the rest are simulated with an electric boiler.

[4] Solar collectors mainly for domestic hot water (DHW). This is mainly a storage project with an aquifer used for heating and cooling.

Legend:

co = concentrating
hor = horizontal
suppl = supplementary
gas = natural gas
el HP = electric heat pump
el res = electric resistance

fp = flat plate
vert = vertical
distr = district

Nine of twelve **collector systems** (one installation includes two types of systems) incorporate roof integrated or roof mounted collectors and three systems incorporate ground mounted collectors, as follows.

- 1 concentrating collector system
- 2 evacuated tube collector systems
- 2 unglazed collector systems
- 7 flat plate collector systems

A total number of thirteen **seasonal storage systems** are represented (two installations include more than one storage type).

- 1 aquifer storage system
- 5 water storage systems (one with water and gravel)
- 7 ground storage systems

The heating plant configurations can be divided in three types related to the type of **supplementary heating equipment**.

- 3 systems with boiler (only)
- 7 systems with heat pump (and backup or peak boiler)
- 1 system with heat pump and a district heating connection (pilot plant)

Two types of **heat pump systems**,

- 1 diesel driven heat pump system (engine/compressor)
- 7 electric driven heat pump systems (motor/compressor)

and three types of **boiler systems** are used.

- 2 natural gas boiler systems
- 3 electric boiler systems
- 4 oil boiler systems

This, all together, means that the main experiences are from systems with flat plate collectors and water or ground storages. The most common load type is a group of row and/or multifamily houses with air heating or radiator heating system. The main experiences are, furthermore, from system configurations including electric heat pumps.

2.2 Thermal performance evaluations

A comparison between design performance and actual measured performance for at least one year is presented for eight projects. The performance of almost each project has, furthermore, been simulated using actual weather and load characteristics, and the simulation results have been compared to the measured results from the same project. In some case, and especially in Ingelstad, the system design or the operational strategy has been changed as a result of the monitoring or the simulations. The performance predictions have primarily been made with the help of MINSUN.

2.2.1 Evaluation summary

The main results concerning annual thermal performance, simulated or actual, are summarized in the following tables. More detailed information about the analyses is to be found in the appendices summarizing the national evaluations.

Design, measured and simulated (made after monitoring) results are compared for each installation. The design and simulation models are indicated. The designs are based on an average year in all cases, but the simulations are either made for a specific year, to be directly compared with the monitored results of that year, or an average year. The following abbreviations are used to identify different thermal performance parameters:

D = Design performance (average year)
M = Monitored performance (year is indicated)
SXX = Simulated performance year 19XX
SA = Simulated performance an average year

Three main parameters have been used to describe performance;

Solar fraction (Solar frac),
collector efficiency (Coll Eff), and
storage efficiency (Storage Eff).

The solar fraction is defined as the relation between the net output solar heat (collectors and storage) and the total load (Annual demand). The collector efficiency is defined as net output heat in relation to global solar radiation on the collector. The storage efficiency is defined as the relation between discharged heat and charged heat.

The heat pump (HP) Seasonal Performance Factor (SPF) is also presented and defined as the relation between the heat from the heat pump condensor and the drive energy (electrical) to the heat pump.

Indicated storage temperatures (Temp min/max) are the minimum and maximum average storage temperatures during one storage cycle. These temperature levels are important in relation to the collector efficiency and the storage efficiency, as well as the heat pump SPF (storage as heat source). The storage volume should be considered in relation to the storage efficiency and the load temperatures, nominal load design, supply and return (Temp supply/return) influence the whole system performance.

Groningen - The Netherlands

The Groningen project was designed with a specially developed simulation model. The collector performance is less than expected, mainly due to slightly overestimated design performance and some minor malfunctions. Storage losses are larger than expected due to a larger U_l-value of top insulation, a slightly higher minimum useful temperature in the system, and greater ground water movements than expected.

Table 2.3 **Groningen - Evacuated Tube collectors and 23 000 m^3 ground storage**

		Load		Coll	Storage		HP	Remark
	Annual demand (MWh)	Temp supply/ return (°C)	Solar frac (%)	Eff (%)	Eff (%)	Temp min/max (°C)	SPF	Model or Year
D	1 163	43/33	63	48	61	30/60	-	TPD-LT1
D	1 169	43/33	65	45	80	28/53	-	MINSUN
M	1 275	45/33	35	39	23	27/42	-	85/86
M	1 182	45/33	49	42	23	31/49	-	86/87
M	917	45/33	68	41	48	32/49	-	87/88
M	837	45/33	67	41	43	32/47	-	88/89

The simulations with MINSUN is in fairly good agreement with monitored results. The Groningen system includes a short term heat store, combined collector and distribution network and a collector-to-load connection. These options are not implemented in MINSUN and some assumptions had to be made. Further, MINSUN does not take the effects of ground water movements into account and was used with design input for the collectors and the storage that differ slightly from the real monitored parameters.

Kerava - Finland

The first design of the Kerava project was made as a simple hand calculation of annual performance, which gave an unrealistically high solar fraction. The storage capacity was found to be too small (only the water storage is effective) to achieve the design solar fraction.

Table 2.4 **Kerava - Flat Plate collector, 1 500 m^3 water storage and 11 000 m^3 rock storage**

	Annual demand (MWh)	Load Temp supply/ return (°C)	Solar frac (%)	Coll Eff (%)	Storage Eff (%)	Storage Temp min/max (°C)	HP SPF (-)	Remark Model or Year
D	555	60/45	75	43	83	25/50	na	-
M	574	60/42	26	24	85	21/49	2.59	1984
SA	576	60/45	22	22	87	19/51	2.67	SUPERSOL

MINSUN has only been used to a minor extent within the evaluation of the Kerava system as a more detailed simulation model was developed for the rather complicated system configuration. Using the simulation model SUPERSOL, the calculated performance agrees well with the monitored results.

Lyckebo - Sweden

The presentation of the Lyckebo system requires a special explanation. The supplementary heat is not supplied to the load, as in the other installations, but to the storage. A major part (85 %) of the collectors is furthermore simulated with an electric boiler. The solar fraction presented in the Lyckebo case is therefore calculated as solar heat (actual and simulated) in relation to heat load plus storage losses.

Table 2.5 **Lyckebo - High Temperature Flat Plate collector and 105 000 m^3 water storage in a rock cavern**

	Annual demand (MWh)	Load Temp supply/ return (°C)	Solar frac (%)	Coll Eff (%)	Storage Eff (%)	Storage Temp min/max (°C)	HP SPF	Remark Model or Year
D	8 500	70/60	100	na	na	40/90	-	MINSUN
M	7 910	70/60	62	29	74	47/73	-	84/85
M	8 100	70/60	75	26	72	45/75	-	85/86

The Lyckebo project was designed with the assistance of an early version of MINSUN (before Task VII use of MINSUN). The collector performance was estimated by the contractor and agrees well with the monitored results. The storage was designed using the SST-model (storage model in MINSUN). Storage losses are larger than expected, probably due to convection losses through the old access tunnel. Storage performance is, however, approaching design performance.

MINSUN simulations performed during the evaluation of the Lyckebo project are not able to simulate the performance of the system in detail because the supplementary heat is put into the storage. It is, however, possible to simulate the general performance of the system with flat plate collectors and a water-filled cavern storage quite well.

Ingelstad I - Sweden

Table 2.6 **Ingelstad I - Solar collectors with a water storage in a 5 000 m^3 water-filled concrete tank above ground.**

	Annual demand	**Load** Temp supply/ return	Solar frac	**Coll** Eff	**Storage** Eff	**Storage** Temp min/max	**HP** SPF	**Remark** Model or Year
	(MWh)	(°C)	(%)	(%)	(%)	(°C)		
System Ia:								
D	1 160	80/60	50	54	93	40/95	-	-
M	912	80/60	15	30	52	40/65	-	1982
System Ib:								
D	900	80/60	50	na	na	40/70	-	SUNSYST
M	888	80/60	38	na	75	38/65	-	1985
S85	926	80/60	41	na	78	40/70	-	SIMSYS
SA	916	80/60	48	na	80	40/60	-	SIMSYS
System Ic:								
D	915	80/60	70	na	81	38/95	-	SIMSYS
M	914	80/60	62	na	78	40/85	-	1988

Ia - Concentrating Parabolic Trough collectors (CPT)
Ib - High Temperature Flat Plate collectors (HT FP)
Ic - High Temperature Flat Plate collectors, increased area

The Ingelstad I project was originally equipped with CPT collectors (Ia) which were later replaced with HT FP collectors. The design solar fraction in the first configuration was badly estimated mainly due to an overestimating of beam solar radiation and collector field performance. The second (Ib) and third (Ic) design agrees better with the monitored results, due to the use of validated simulation models.

MINSUN has not been used in the evaluation as the main issue has been to evaluate the system layout (MINSUN has a fixed system layout). SIMSYS, the model used for the evaluation, is quite similar to MINSUN in other major aspects.

Stuttgart University project - FRG

The given heat load was overestimated and the solar fraction is thus quite low, taking a low heat pump SPF into account. An improved heat pump was installed in 1988.

Table 2.7 Stuttgart University project - Absorbers and a 1 050 m^3 gravel- and water-filled pit

		Load		**Coll**	**Storage**		**HP**	**Remark**
	Annual demand	Temp supply/ return	Solar frac	Eff	Eff	Temp min/max	SPF	Model or Year
	(MWh)	(°C)	(%)	(%)	(%)	(°C)	(-)	
D	150	50/40	74	35	74	0/33	3.6	MINSUN
M	97	50/40	60	32	82	0/33	2.8	86/87
M	95	50/40	59	31	80	0/31	3.1	87/88

MINSUN is not able to simulate the direct connection between the unglazed collectors and the heat pump evaporator in the Stuttgart University project. MINSUN simulations were, however, performed for the first year of operation (1986/87). A good overall agreement between measured and simulated performance was obtained, but MINSUN simulations gave a greater than measured heat pump COP at evaporator temperatures of 20 °C and higher.

Treviglio - Italy

The first design of the Treviglio systems was made with a simple hand calculation of annual performance. The monitored solar fraction is, however, close to that predicted because the annual load was lower than expected. The high storage efficiency (>100 %) for the CT2 system is mainly due to a large winter undercooling by means of the heat pump. The presented storage temperatures are, however, not comparable as the storage volumes are defined different.

Table 2.8 **Treviglio - Flat Plate collectors and two 15 000 m^3 ground storages**

	Annual demand (MWh)	Load Temp supply/, return (°C)	Solar frac (%)	Coll Eff (%)	Storage Eff (%)	Storage Temp min/max (°C)	HP SPF (-)	Remark Model or Year
System CT2:								
D	417	35/25	76	45	80	na	4.2	-
M	374	35/25	64	20	>100	8/28	4.0	1987
System CT3:								
D	273	35/25	76	45	80	na	4.2	-
M	184	35/25	72	30	59	4/30	3.7	85/86/87

CT2 - Flate plate collectors and vertical ground storage,
CT3 - Flat plaet collectors and horizontal ground storage,
where CT stands for Centrale Termica (heating plant).

MINSUN has been used, but as the real system can not be fully modelled with MINSUN, no meaningful comparison can be made. Later, TRNSYS has been used with better results. No redesign simulations have been carried out, as there was no possibility to implement the results of a re-design.

Vaulruz - Switzerland

The first design of the **Vaulruz** project was made with a special simulation model. The measured annual load is larger and the collector performance is higher than expected and thus, gives a higher solar fraction than expected. Storage performance is close to predicted due to the use of a detailed storage model.

Table 2.9 **Vaulruz - High Temperature Flat Plate collectors and a 3 300 m³ horizontal ground storage**

	Annual demand	Load Temp supply/ return	Solar frac	Coll Eff	Storage Eff	Storage Temp min/max	HP SPF	Remark Model or Year
	(MWh)	(°C)	(%)	(%)	(%)	(°C)	(-)	
D	341	70/50	46	36	85	5/50	3.0	VAU/LT
M	413	70/50	54	39	75	7/53	2.5	1986
S86	413	70/50	54	38	82	5/56	2.7	MINSUN

The MINSUN results concerning solar collector yield and storage temperatures are in very good agreement with measured results, even at the monthly level. MINSUN has also been used in a reoptimization study of the Vaulruz project, which is presented in the national evaluation summary (Appendix G).

2.2.2 Simulation models

All evaluated existing plants were designed with different pre-design tools and in some case even without any detailed design tool (simulation model). In two of the installations (Ingelstad I and Kerava), where no detailed design tools were used, the actual overall performance was far away from predictions. In these countries (Sweden and Finland) this has led to the development of simulation models (computer programs) in parallel with the development of the MINSUN program within Task VII.

Table 2.10 shows the design tools that have been used in the design as well as the evaluation phase in the different projects covered in this report. Projects in **bold** are the ones presented in this chapter.

Table 2.10 **Pre-design and evaluation tools**

Project	**Design**	**Evaluation**
Groningen	TPD-LT1	MINSUN
Ingelstad Ia	-	SST [1]
Ingelstad Ib	SUNSYST [2]	SIMSYS
Ingelstad Ic	SIMSYS	
Kerava	AUKER	SUPERSOL
Kullavik	SUNSYST	SUNSYST
Lambohov	(SIMSYS)	SIMSYS
Lyckebo	(MINSUN) SST [1] SUNSYST [2]	MINSUN SST [1] SIMSYS
Scarborough	Merriwether [3] ABES	-
Stuttgart University	(TRNSYS) [4]	MINSUN (FEM) [1]
Sunclay	(SUNSYST)	SUNSYST (MINSUN)
Treviglio	-	MINSUN TRNSYS
Vaulruz	VAU/LT (TRNSYS) [4]	MINSUN

[1] only storage
[2] only collectors
[3] only building
[4] mainly control strategies and system configuration

There are three computer programs that have been used in the evaluation of more than one project, MINSUN, SIMSYS and SUNSYST. All three programs can be used on a PC. MINSUN and SIMSYS require a math co-processor.

All of these programs have specific applications and limitations, advantages and disadvantages and so on. One advantage with the MINSUN program is that it is internationally accepted and applied through the collaboration within Task VII.

The MINSUN program

MINSUN was developed and used mainly within Task VII. It had only been validated and used in real projects to a minor extent previous to Phase III, and the confidence in MINSUN results has thus increased significantly as a result of the work carried out in Phase III.

The first version was developed in Sweden in FORTRAN on a CYBER computer. It was built up using modules from TRNSYS, an optimization routine and some new code. A pre-processor (the UMSORT program) was developed to calculate the collector yield before the full simulation was executed.

MINSUN development in Phase II of Task VII involved the implementation of three new storage models. The storage models Stratified Storage Temperature Model (SST), Duct Storage Temperature Model (DST) and Aquifer Storage Temperature Model (AST) are developed at the Lund Institute of Technology in Sweden and can be used as stand-alone models. The implementation in MINSUN has meant that some simplifications have been made to speed up the calculations. This is particularly the case for AST as a detailed aquifer storage model requires a lot of computation time.

Sweden, Canada and USA carried out most of that work. The program was distributed in source code and a lot of early problems occured when different FORTRAN compilers were used on different computers. MINSUN was used to make all the runs for the Phase IIb report (Bankston, 1986).

A new version (5.2) is available for PC in standard FORTRAN 77 source code, and a new manual is also available (Mazzarella, 1989). The major work in connection to Phase III has been to improve the input and output routines in order to make it more user-friendly. Various parts of the program have been improved as well. The MINSUN program is suitable for single simulations or multiple runs where one or more parameters are varied within specified limits. Italy has carried out most of the MINSUN development work in connection to Phase III, and further development is on-going.

Other Programs

SIMSYS is a program similar to MINSUN. The first version was developed in 1978, in connection to the design of the Lambohov project, on a DEC computer in SIMULA code. A new version including the SST model is available and a version including the DST model will soon be available on PC in executable code (Turbo Pascal).

The main difference, compared to MINSUN, is that it is possible to evaluate different system configurations within the same executable code. MINSUN has a fixed system configuration for each storage type. Another difference is that SIMSYS includes a detailed on-line (hour by hour or month by month) presentation of the thermal behavior of the system that is simulated.

SUNSYST is a program developed and used by a Swedish consulting company. TPD-LT1 and VAU/LT are programs developed in connection to the designs of the Groningen and the Vaulruz projects. SUPERSOL is a general purpose program from the Helsinki University of Technology in Finland developed in connection to the evaluation of the Kerava project.

SST is the original stand-alone stratified storage temperature model (Lund Institute of Technology, Sweden). FEM is refering to simulations using the finite element method in connection to the evaluation of the Stuttgart University project. TRNSYS is the well-known set of FORTRAN programs that is developed at the Solar Lab at the University of Wisconsin in Madison, USA.

Merriwether is a building energy systems analysis program used in Canada, and ABES is a special simulation program for buildings using aquifer storage developed and used for the Scarborough ATES project.

3 LESSONS FROM PLANTS IN OPERATION

This chapter represents the collective opinions of the experts participating in Task VII, having first compiled and reviewed experience stated in the national reports for each project. More detailed information can be found in "Lessons from plants in operation" (Dalenbäck, 1988).

3.1 Overall system

Loads less than 500 MWh/a are not suitable for seasonal heat stores due to high relative storage costs and large relative storage heat losses. Whether using solar heating for a sizeable multifamily house, an office building, an industry, a group block of houses or a city, it is necessary to use a central heating plant supply system. The heat distribution system is usually designed as a hydronic pipe network and the heat density in the area of a group of residential units has to be high enough to make district heating economical.

At present, a solar heating plant requires more advanced design methods than does conventional boiler heating system. It must be designed to allow for the following characteristics:

- The heat source (solar radiation) has a **low power density**, which requires a large collector area with small heat losses. However, the output from a stratified (water) storage benefits from a high power density.

- Heat output is **temperature-dependent**, for ambient as well as system temperatures. All temperature levels must be low, especially that of the return water in the distribution system and, therefore low temperature space heating is preferred.

- Heat is supplied at a **low temperature level**, not far above the lower limit of utility. Temperature degradation in each process element must be low.

Solar heating systems are furthermore designed for the **quantity of heat energy** to be supplied, and not for the required power, as is done for conventional boiler systems. The cost of heat provided by solar heating is dominated by the capital cost, which means that a solar heating system must not be over-dimensioned. In a conventional plant operational costs are dominant, which makes the sizing less important.

3.1.1 Planning and design

A new installation designed and built with present knowledge about the solar technology, together with a correct use of conventional heating technology, would perform much better than most existing plants.

Ideally the planning and design of a CSHPSS would be undertaken along with the planning of a new residential building area, especially if roof-integrated collectors are to be used. Thus, new constructions offer the best prerequisites for solar heating. Low temperature space heating systems, in the connected load, are essential for the overall performance and are normally used in new buildings.

If, however, a suitable ground area for collectors, as well as a suitable storage site, is available near existing residential buildings - where it is possible to adjust the existing heating equipment to low temperature distribution systems (change heat exchangers, etc.) - it could be possible to retrofit the buildings with a CSHPSS system. In the short term, the potential demand for such systems might be large. The development of centralized collector systems is more advanced than that of roof integrated or roof mounted collector systems.

In some existing installations the solar collector array and/or the heat store has been added to an existing system without solar. This should be avoided unless the combined design is suitable enough for efficient use of solar heat.

Almost all types of seasonal heat stores are related to the ground, either using the ground material as the storage medium or locating the storage within the ground. This is mainly due to the technical requirements of large scale seasonal stores. Consequently, a careful geotechnical investigation is necessary before a proper heat store can be designed.

A frequently encountered problem is poor coordination between the many different consultants and contractors involved. This is because there are few experts with comprehensive knowledge about complete systems.

Design tools

New plants can now be designed with the benefit of past experiences and the help of proven pre-design tools (for example MINSUN).

A number of the existing plants were designed almost ten years ago. Some were carefully designed, some less so. Advanced pre-design tools (computer simulation models) were sometimes used for parts of the installations (collector, storage), but very few such tools were available for the design of complete plants at that time.

Furthermore, even when a sophisticated design tool was used, in most cases it had never been tested in a real project, as these were among the first of their kind. As a result, the actual performance has often been disappointing.

Solar collectors and heat store

Most of the plants include completely new solar collector designs and/or heat stores. The only plants that have common collectors are Lyckebo, Ingelstad Ib and Ic, while Sunclay and Kullavik have common heat stores.

This means that it has not been possible to use past experience to create a new design in more than two out of eleven described projects. The present experience will create a sound base for future project designs. The same type of collector systems that are used in Ingelstad and Kullavik have already been further developed in other projects without seasonal storages.

Heating plant

Many of the problems concerning operation of these plants are due to an incorrect use of conventional heating technology, rather than incorrect use of solar heating. Several factors contribute to this situation. The new technology is often developed by young and enthusiastic minds lacking experience and knowledge of conventional technology. Old rules of thumb, however, may not always be valid when new technology is mixed with conventional techniques. The design and use of a heat pump in a solar heating application, for example, has to be considered more carefully than has been the case so far.

Simpler and fewer control modes within a less complicated installation are needed in future plants. Due to the R&D nature of CSHPSS projects, some installations are highly complex, as the designers wanted to answer many questions with the same project. The result in many cases is that a number of built-in control modes are never used as they do not improve performance. This has caused many complications in existing installations.

To minimize operational problems it is essential to make careful checks on the functioning of control and piping systems as soon as the construction is completed. Such commissioning is normally done in conventional heating plants, and is essential in an installation with new technology such as solar heating.

The main problems documented result from the difficulty of finding consultants with an interest in, and experience of, all aspects of solar heating. If these problems are to be avoided in future projects, many more consultants with a specialised knowledge of solar heating equipment are needed.

3.1.2 Construction

Most of the installations are relatively small, with a very high initial investment cost. Future plants should be larger for a more economic use of the technology. In general, collector constructions are now far more cost-effective than most of the existing heat store constructions.

Most CSHPSS include completely new designs of solar collectors and/or heat stores, and involve new construction methods. The experience is related to the specific designs, and is presented in the text on collectors and heat stores. Very few conclusions are made for the overall system, as construction aspects are mainly dependent on the equipment used in each individual case.

3.1.3 Performance and operation

With few exceptions, the performance of the plants has been quite acceptable when they are considered as field trials of new designs. Although performance lives up to expectations in some installations, this is not always the case. In some cases the solar collector performances have been over-estimated and the heat store losses have been underestimated.

There are several reasons to this. One is that no proper tools for pre-design studies were used. Other reasons are that incorrect input were used, that the design tool was applied in the wrong way, or that the design tools were not validated. In some cases new construction techniques were tried, not always successfully. The electricity needed for pumps has often not been taken into account.

It is not surprising that performance has not always met expectations since theoretical models used in pre-studies describe performance under ideal conditions. But new, rather complicated installations will not have ideal conditions.

Too many operational problems are related to an incorrect use of conventional heating technology rather than the use of solar heating. For example, many installations include heat pumps which have not performed as well as expected. The solar heating designers have not been knowledgeable enough about heat pumps, and the heat pump contractors have not been well enough informed about the solar heating application. In addition, basic maintenance of the heat pump has sometimes been poor.

Other common problems include water leakages from pipes due to the use of wrong materials or their incorrect application, incorrect flow distribution in solar collector arrays and air infiltration in water circuits. These problems should be avoided in future projects. Collector arrays can be designed with a proper flow distribution, as is conventional in existing pipe networks.

A close and simple regular evaluation with some kind of check-list or manual for use by the operating staff is recommended. It must be possible to detect major malfunctions without being an expert on solar.

It is hard to judge the performance of a CSHPSS without proper monitoring, particularly if a supplementary heating unit (normally a boiler of some kind) is incorporated as stand-by. In the case of a malfunction involving solar collectors, heat store or a heat pump, the supplementary unit usually covers the heating load. Thus malfunctions may not be noticed unless there is a very careful follow-up.

3.2 Collector system

A clear indication that solar heating is in the early development phase is that six out of eleven installations described include new specially-designed solar collectors. Established solar collector dealers normally manufacture small collector modules for DHW-systems and do not yet have a market for large scale applications.

At present, only large scale projects using solar heating with seasonal storage are cost-effective. An installation with a collector area less than several hundred m^2 is unlikely to be feasible when combined with seasonal storage.

All installations, except Lyckebo and Ingelstad, use some kind of roof-integrated or roof-mounted collectors. In densely populated areas these systems seem to have a larger potential, than ground-mounted systems, as the land use is expensive.

3.2.1 Planning and design - Collector

Future designs should be based on validated design tools. The real measured collector performance is close to expectations in some installations, but has been less than expected in several installations. This is in most cases traceable to inadequate design tools.

The collectors to be used in these large scale applications must be designed for the purpose. Conventional collectors used in DHW systems are not relevant in large scale applications. The collectors must be easy to install and connect in large arrays, and the operating and maintenance costs must remain minimal over the long run. The collector investment is always a dominating part of the total investment in a solar heating system.

A collector field design having these characteristics was used in Lyckebo and Ingelstad. These collectors stand on the ground arranged in large modules of about 12 m^2, with a minimum of piping (Ingelstad).

The design and planning of a system with roof-integrated collectors is closely related to the planning and design of the buildings, and should only be applied to new residential areas at the moment. The collector roof must be in a SE- to SW-orientation, and if there are several collector roofs, the buildings should be close together to ensure that the connecting pipes are quite short.

Balancing the capital cost and energy yield against each other, it is considerably more cost-effective, particularly with efficient collectors together with a water storage, to design the solar collector circuit for a low flow rate. This influences the size, and therefore the cost, of the main supply and return manifolds, which has an important effect on the overall capital cost.

At present, it seems that a closed loop with anti-freeze mixture is best for future installations. Experience from several installations in Sweden show that these systems are reliable. One out of eleven installations is designed with a drained collector circuit to avoid thermal inertia losses. The remainder have a closed loop, most of them with anti-freeze mixtures. However, the thermal inertia losses are not as important as the reliability of the operation of the collector system.

3.2.2 Construction - Collector

Swedish collectors were the first to be designed for large scale applications in CSHPSS. Lyckebo and Ingelstad use large module flat plate collectors mounted on the ground. The installation in Ingelstad Ib represents the third generation concerning the design of the collector and the connecting pipes.

The erection in most of the other installations has been time-consuming as most of the collector arrays were made of rather small collector modules with a lot of piping. Roof-integrated collectors systems need to be further developed for applications where several roofs are connected.

3.2.3 Performance and operation - Collector

The actual measured collector performance is close to the design values in some installations and less than design in several others. Inadequate performance is, in most cases, related to the use of inadequate pre-design tools.

A common observation is that snow and dust on the collectors have not caused any problems. Freezing has been detected in a few installations, but this problem is easy to manage.

Other common experiences are incorrect flow distribution, heat losses, leakages in connecting pipes and air in the collector loop. All these problems are manageable with correct and conventional design methods together with the use of proper materials. This has been done in several installations.

3.3 Seasonal heat store

The main heat store technologies to be considered are ground storages and water storages. Ground storages (in clay and soil) have mainly been used for rather small low temperature storage applications, and aquifers have been used for large low temperature storage applications. Water storages (pit and cavern) have been used for small and large high temperature storage applications. Large water-filled pits, boreholes in rock and aquifers can be considered for large high temperature storage applications, but construction and thermal performance have not been properly investigated.

A seasonal heat store is normally underground, as a large heat store above ground is expensive and unsightly near a residential area. Only one of the eleven installations contains an above ground heat store design. Another advantage, with a heat store in the ground, is that the area above the store can be used as recreation area, parking space, etc.

Six of thirteen systems have been designed with a heat store using the ground as heat storage medium in combination with heat pumps, and one system uses ground storage directly (Groningen). Five systems are designed with water heat stores, three of these include a heat pump (Lambohov, Kerava and Stuttgart). One system uses heat stored in an aquifer.

3.3.1 Planning and design - Heat store

A preliminary geotechnical study of the site, including an inspection of ground water flows, should be completed before further design studies are undertaken. If this study is positive, it should be followed by a detailed geotechnical and hydrogeological inspection. It is recommended that the permission of the local ground water control authority is obtained.

Well-validated heat store pre-design tools for the most common types of heat stores, are now available. In order to keep heat store losses in a high temperature (40-90 °C) storage to an acceptable minimum, the storage either has to be of large volume (in the order of 100,000 m^3 water equivalent), or partly insulated. A low storage temperature (10-40 °C) will decrease the losses, even without insulation, but in most cases a heat pump has to be used to "lift" the stored heat to the required temperature levels for space heating and DHW, thus changing the system to a solar assisted heat pump system.

3.3.2 Construction - Heat store

The problem with insulated water stores in the ground is finding an inexpensive combination of insulation and liner that is easy to install and withstands hot water (up to 95 °C). The investment cost for such a storage will be offset by a high usable temperature difference in the storage. Existing plastic liners, such as high density polyethylene (HDPE), are available and have been tested for temperatures above 80 °C, but water transmissivity through the liner is a consideration. The use of metal-coated plastic liners or metal-liners avoid this problem. These materials are, however, expensive and experience from such applications is poor. Further, the placing of the insulation must be properly made to avoid cold bridges.

Another problem is the construction of the lid and the supporting walls (if required). There are different lid constructions. Solid lids (concrete panels on pillars) can be loaded, but are more expensive than floating lids that cannot be loaded. A cost reduction concerning excavation and transport of soil can be achieved if a dam is built on the rim of the pit using the excavated soil ("mass balance"). There is also a question whether or not these storages should be designed as closed systems to avoid biological and chemical problems. The field needs much further development.

The main problem with ground storages is finding an inexpensive method of inserting pipes or boreholes into the ground. Some progress has been reported from Groningen (water jet-injection) and Sunclay/Kullavik (pile-driver in clay), but more development remains to be done. More attention should also be paid to finding appropriate filling materials for vertical boreholes to obtain good heat transfer between pipes and ground. Another problem is that common pipe materials are not suited for high temperature applications.

The construction of very large stores, greater than 100,000 m^3 water equivalent probably requires solid rock to avoid ground water movements, both for boreholes where the depth has to be considerable, or for water-filled caverns. The quality and temperature required is normally lower for applications with boreholes than for applications with water-filled caverns.

The construction of rock caverns and aquifer stores can be regarded as known technology, but both are restricted to sites with suitable geology, and aquifers can in many countries only be constructed in areas which are not protected as sources for drinking water.

All seasonal heat store designs are more or less new and unique designs. The Scarborough aquifer was constructed mainly of wells, using the experience from cooling aquifers to help in the design, and Kullavik was constructed with experiences gained in Sunclay.

More general recommendations concerning construction of water and ground heat stores should be based on experience from construction of a larger number of installations.

3.3.3 Performance and operation - Heat store

A common experience is that the heat losses, mainly from stores designed for relatively high temperatures, have been somewhat higher than expected. The use of inadequate storage design tools has been one cause. In addition, untried storage design and construction methods have also caused higher than expected losses (Lambohov and Lyckebo).

For example, methods of dealing with ground water problems for cavern and pit stores must be improved. Considerable differences between established and real measured heat conductivity values, especially in insulation materials, have also been observed in some installations (factor 2 in Groningen and Vaulruz), and pumping energy for fluid circulation in the pipes in ground heat stores should be given more consideration.

Several arrangements to utilize stratification in water heat stores have been tested. These arrangements have probably added too much complexity and increased control in relation to the improvements gained in the performance.

3.4 Heating plant

Eight of the eleven installations described incorporate the use of a heat pump, and much of the experiences and observations about performance and operation of the heating plants are related to heat pumps.

Because of its large capital cost, an economic use of a heat pump must involve a high utilization time. To some extent this can be compensated for if the seasonal performance factor (SPF) is improved by using a high temperature heat source such as solar collectors. This heat source should, however, be compared with other available sources. Because of pressure limitations, most heat pumps do not work well when evaporator temperatures are too high. Also, there must be a significant temperature rise from the evaporator to the condensor.

3.4.1 Planning and design - Heating plant

A low temperature space heating system is essential for an efficient overall performance of a solar heating plant. The distribution supply temperature will influence the solar fraction. The distribution return temperature will influence the collector performance, the heat store capacity and losses in a solar heating system, as well as the SPF in a solar assisted heat pump system. The distribution system should be designed to avoid by-passing, with resulting high return temperatures. Designers of conventional systems do not always consider these aspects of solar heating.

The control of solar heating plants and their overall system design should not be much more complex than a conventional one. For example, conventional thermostats and regulators are used with good results in at least two of the installations (Sunclay and Ingelstad). These have simple, but quite different, system layouts.

Future projects should employ simpler control systems and strategies so that ordinary operating staffs can learn to use them to their best advantage.

Most of the heating plants described are considerably more complex than conventional heating plants. One reason for this is that the goals of the evaluation program have been too ambitious and thus influenced the design and the control systems. The overall system design and control of heating plants should be considered more carefully.

The utilization time (number of operating hours) of a heat pump is crucial to determining how economic it will be. The heat pump should, with few exceptions, not be rated to supply the peak load requirements. It is also important that established heat pump contractors are engaged under contract to properly service and maintain the heat pump.

3.4.2 Construction - Heating plant

The heating plant must be designed by a competent designer/consultant. The construction, however, should not require any specialized contractors.

The heating plants have been quite expensive due to pilot plant characteristics, small size and the complexity in many installations. A high level of monitoring, in some cases used even for control, has also added to the cost.

3.4.3 Performance and operation - Heating plant

Many of the problems experienced with the heating plants are related to conventional heating technology. A small error in the design of the non-solar parts of the equipment can have a large influence on the performance and operation of the solar parts. The reason is that the solar parts in most cases are more sensitive to heat losses and high temperatures than the conventional parts. A lower than expected performance of the overall system can originate either from a conventional design and dimensioning of the non-solar parts (e.g. heat exchangers with poor efficiency) or from an incorrect use of conventional heating technology in the solar parts (e.g. incorrect flow distribution in the collector).

Eight of the eleven installations include a heat pump, and the majority of heating plant problems are related to its operation, or to the control system. Often the heat pump is too large for the plant, by a factor of three in some cases, which result in short operating periods and problems with the on-off regulation. The use of water buffer storages and partial load operation should be considered together with a careful sizing. Furthermore, ordinary heating plant staffs are not always familiar with heat pumps or sophisticated control systems.

4 NEW PROJECTS

Originally only two new projects were included in the exchange of information and experience within Task VII Phase III, namely the Danish/American project Tubberupvaenge II and the Swedish project Kronhjorten.

When compiling this report it was felt that available information from some other Swedish projects should be included. The Swedish solar heating R&D program has for some years beeen concentrated on the CSHPSS concept, and the accumulated experience from a series of projects is particularly interesting as the CSHPSS experience in most other countries is based on small, single and unique projects.

The Swedish R&D on CSHPSS has two main directions. One is the development of rather small systems, using insulated heat stores and supplying heat to at most a few hundred residential units. The other is the development of large systems, using water-filled uninsulated rock caverns for heat stores and supplying heat to systems serving more than approximatly 500 residential units or a similar load. This line of development is in this report represented by the Kungälv project (previously the Lyckebo project has been reported), while the small system development is represented by Kronhjorten, Malung and Särö.

New CSHPSS projects have also been considered in other countries and feasibility studies are under way, in the U.S.A. (Bankston and Breger, 1989), in Switzerland and in the FRG, where a new full-scale demonstration project is being considered.

4.1 Small CSHPSS in Sweden

The evaluations of the solar heating plants Ingelstad I and Lambohov (1980-83) showed that cheaper and better solar collectors and heat stores were required to make solar heating with seasonal storage competitive with conventional smaller heating plants for 100-500 residential units.

A new solar heating plant, with a newly developed large module flat plate collector, was then built in Lyckebo. The heat store used is an uninsulated water-filled rock cavern with a promisingly low investment cost. This kind of heat store has, however, to be of the order of 100 000 m^3 or larger to be feasible. The techniques to build smaller insulated heat stores, available at that time, were still too costly.

The evaluations, including Lyckebo, revealed substantial scope for cost reductions in the system design, particularly the piping and control. A pre-study for a new smaller solar heating plant was initiated, with the objective of designing a cheap insulated heat store and a cheap and simple system, as the existing new collector design looked promising. The heat store should be placed near or under the ground surface so that the upper area can be used for other purposes, as this kind of storage is usually built close to residential building areas.

Another pre-study for a larger solar heating plant, for the town of **Kungälv**, was initiated. The Kungälv study is based on the same collector design as in Lyckebo and a new simplified system design. The plant size is large enough for some thousands of residential units so that a rock cavern heat store, similar to that in Lyckebo, can be used.

The concentrating collectors in Ingelstad I were replaced after 5 years with improved flat plate collectors and the system was rebuild in order to test the performance of the new simplified system design approach.

Ingelstad I has thus been used as a testing ground for new collectors and a new system design, using the original heat store. To test a new heat store design, a totally new system was studied close to Ingelstad I. This study was based on a district heating investigation from 1980, that had shown that it was possible and economic to connect existing buildings in the centre of the Ingelstad village to one central heating plant. This pre-study (Ingelstad II) was presented at an Task VII expert meeting in Gothenburg in March 1985.

The Ingelstad II project would incorporate the Ingelstad I flat plate collector, and an insulated water-filled rock pit with self-supporting top, quite similar to the insulated rock pit developed at Lambohov, and would supply heat to an existing residential building area.

The pre-study included computer simulations with established simulation models SIMSYS and MINSUN as well as SUNSYST. To be able to cover around 70 % of the total calculated annual heat load of 1 800 MWh, a solar heating plant with about 4 000 m^2 flat plate collectors connected to a new type of insulated water-filled rock pit, with a volume close to 10 000 m^3, was suggested.

A small (30 m^3) test pit was built and a comprehensive design study for this new pit concept was carried out. The design study showed that it should be possible to build an insulated rock pit for around 300 SEK/m^3 (10 000 m^3) at the suggested site (1 US$ = 6.80 SEK, June 89). This can be compared with the cost for the concrete tank in Ingelstad I, the insulated rock pit in Lambohov and a conventional insulated steel tank, all at least twice as expensive. A rock cavern is much less costly, having an investment cost around 140 SEK/m^3 (200 000 m^3).

However, since a 10 000 m^3 pit was too large for the first trial, a new site for a pilot pit had to be found. One suggested site was in Växjö and the pilot plant **Kronhjorten**, with a 800 m^3 pit, was realized during 1987. The Kronhjorten plant is simply a small-scale version of the Ingelstad II plant, and would supply heat to a new office complex with low temperature heat supply requirements.

Two other design studies where carried out along with the Ingelstad II study and are now realized as experimental projects. The **Särö** project is a pilot plant where the storage design will be based on the experiences from the Kronhjorten pilot pit. Roof-integrated solar collectors will be used, as the Särö project contains a new small residential building area. The system concept with roof-integrated collectors in combination with a water pit storage, as in Lambohov, is looked upon as a promising system concept for new small residential building areas.

The **Malung** study was carried out for an existing residential building area similar to Ingelstad II, using MINSUN. The total annual load was estimated to be 2 200 MWh and a plant comprising 5 500 m^2 site-built flat plate collectors connected to a new type of water-filled earth pit, with a volume close to 10,000 m^3, was suggested. The solar coverage was estimated at 55 %. Such a large pit was, as in the case with Ingelstad II, considered to be too large to build in the first trial, and a pilot-plant was suggested instead.

A site-built collector field has now been connected to the existing heating plant and a pilot-pit is under construction to be used as a diurnal storage. The design of the pit is based on the design in the early pilot-pit in Studsvik.

References to these new pilot-plants can be found in the Swedish National Evaluation Summary in the Appendices.

4.1.1 Pilot-plant Kronhjorten

The **system design** is partly new, and is similar to one that was tried out in practical trials in the Nykvarn district heating system in 1985, and then fully implemented in the second redesign of Ingelstad I in 1987.

The solar collector circuit usually contains a glycol and water mixture, though synthetic oil is used in Kronhjorten. It is separated from the heat store by means of a heat exchanger. The collector circuit is designed for a low constant flow rate and a high temperature rise of up to 40 °C across the solar collectors, at high irradiation power levels. Inward flow to the heat store can be directed to two levels, depending on temperature, with the return flow being taken from the bottom of the store. The discharge circuit is separated from the collector circuit, and can exstract its flow from two levels, returning it to the bottom.

The **solar collector** used is a more advanced version of the large module high temperature flat plate collector type previously used in Lyckebo, Ingelstad I and Nykvarn. This collector is a 12 m^2 module, using Sunstrip absorber, and a convection barrier in the front that consits of tetra polyflour ethylene foils (TPFE or Teflon). The collector in Kronhjorten has only one foil, compared to two in earlier designs, and has the same thermal performance.

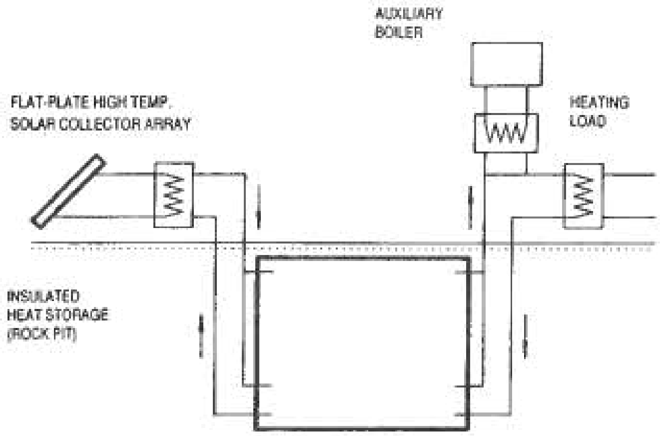

Figure 4.1 Schematic diagram of the Kronhjorten pilot-plant.

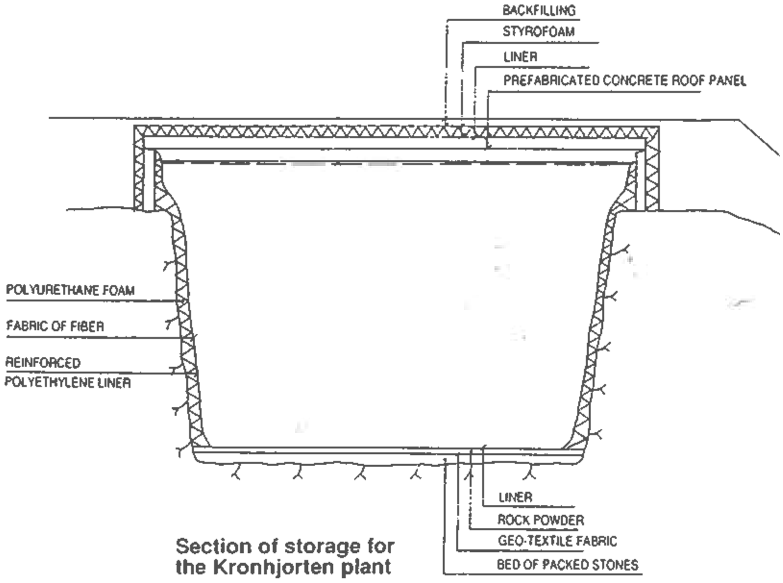

Figure 4.2 The Kronhjorten pilot-pit.

The **heat store** is a water-filled insulated rock pit with a self-supporting top. The pit is excavated in rock. Concrete edge-walls are used as support for a self-supporting top consisting of pre-fabricated concrete hollow slabs. The walls are insulated on the rock with spray polyurethane, having a high density composition of 65 kg/m^3. The top is insulated with styrofoam blocks on the outside. For inside water-proofing a medium density polyethylene (MDPE) liner is used.

The **load** will be space heating and DHW for an office building with 2 500 m^2 of heated floor area. The office is calculated to have an annual heat requirement of the order of 70 kWh/m^2, which gives a total annual load of 170 MWh, including DHW and distribution losses. The space heating system is supposed to be a low temperature hydronic radiator system; a supply temperature of 55 °C is required at a design ambient temperature of -18 °C. The characteristic supply temperature requirement is 50 °C for DHW, and the characteristic return temperature is 35 °C. The distribution network will be insulated iron pipes in the ground.

The **system operation** is quite simple, and ordinary difference thermostats are used. The solar collector circuit and the charging circuit (constant flow rate) is put into operation when the temperature on one representative absorber is higher than the temperature in the bottom of the store. The charging flow is either directed to the top, if the temperature is higher than 70 °C, or to the lower input level if the temperature is lower.

The discharging circuit (variable flow rate) is in operation if the temperature in the store is higher than the return temperature from the load (return pipe). The flows from the top and the lower level are mixed to the required temperature level. An oil boiler is in operation when the temperature in the top of the store is lower than the required supply temperature to the load, and controlled to maintain the required supply temperature by means of a shunt.

Thermal performance calculations for the Kronhjorten plant were carried out at an early stage. The calculations were made with the simulation model SIMSYS. Evaluations of the Lambohov rock pit heat store and the Ingelstad I flat plate collectors had already been used to validate this model.

Simulations were made for an average climatic year and an estimated heating load of a 2 500 m^2 office building. 400 m^2 of large module flat plate collectors and 1 200 m^3 water heat store is expected to give a desirable solar fraction of the order of 65 %. The actual built pilot-plant consists of 450 m^2 collectors, which is related to the collector field design. The heat store volume is only 800 m^3 resulting from problems with the construction. The actual sizing will be calculated when more detailed information about the heat load becomes available.

Construction problems delayed the opening of the plant from May 1987 to late that year. The construction of the office building has also been delayed and the plant is at the moment operated for research purpose only, mainly to study heat losses from the store, and different liner solutions.

The liner installation was another cause of major delays and problems. The liner was not water tight, partly due to unforseen difficulties in mounting it, and partly due to damage caused by mishandling the material. Many small holes of around 1 mm were found after an investigation.

It was decided to accept a certain degree of leakage for some months, to investigate the thermal performance of the pit, such as heat losses and insulation performance, and then change the liner to a new type. The exchange will take place during 1989, together with an optical inspection of the insulation.

The use of spray polyurethane seems, so far, to be an appropriate insulation method, if an appropriate technique is used. The liner technology has, however, to be developed, and some liner material investigations will be done before the exchange of liner in the pilot-plant. The aim is to have a liner that can be used for temperatures up to 95 °C.

Excavation, concrete-work, insulation and liner installation should be contracted separately for a new pilot-plant, as the construction procedure is known more in detail now. This will make it easier to get fixed contracts and thereby decrease the investment cost and establish guarantees for each part of the installation work.

The collector field has been in operation for one year, and the collectors have endured stagnation a whole summer and two winters without any visible degradation.

The Kronhjorten pit design is only appropriate at a site with high quality rock, which was not the case in Kronhjorten. Since high quality rock cannot be found everywhere and and as the rock quality, in a certain site, only can be determined after extensive ground investigation, research has now been directed towards finding a more universal pit design.

4.1.2 The Särö project

A plant using roof-integrated collectors is under construction for a new small residential building area in Särö. The collector area is 700 m^2, and the calculated solar fraction is 60-65%. The rest is supplied by a wood pellet-fired boiler. The collectors are financed using the same kind of governmental building loans as the houses, while the storage is financed by experimental building loans.

The **solar collector** used is a more advanced version of the roof-integrated collector type previously used in several projects (Sunstrip absorber, acrylic cover). The collector in Särö is complemented with a convection barrier (TPFE-foil), thus improving the thermal performance with high temperature difference in the heat store.

The **heat store** is going to be a water-filled insulated rock pit of about 1 200 m^3 with a self-supporting top similar to that at Kronhjorten. The type of insulation and water-proofing liner is not yet decided. A spray polyurethan insulation may be used in combination with plastic sheets (HDPE, TPFE) or reinforced spray concrete as water-proofing liners. Another alternative is to use a conventional steel tank and use lightweight concrete (Leca), or a mixture of mineral wool and concrete, as insulation material. The pit excavation is alredy done and the construction will be completed in the end of 1989 or beginning of 1990.

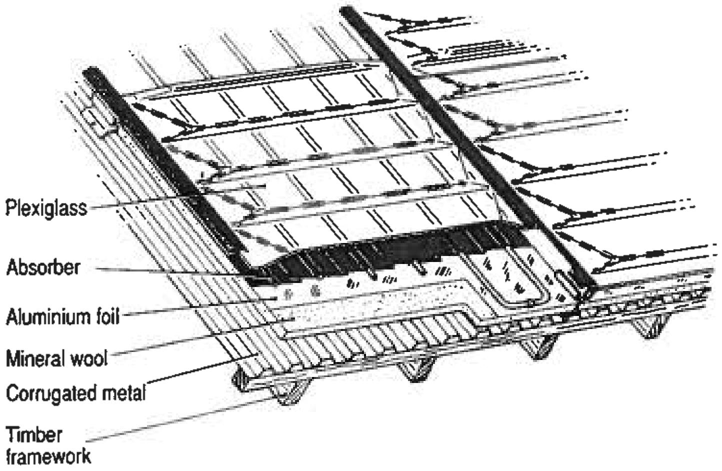

Figure 4.3 Roof-integrated collectors. The collector in Särö will have a convection barrier (TPFE foil) between the acrylic cover (plexiglass) and the absorber.

The **load** is space heating and DHW for a small residential building area with 44 flats in multifamily houses. The houses are calculated to have an annual heat requirement of the order of 440 MWh, including DHW and distribution losses. The space heating system is a low temperature hydronic radiator system with a 55 ^{0}C supply temperature required at a design ambient temperature of -18 ^{0}C. The characteristic supply temperature requirement is 50 °C for DHW, and the characteristic return temperature is 35 ^{0}C. The collector and heat distribution networks will be insulated iron pipes in the ground.

The **system operation** is the same as in Kronhjorten. The system in Särö will be in operation with a short-term storage until the construction of the seasonal storage is finished.

4.1.3 Pilot-pit plant in Malung

The Malung pit is another type of pit construction in ground. The pit is quite small and it will be used as a short-term storage. The main feature is the new liner of copper. An existing collector field is used to heat the storage, and the heat load is an existing residential building area.

The **solar collector** used is a 70 m long ground mounted, site-built, flat plate collector with the same basic design as in Kronhjorten (Sunstrip, TPFE-foil). The collector area is 600 m².

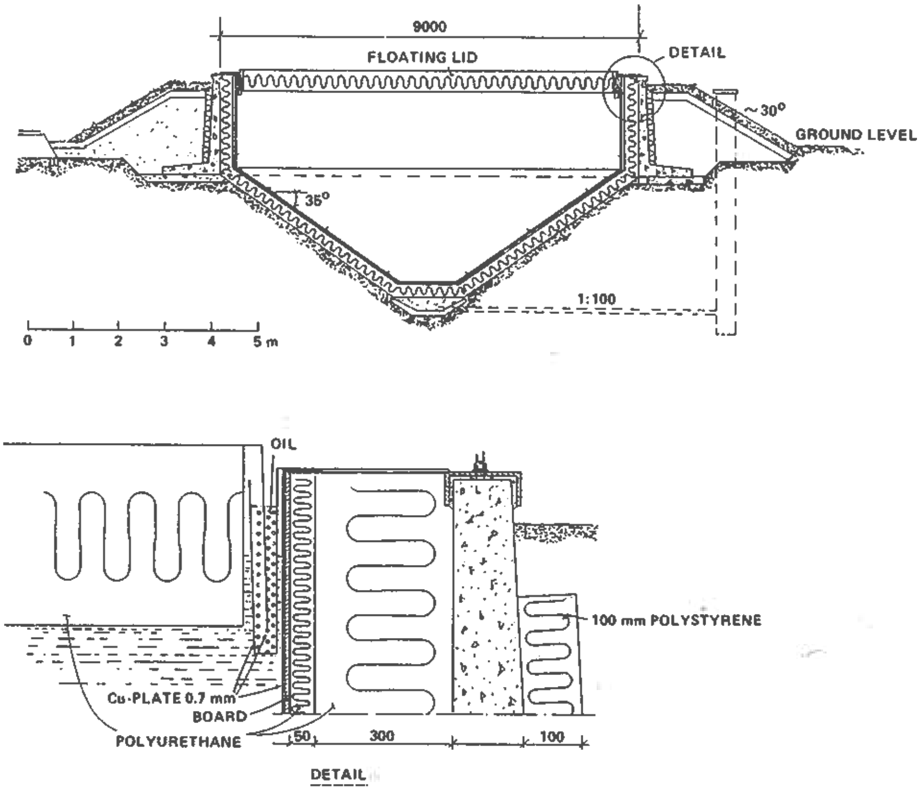

Figure 4.4 The Malung pilot-pit.

The **heat store** is a water-filled insulated earth pit of 350 m³ with a floating top. The excavated earth is used as filling material outside concrete edge-walls. The walls will be insulated with polyurethane blocks. The water-proofing liner is made of thin copper plates welded together at the site.

The **load** is space heating and DHW for a small residential building area with 200 flats in multifamily houses. The houses have an annual heat requirement of the order of 2 200 MWh, including DHW and distribution losses. The space heating system is a conventional hydronic radiator system with mideum temperature requirements of around 60 °C most of the year.

The **system design and operation** is quite similar to the one in Kronhjorten. The pilot-pit in Malung will, however, be in operation as a short-term storage together with an existing electric boiler.

4.2 The Kungälv study

On a national level, it is estimated that around 150 to 200 large scale solar heating plants could meet 10 % of the annual energy requirement for DHW and space heating in Sweden.

A plan has been developed to introduce district heating on a wide base in the town of Kungälv in the west of Sweden. The initial project phase, a design study of the technology and economics for a large solar heating plant planned to be in operation in the 1990's has been completed (Claesson, et.al. 1988). The essential aim of the project is to present a feasible system concept featuring a substantial part of solar heat for the building stock in the town.

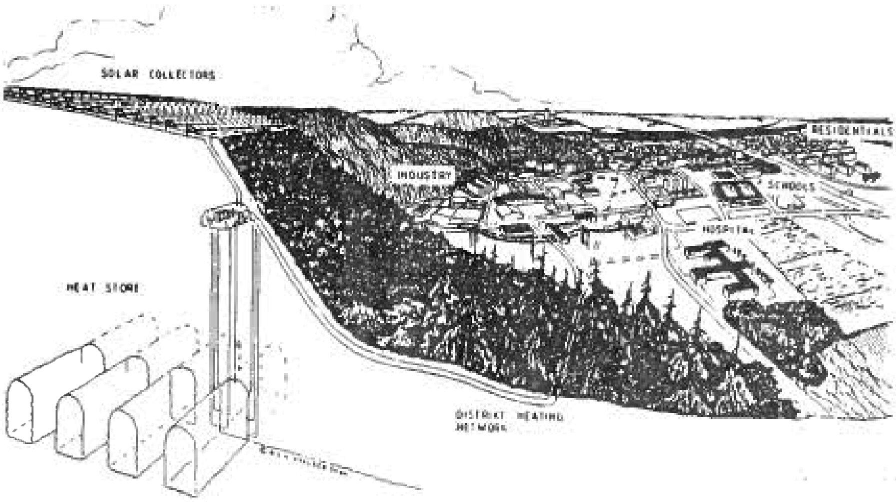

Figure 4.5 View of the planned Kungälv project.

Since the middle of the 1970's there has been a significant progress in the Swedish development of large scale solar heating technology. At present, four

Swedish CSHPSS with water storage are in operation, and the comprehensive experiences gained, especially from Lyckebo, have been utilized for the planning of the Kungälv plant.

The preliminary outlined plant design employs 126 000 m^2 of high temperature flat plate (HT FP) solar collectors and 400 000 m^3 of water-filled rock caverns for seasonal storage. The plant would be connected to an extensive district network, in total 9 800 m piping.

At present, about 90% of the heating demand for the buildings in Kungälv is produced by oil-fired boiler plants. The annual heat demand has been estimated to 56 GWh for space heating and DHW in the 1990's. About 60% is required for residential houses comprising 6 000 inhabitants. The remaining 40 % is required for commerce, municipal service and light industry buildings, comprising 115 000 m^2 of heated building area.

The existing heating plants, 15 multi-building and 30 single-building plants, will be replaced by service units connected to an extensive district heating network, which requires lower supply and provides lower return distribution temperatures than normally supplied by heat from a central plant.

4.2.1 System design and performance

The design objective is to meet 75% of the annual heat demand by solar heat. The rest is expected to be met by heat from high grade fossil fuel. If natural gas boilers are used NO and CO_2 is reduced by 80 %, while other pollutions from the existing oil burning boilers are completely eliminated.

The choice of a suitable **solar collector** is facilitated by Swedish developments in large scale solar heating technology since the beginning of the 1980's. Rapid developments in the field of HT FP collectors have taken place. Thermal performance standards have been improved and collector array costs have been lowered to great extent. These collectors are suitable for use at 70 °C, the intended average operating temperature in the Kungälv installation. It appears possible to design for around 360 kWh/m^2 of annual thermal yield.

Water-filled rock caverns will be used as seasonal **heat stores**. The water temperature in the caverns range from from 40 to 90 °C. A temperature swing of the order of 50 °C is possible through the use of HT FP collectors in combination with low district heating system temperatures. The expected top layer maximum temperature is expected to be 90 °C in a normal year, while 105 °C is reached in a year combining high solar radiation and moderate winter temperatures.

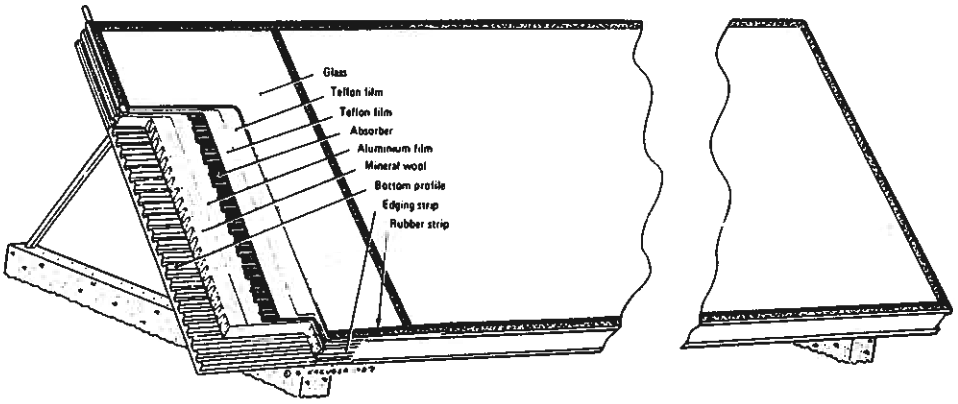

Figure 4.6 The large modular high temperature flat plate solar collector earlier used in Nykvarn and Ingelstad Ib.

The choice of a suitable heat store has been based on Swedish experience of underground building technology, and science in geology and hydraulics. Blasted water-filled rock caverns have been compared to boulder and water-filled rock caverns, deep vertical ducts and ducts combined with water-filled rock tunnels. Essential aspects treated are; structural mechanics, hydro chemistry, thermal performance and economics.

The best alternative appears to be water-filled rock caverns, because of good abilities to maintain thermal stratification, small thermal mass, large heat storage capacity, and no severe hydro-chemical problems. The building technology for rock caverns is very well known from the field of crude oil storage. A 100 000 m^3 water-filled rock cavern, constructed in a similar way, has been in operation for five years for seasonal storage of solar heat in Lyckebo.

The system operation is quite simple and similar to the system operation in the Kronhjorten plant.

4.2.2 Economics

The calculated total cost of heat generated in the Kungälv plant is 62 US$/MWh (420 SEK/MWh, June 89) including capital costs, supplementary fuel cost (natural gas) and district heating network. The cost assumes a solar coverage of 75 %. The heat cost corresponds to a collector system cost of 164 US$/$m^2$ (1 115 SEK/m^2) and a heat store cost of 15 US$/$m^3$ (105 SEK/m^3). The additional cost for piping and equipment, including the boiler plant, represents about 10% of the total collector and heat store cost.

The cost assumes further 4 % real interest rate, an economic lifetime of 40 years for the heat store, 20 years for the collectors and 15 years for the rest of the plant. The total investment cost amounts to 39 000 US$ (264 million SEK), out of which about 53% corresponds to the collectors, 19% to the heat store and 18% to the district heating system.

The solar heating cost has been compared to present cost of employing many individual boiler plants using oil and other conventional fuels. The main new alternative is a district heating plant with natural gas boilers, and a heat cost of 44 US$/MWh (300 SEK/MWh).

At present, solar energy costs are not as competitive as those of 100 % fossil fuel plants. However, a comprehensive cost analysis must include an estimate of long-term changes. As global reserves of fossil fuels shrink, prices are likely to increase. Local environmental problems caused by pollutants are attracting a growing attention. The impact of these changes is already being felt and will affect fossil fuel costs in the future.

Already the Swedish authorities are considering pollution fees for fossil fuels. Numbers in the order of 7-15 US$/MWh (50-100 SEK/MWh) have been discussed which would close the gap between fossil fuel and the solar heat costs after further development of solar technology. Studies in the Kungälv case shows that it is possible to lower collector costs down to the order of 100 US$/m^2 (700 SEK/m^2), if industrial manufacturing methods are used. In that case the solar heating alternative should be fully competitive during the next decade.

4.3 The first Danish CSHPSS

Tubberupvaenge II is a housing project near Copenhagen comprising 8 blocks with a total of 92 housing units in all (Ussing, 1989). Financing of the energy system employed in the project is supported by the CEC and the Danish Government as a demonstration project. It has been studied in this Task jointly by the US and Danish experts. The project has been under design 1986-88 and will be constructed 1989-90. It is the first CSHPSS system in Denmark.

It is the purpose of this project to demonstrate the important reduction in energy consumption achieved by application of all the present day technologies of energy conservation, using active as well as passive solar energy. Thus, the design of the houses, as partly passive solar houses, has been an important part in the design study.

The heating plant consists of a central plant comprising 1 050 m^2 high temperature flat plate solar collectors with a 3 000 m^3 water-filled pit storage, a natural gas driven heat pump and a natural gas fired boiler. To reduce distribution costs in the warm half of the year 8 local solar plants, each comprising 46 m^2 roof integrated solar collectors and a 2.6 m^3 storage tank, has been planned to heat DHW and radiators in individual units during that time.

The estimated winter heating requirement should not surpass 604 MWh. The winter season DHW load is estimated as 114 MWh. Local losses and distribution losses in the same period comprise 80 MWh, thus making the winter season load 798 MWh out of a total annual load of 1 016 MWh. The central solar plant is planned to contribute to the coverage of the winter season load, while the local plants contribute to the coverage of the summer season load. The solar fraction of the combined plants is expected to be about 64 %.

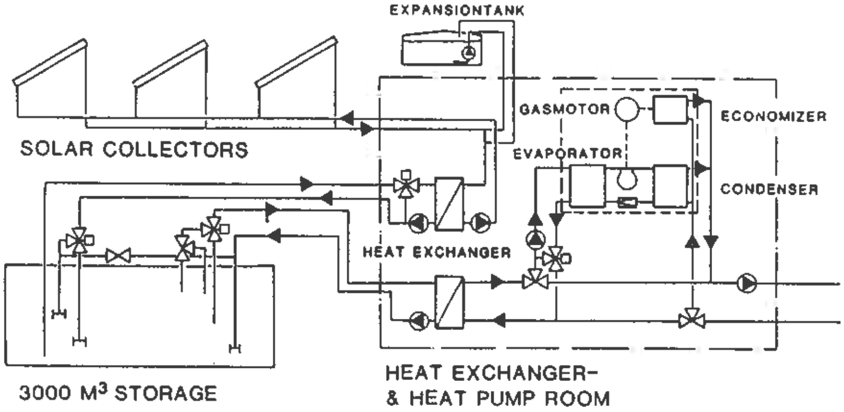

Figure 4.7 Schematic diagram of the Tubberupvaenge II central system.

5 GENERIC SYSTEMS STUDY

The aim in Phase III was to make a more detailed analysis and presentation of a few promising systems, following the wider general analysis of Phase II (Bankston, 1986). The work was concentrated on two generic system configurations that were found to be of major interest among the participating countries; Solar heating systems with high temperature flat plate (HT FP) collectors and seasonal storage in water or the ground. The simulations for these two systems have been carried out with MINSUN using updated cost data together with the experience gained from the national evaluations concerning system design and validations of the simulation program MINSUN.

A third generic system has also been studied during Phase III: A solar assisted heat pump system with unglazed collectors and an aquifer storage. This system was regarded as one of the most promising CSHPSS concepts in Phase II, but it had not been possible to make the same comprehensive analysis for this system as for the others. The aim in Phase III was to supplement the earlier analysis.

5.1 Background

During previous work within Task VII, it was found practical to evaluate the design configurations and economy of CSHPSS according to families of plants with common features. These features were mainly the storage type to be used in the system. This approach was quite natural as CSHPSS was a new technology and the main difference compared to other solar heating systems is the seasonal storage. The storage type and the storage temperature also influences the rest of the system, the type of solar collector suitable to heat the storage, the use or nonuse of heat pumps, recommended flow rates, etc.

Five CSHPSS systems related to the storage type were defined and used during Phase II; duct, cavern, pit, tank and aquifer. Cavern, pit and tank storage systems all used water as the storage medium and the evaluation was thus done for three main system types. The main characteristics of these systems are summarized as follows.

The minimum storage temperature is usually limited by freezing (0 °C) in a system with heat pump and by the dominating return temperature in the heat distribution system in a system without a heat pump.

Water storage systems: The storage medium is water. This type of storage has a high volumetric heat capacity and a high charging/discharging capacity. The storage medium can also be water mixed with some other material, for instance gravel in a pit or cracked pieces of rock in a rock cavern.

The system can make use of the temperature stratification, both for charging and discharging. The storage maximum temperature is mainly limited by the collector type but also by the liner material and the pressure permitted. High temperature (HT) collectors are suitable for charging, which makes it possible to discharge the storage without the assistance of a heat pump.

Tank and pit storage might be fully or partly insulated, and very large scale cavern storage may be uninsulated. The investment cost is dominated by excavation, construction and insulation.

Ground storage systems: The ground itself, whether soil, sand, clay or rock, offers storage capacity if heated up in a suitable way. This type of storage has, in general, a low to medium volumetric capacity and a low charging and discharging capacity, related to the heat exchanger surface in the ground. Therefore, a buffer storage of water is often used in combination with these stores when charged by solar collectors (high charging capacity).

The heat must be transferred to the ground by means of vertical (or horizontal) pipes or ducts forming a closed water loop. The maximum storage temperature is in most cases limited due to soil conditions and pipe material durability, and it is hard to develop and use any essential stratification in the storage volume. Low temperature (LT) collectors or unglazed (UG) collectors are suitable for charging, and discharging is normally assisted by a heat pump.

High temperatures are possible in large ground storages (especially rock). This makes possible the direct use of the storage without a heat pump. HT collectors are suitable for charging, in this case.

This storage type is usually uninsulated except for the ground area above the pipes that is exposed to the outdoor temperature, and the investment cost is dominated by the depth, the number of pipes and the insulation.

Aquifer storage systems: Aquifers are natural bodies of water-carrying soil embedded between layers of clay or other tight soil types. Aquifers have a medium to high volumetric and charging/discharging capacity.

The natural water flow rate of aquifers should be low in order to keep heated water within the storage region. Aquifer water is commonly pumped from a supply well, through a heat exchanger, and fed into a companion recharge well in a closed loop. The flow resistance should be low enough to take water out or supply water to the aquifer with sufficient capacity.

The maximum storage temperature in an aquifer is often limited due to chemical reactions of heated water with soil, and due to heat losses. HT, LT and UG collectors are, however, suitable for charging, but discharging is normally assisted by a heat pump. Aquifers cannot be insulated, and the investment cost is dominated by the drilling and development of the wells.

5.2 Analysis in Phase III

The CSHPSS systems are here defined as **solar heating systems** and **solar assisted heat pump systems.** This classification of systems is based on the operation principle of the system from the user's point of view. The main reasons to make these distinctions is that a system with a heat pump can be operated using heat sources other than a solar heated storage. The main characteristics of the generic system categories are summarized as follows.

5.2.1 Introduction

A **solar heating system** with high temperature collectors and a high temperature storage is a straightforward system which can supply a high solar fraction of the load and requires only a supplementary boiler to cover the peak load.

Systems using a solar heated storage in combination with a heat pump are defined as **solar assisted heat pump systems**, and require drive energy for the heat pump, as well as a supplementary boiler to cover the peak load.

Both types of systems would of course be economic if the total cost of heat supplied by the system is comparable to the total cost of heat supplied by other available heat supply systems. Solar heating systems would certainly also be economic if the annualized cost of heat from the solar collector and storage system (solar cost) was comparable to the cost of competing supplementary fuels available. A supplementary boiler (normally a fossil-fuel boiler) is anyhow needed and designed to meet the peak load in most cases.

Solar assisted heat pump systems should be compared to other heat pump systems. MINSUN cannot handle other heat sources than solar, and thus only the total cost for solar assisted heat pump systems is presented in this analysis.

Figures 5.1-5.3 show the primary energy used in three different CSHPSS systems assuming that electricity is generated in a fossil-fuel power plant. One is a solar heating system with high temperature collectors and storage (direct to load). The other two are solar assisted heat pump systems with low temperature collectors and storage, one with an electrically driven heat pump and one with a gas engine driven heat pump. The systems are all supplying the same load. Further, the collector efficiencies and the storage efficiencies are assumed to be the same in all cases.

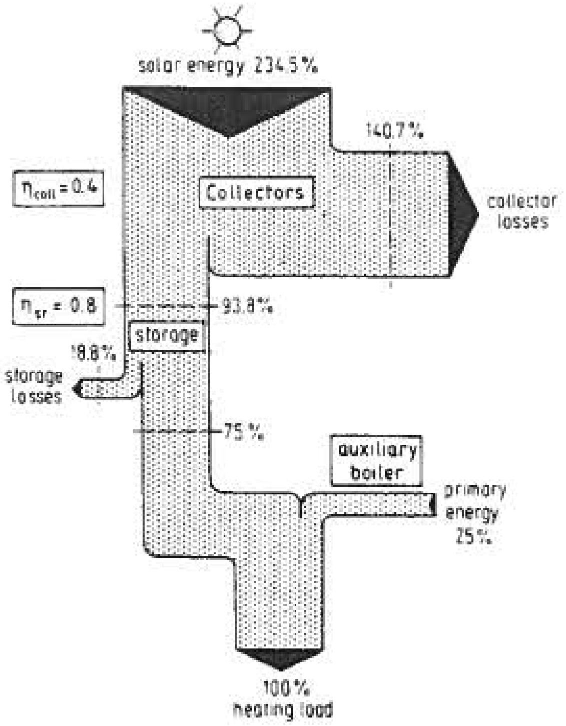

Figure 5.1 Energy flow diagram for a solar heating system.

A solar heating system is able to save a lot of primary energy when it is combined with a fossil-fuel boiler as shown in Figure 5.1. Solar assisted heat pumps, using fossil-fuel generated electricity as drive energy, may save no primary energy (Figure 5.2). Natural gas and diesel driven heat pumps consume less primary energy than electrically driven ones, under these assumptions (Figure 5.3).

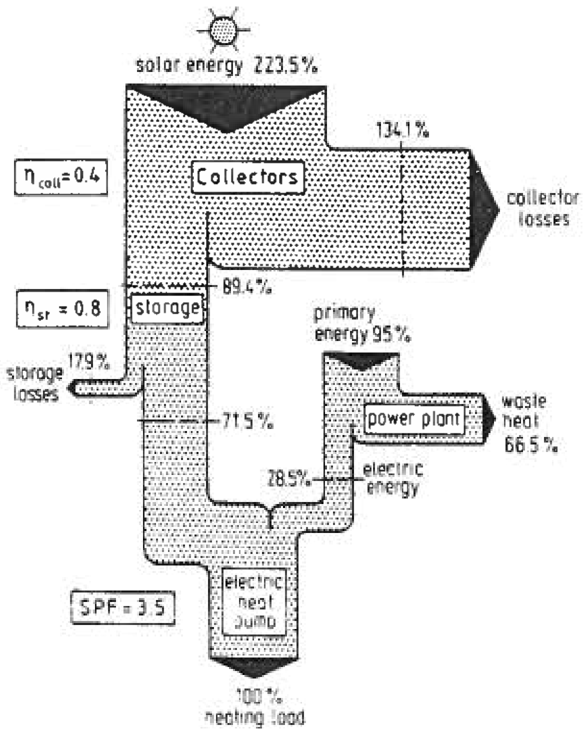

Figure 5.2 Energy flow diagram for a solar assisted heat pump system with an electric driven heat pump.

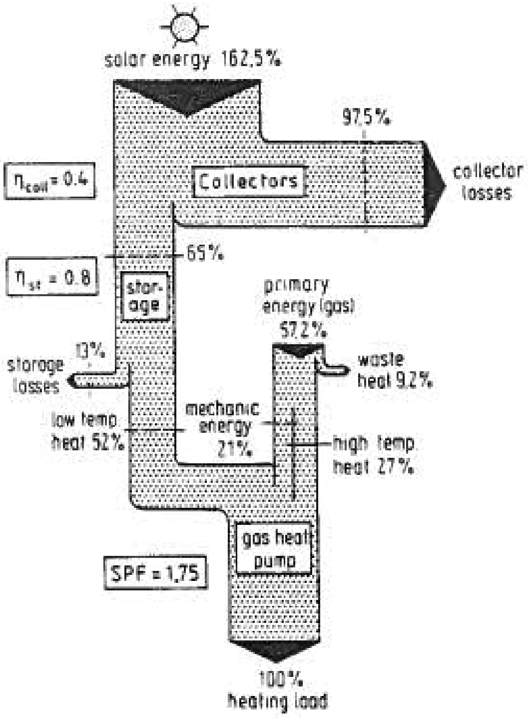

Figure 5.3 Energy flow diagram for a solar assisted heat pump system with a gas driven heat pump.

5.2.2 Description of the solar heating systems.

Two solar heating system configurations have been chosen for the analysis during Phase III. One with high temperature flat plate collectors in combination with water storage and one with the same type of collectors in combination with ground storage. Simple schematic drawings of the system configurations are shown in Figures 5.4 and 5.5.

The system with water storage includes mainly two types of storages, pits and caverns. The systems with ground storage include mainly two types of ground storages; vertical pipes in soft ground and boreholes (with or without pipes) in hard ground (i.e. rock).

The **solar collectors** used are High Temperature Flat Plate (HT FP) collectors already on the market. The collectors can be placed on the ground, or integrated in the roof in the case of new installations. Collectors used in Lyckebo, Ingelstad, Kronhjorten and Malung are examples of the ground mounted type. The collector in Särö is an example of the roof-integrated type.

The tilt of the collectors is between 30° (lat 40°) and 45° (lat 60°). The performance parameters used are better than the performance parameters used for flat plate collectors during Phase II, as shown in Table 5.1. The array factor is the relation between ideal collector module performance and actual collector array performance.

Table 5.1 **Collector parameters**

Parameter	Phase II	Phase III
Optical efficiency ($F_R \tau \alpha$)	0.81	0.75
Operating U-value ($F_R U_L$)	4.40	2.90
Array factor	0.66	0.88

Evacuated tube (ET) collectors have not been considered in this analysis due to present unfavorable costs, but might be considered in future analyses. Large concentrating parabolic trough (CPT) collectors might also be considered in future analysis concerning ground-mounted collector arrays.

The **pit storage** (Walletun and Zinko, 1988) is partly insulated on the top and part of the side, and filled with pure water or a mixture of water and gravel (Fisch and Hornberger, 1988) that can be heated up to 95 °C (constraint). A pit storage may be constructed in both hard and soft soil as well as in rock. The storage is considered to be 12 m deep and cylindrical (cylindrical model in MINSUN), which is a good estimation in this analysis, but this depth does not apply to pits with volumes less than some thousands of m^3.

Such a construction has not yet been developed for the market, but the performance and the cost are based on the existing experimental designs at Lambohov, Stuttgart, Kronhjorten and Malung. The recently designed small pilot plants in Sweden and Denmark are examples of new systems with pit storage.

The **rock cavern** (Walletun and Zinko, 1988) is similar to those used for storing crude oil, which exist in some countries in granite or gneis. Maximum temperatures are 100 °C or even somewhat higher. The storage is considered to be 30 m deep, cylindrical (cylindrical model in MINSUN), and situated 20 m below the ground surface.

One cavern used as heat storage for solar heat and off-peak electricity exists in Lyckebo, another rock cavern has been used for waste heat storing in Avesta and a few new Swedish projects are planned or under construction for operation as short-term heat stores. The proposed Kungälv plant is an example of a new system with rock cavern storage.

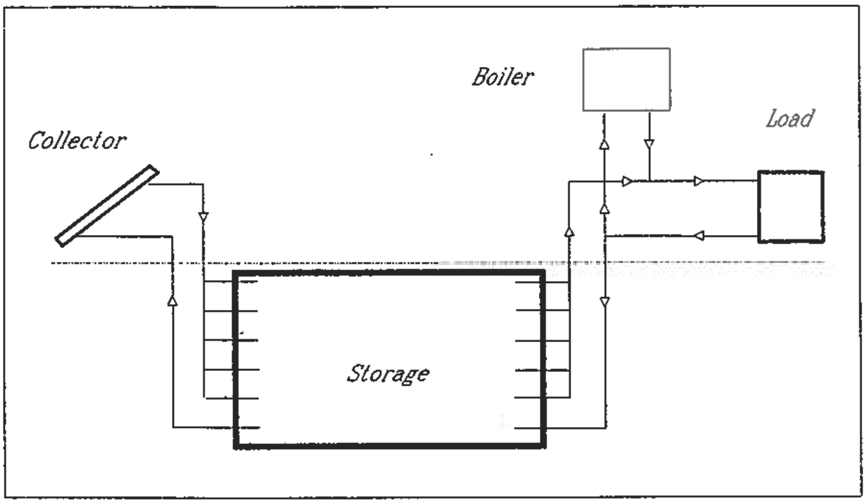

Figure 5.4 Schematic drawing of the solar heating system with water storage.

The **ground storage** (Jaboyedoff, 1989) can be defined as a vertical pipe or duct storage in soil or rock, that can be heated up to 90 °C (constraint). The ground storage is insulated only on the top. Two levels of investment costs for different ground conditions and pipe sizes have been analyzed, as this kind of high temperature ground storage is very site specific and there is real experience from two large scale installations; Groningen uses soil storage and Luleå rock storage.

Ground storages can be constructed in many different ways depending on soil conditions. Boreholes can be drilled in rock and hard soil, and pipes can be pushed into soft soil with the help of vibrations, water injection or pile-drivers. Closed water loops, using plastic pipes, can be used in all types of ground, while open water loops can be used in boreholes in tight rock.

The system performance is influenced by the number of boreholes, their depth and diameter, the number of pipes in the borehole, the heat transfer coefficient between the pipe and the soil and the soil characteristics. A large number of boreholes with a large diameter will increase the performance, since the collector can operate at a lower temperature. This analysis is made for a borehole diameter of 0.10 m. The thermal performance of such a borehole is equivalent to a common plastic U-pipe with a distance of 0.20 m between the pipes. The analysis include sensitivity analsyses for three different ground materials with different characteristics as volumetric heat capacity and thermal conductivity.

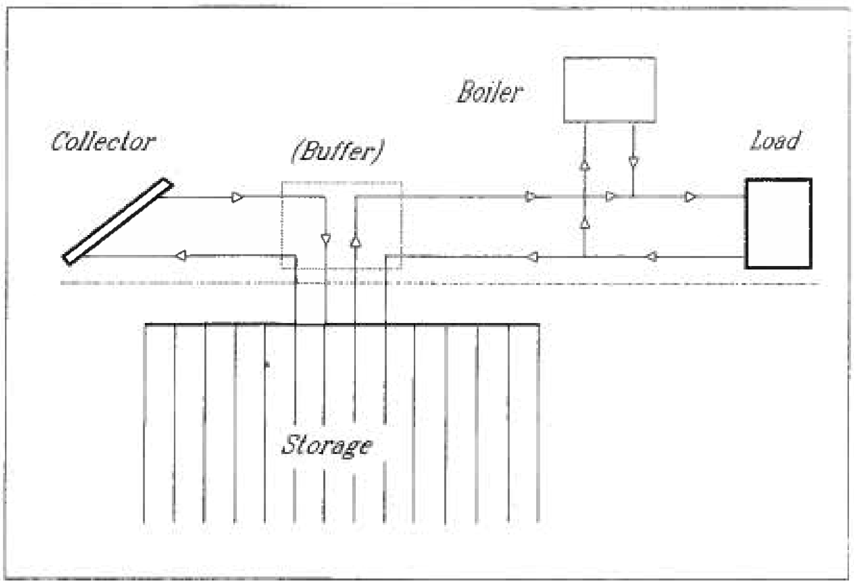

Figure 5.5 Schematic drawing of the solar heating system with ground storage.

The storage is considered to be 25 m deep and cylindrical (cylindrical model in MINSUN), which should apply to all kinds of ground. However, the performance of large systems (50 000 m^3 or greater) might be improved by drilling to greater depths, as the storage surface area to volume ratio is decreased. Soft soils may, however, be drilled from 10 to 40 m, and some kinds of rock from 100 to 150 m, as the experience of Luleå shows. It is more cost-effective to make a rock storage deep than to make a ground storage deep at present. Further studies should be made for more appropriate combinations of soil characteristics and depths.

The **operating strategy** is the same for solar heating systems using either a water or a ground storage.

1. The collectors are continually charging the storage when possible.

2. The load is covered by;
    1. storage only
    2. storage together with supplementary boiler, or
    3. boiler only.

A water tank should be used as a daily buffer storage in connection with the storage loop in order to level out the charging power of the collectors over a longer period (lowering the storage maximum temperature). The extra cost for the buffer storage can be compensated by installing fewer pipes in the storage or by installing fewer collectors.

MINSUN does, however, not include this daily buffer storage. Charging and discharging is only done in relation to the number of sunshine hours in MINSUN, which might be a conservative approximation.

The existing Groningen installation is an example of this type of system, as HT FP collectors have about the same performance as ET collectors in this application.

5.2.3 Description of the solar assisted heat pump system

The generic system analysis during Phase III has only included one system with an electrical heat pump (Peltola, 1989). This system is an aquifer, where the ground water is heated with unglazed collectors.

This system is suitable where a residential area is situated close to an existing aquifer. Systems with solar heated aquifers can be justified when the natural recharging of an aquifer is not adequate to raise the temperature to the required level. There exist a few installations of this system type such as in Bunnik.

The generic systems analysis included originally also simulations for a larger Stuttgart University project (Fisch and Hornberger, 1988), incorporating unglazed solar collectors, a water and gravel-filled pit and an electric driven heat pump. This analysis did not show any improved cost-effectiveness, compared to a solar heating system with high temperature flat plate collectors and a gravel and water pit, and is thus left out in this presentation.

The **unglazed collector** (solar absorber) used is a conventional type already on the market (Stuttgart, Sunclay), and the **aquifer** storage considered is similar to the aquifer in the Scarborough project (Appendix A). Aquifers without charging of solar heat from collectors have been used to a large extent troughout the world.

The **heat pump** is an ordinary electric motor driven heat pump with a conventional refrigerant. Either a small, piston type compressor or a large screw compressor, may be used. Engine driven heat pumps using natural gas or diesel have not been considered, but should be taken into account in future analyses of solar assisted heat pump systems.

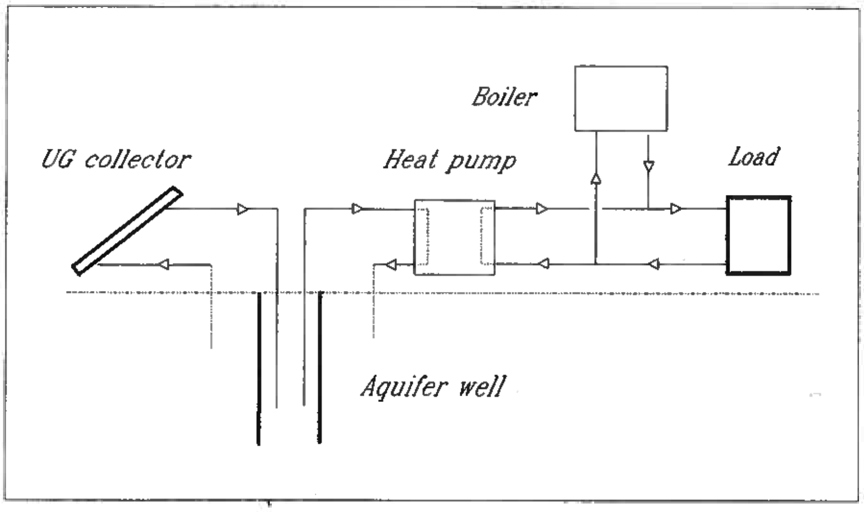

Figure 5.6 Schematic drawing of the solar assisted heat pump system with aquifer storage.

The **operating strategy** for this system is as follows:

1. The water is taken from the aquifer via the cold well and heated by the absorbers if possible. The warm water from the absorbers is pumped back to the aquifer via the warm well. Water to the heat pump evaporator is taken from the warm well and pumped back to the cold well.

2. The load is covered by;
   1. the heat pump, or
   2. the boiler.

As shown in the operating strategy, MINSUN cannot simulate the use of the heat pump and the boiler at the same time, which would be the case in a real installation. The load is therefore either covered by the heat pump or the supplementary boiler in MINSUN. This does not have a great influence on the result, as the heat pump is designed to cover the load most of the time.

It was, furthermore, the intention to make a more detailed analysis of this system in Phase III. The result is, however, that it has not been possible to make any further improvements in the evaluation of this system configuration, and the same approach as in Phase II has been used. The aquifer model in MINSUN is a single well model and does not include a coupling between the warm and the cold well, as in a double well model. The water in the cold well is assumed to be at natural ground water temperature (10 °C) and is, if possible, heated to 15 °C in the absorbers.

A double well aquifer model should be used, together with a higher absorber set point temperature, in a future analysis. More details about this limitation and comparisons with other aquifer storage models can be found in the generic system study by Peltola, 1989.

5.2.4 Basic assumptions and methodology

The basis for the evaluation of each generic system is annualized energy cost versus solar fraction. These costs have been calculated for numerous combinations of climates, load sizes, and investment cost. The presented curves are all envelope curves representing the minimum cost for each solar fraction. These minimum costs have been obtained by varying collector area and storage capacity in each case.

Table 5.2 gives an overview of the studied combinations in this analysis. The sensitivity of certain parameters, such as collector cost and storage cost, has also been studied in some cases.

Economic parameters

The analyses are made for 5 % real interest rate and a 25 year life expectancy. Real rate has been used as the main issue is to performe a comparison between different systems. The same life expactancy for all components has been used for simplicity. The life expectancy for collectors is judge to be about 20 years and for storages about 30 years.

The economics of solar heating systems is based on the annualized **solar cost** (envelope curve), including collector and storage investment costs (mainly capital), compared to the price of an available supplementary fuel. 50 US$/MWh (400 US$/m^3 of oil, 80 % efficiency) was used to judge the economics of solar heating systems in this analysis. This price can be considered to include some adjustments for pollution fees etc. in those countries where actual prices are lower than this price.

The economics of the solar assisted heat pump systems is based on the minimum **total cost** (envelope curve), including collector, storage, heat pump and supplementary boiler investment costs as well as the cost of drive energy to the heat pump and supplementary fuel cost, compared to the cost of another available heat supply system. A 2% per year real fuel and electricity cost escalation is also applied when calculating the total cost. The supplementary fuel cost was set to 50 US$/MWh, and the cost for electricity to the heat pumps was set to 80 US$/MWh, in the base case. 50 US$/MWh is also here judge to be a reasonable total cost to be used to judge the economics of solar assisted heat pump systems.

The investment cost of the distribution system (hydronic pipe network) is not included in solar costs or total costs presented. The distribution system will add approximatly 5 US$/MWh to these costs.

Table 5.2 **Studied combinations**

	Solar heating systems							**Solar assisted HP system**
	HT FP collectors and storage in							**UG collectors** and storage in
			Water			**Ground**		**Aquifer**
	Pit		Pit[1]	Cavern	Clay	Soil	Rock	
Climate								
Helsinki	*		*	*		*		*
Zürich	*	*	*		*	*	*	*
Milano	*		*			*		*
Madison	*	*	*			*		*
Load								
50 houses	*	*				*		*
200 houses	*	*	*		*	*	*	*
1000 houses	*	*		*		*		*
Collector cost								
Today	*		*	*	*	*	*	*
Future		*				*		*
Storage cost								
Today (water)	*		*	*				*
Future (water)		*						*
High (Ground)					*	*	*	
Low (Ground)						*		

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[1] Water and gravel-filled pit

Load parameters

Analyses of Phase II showed that CSHPSS are less competitive for high temperature load applications. A **low temperature space heating system** has therefore been used to ensure optimal thermal performance. The nominal supply temperature was taken as 60 °C at -20 °C outdoor temperature with a linear decrease to 50 °C at 0 °C outdoor temperatures. This minimum supply temperature is required for the preparation of DHW. The return temperature was taken as constant at 30 °C.

The load size is an important parameter, since collector costs, storage costs and specific storage heat losses are all subject to economies of scale. Three load sizes have been considered in this analysis (Table 5.3) The majority of results are reported for the 200 house load.

The loads were assumed to be the same in all the locations, as there is little variation in the heat consumption per house unit between different industrialized countries. The overall U-values (Table 5.4) presented are calculated so that the same number of houses will give the same load in each climate. The DHW is approximatly 25 % of the total load.

The sizes of the distribution system main pipes are indicated in Table 5.3). The distribution heat losses are considered as a part of the load.

Table 5.3 **Heat load sizes used in the analysis**

Number of houses (units)	**50**	**200**	**1,000**
Total load (MWh/a)	800	3 200	16 000
Distribution network length (m)	750	3 000	15 000
Distribution pipe diam (m)	0.06	0.12	0.25

Climates

This analysis was carried out for four different climates (Table 5.4), based on hourly weather data from official national weather authorities. These locations are chosen to be representative of the countries where CSHPSS are most likely to be applied, in a latitude band between 40° and 65°.

Table 5.4 **Climates used in the analysis**

Location	**Helsinki**	**Zürich**	**Milano**	**Madison**
Latitude (°)	60	47	45	43
Residential load unit U-value[1] (W/m²,K)	0.38	0.525	0.72	0.425
Annual outdoor temp (°C)	5.3	8.1	12.4	7.9
Degree days (20/12 °C)	4 828	3 613	2 585	4 215
Annual global horizontal solar radiation (kWh/m²)	900	1 150	1 300	1 350

[1] U-value is the overall heat transfer coefficient of the building.

Many other parameters influence the system performance and cost. The influences of most of these other parameters have been investigated in earlier Phases of this Task, and they have been set to appropriate values in this analysis.

5.2.5 Costs used in the analysis

One of the main objectives with the generic system analysis in Phase III was to use updated cost data based on existing installations or recent studies. The investment costs used in Phase III are listed in Tables 5.5 and 5.6.

Estimated future costs are assumed to reflect 10 years of development, and a market for the technology. As a comparison, Table 5.5 also shows the cost parameters used in Phase II, subtask IIb, and documented in the "Evaluation of Concepts" (Bankston, 1986). The table shows mainly that the collector costs are lower under Phase III, where large arrays are used, and storage costs are the same, or higher where pit or ground storage is used.

The costs used in this analysis are considered to be quite representative of the present state of the art in some countries. If the costs seem to be optimistic, seen from a particular country, one should remember that the effect of an international collaboration, and the broader market to be established in the European Communities, will reduce differences in national costs.

Table 5.5 **Collector and storage costs**

	IIb report (1983-85)	Phase III (1989)	Future (2000)
Flat plate collectors total investment cost (US$/m^2)			
50 houses (units)	245	250	200
200 houses	245	200	170
1000 houses	245	183	133
Unglazed collectors total investment cost (US$/m^2)			
50 houses (units)	140	140	130
200 houses	140	140	130
1 000 houses	140	140	130
Pit storage total investment cost (US$/m^3)			
Size "small" (m^3)	5 000	3 000	3 000
Cost "small size"	30	[1] 70	60
Cost "large size"	20	[2] 50	30
Cavern total investment cost (US$/m^3)			
Size "small" (m^3)	50 000	50 000	50 000
Cost "small size"	48	28	28
Cost "large size"	10	20	20
Ground storage investment cost (US$/m)			
Borehole/pipe [3]	30	60	60
Borehole/pipe [4]	30	30	30
Aquifer total investment cost (US$)			
"Typical" site[5]	150 000	150 000	150 000

[1] 130 US$/m^3, using gravel-filled water pit, Stuttgart type.

[2] 45 US$/m^3, using gravel-filled water pit, Stuttgart type.

[3] Hard soil or rock today or future high cost.

[4] Soft soil (clay) today or future low cost.

[5] 100 US$/m well is also used to have some size-dependence.

Collectors

The investment costs for the solar collectors are based on investment costs in existing installations and related to the size of the collector array (number of houses or residential units). Current collector investment costs are mainly taken from Denmark and Sweden. Future flat plate collector cost is estimated from the Kungälv study in Sweden. No similar studies have been made for unglazed collectors.

Water storage

Water pit storage investment costs are based on comprehensive pre-design studies in Denmark, Sweden and FRG and directly related to the size of the storage . Cavern investment cost is based on current costs in Sweden and can only be applied to sites with similar rock conditions (as Helsinki).

Ground Storage

Ground storage investment costs are based on existing installations and related to the total length of the pipes. The borehole pipe cost is influenced by many factors; mainly soil conditions and depth of the borehole. The cost for connecting pipes are included.

The investment costs used in the present analysis are set to 60 and 30 US$/m, assuming that different applications today and in the future will be in that range. The cost for the insulation on the top of the storage is added to this cost. Current costs in Sweden are, however, about 50 US$/m borehole in rock greater than 100 m in depth, and 15 US$/m plastic U-pipe (using pile-driver) in soft clay of about 30 m depth.

Aquifer storage

Aquifer storage investment costs involve the drilling and development of high capacity water wells with reinjection capability. This requires large diameter wells and large cost penalties for unsuccessful wells. Costs are predictable as long as normal drilling rigs can be used.

A "typical" site requiring a depth of 50 m has been assumed (same as in Phase II). The cost includes two wells, plus other required equipment based on the Scarborough project experience. Costs are assumed to be less in the year 2000 and projects with decreased well drilling costs have been documented in The Netherlands and Canada. No attempt has been made to use these reduced costs (about 50 %) for the Phase III analysis.

Heat pumps and boilers

The investment costs of the heat pump and supplementary boilers are related to the thermal power and based on real costs in existing installations. The investment costs for electric driven heat pumps and boilers are not expected to decrease in the future, as these systems can be regarded as conventional technologies that already have a large market penetration. Heat pump costs used in this analysis are, however, about twice as high as assumed in Phase II.

The investment cost for boilers is only considered when calculating the total cost and has even then a minor influence on the result. The investment cost used is around 200 US$/kW depending on size and includes building, exhaust chimney and fuel handling equipment.

Table 5.6 **Heat pump costs**

	Phase III and future (1989)
Heat pump total investment cost (US$/kW thermal)	
50 units	370
200 units	240
1000 units	125

5.3 General results

The results of thousands of simulations performed with MINSUN for a variety of system parameters and economic conditions are presented in this section in a special way. Most of the results are presented as plots of solar cost versus solar fraction.

The solar cost is the annualized capital cost of all the solar specific system components including the collector array, the storage subsystem, the collector-to-storage transmission pipes, and the heat pump (if present). Operating and maintenance costs are included implicitly in the capital cost assumptions, but purchased heat (to meet 100 % of the load) and power to drive water circulation pumps (in collector, storage and distribution subsystems) is not included. As previously stated, the economic life of the system is assumed to be 25 years and a real discount rate of 5 % is used.

Some of the figures (system including heat pump) show the total annualized cost of heat delivered by the system which is obtained by combining the solar cost and the annualized cost of auxiliary. An auxiliary energy real escalation rate of 2 % is used to calculate the total cost.

The curves, such as those shown in Figures 5.7-5.9, actually represent the lower bound (or envelope) of many simulations performed with MINSUN for the specified load, climate, and economic conditions, but with varying component size and specifications (i.e., the collector area, the storage volume, the borehole (pipe) length, etc.). These lower bounds, therefore, represent the locus of a continuum of different systems that yield the minimum cost for a given solar fraction. These curves have been referred to in our previous work (Bankston, 1986) as expansion paths.

It may be helpful to the reader who is familiar with the earlier results which are presented in a similar format, to note the most important differences in the input data and in the presentation format. The current results are based on updated cost and performance parameters for the important components. The most significant changes are in the collector array where the cost has decreased from 245 to 183 US\$/m^2 (todays cost in large systems) with increased performance and in pit and duct storage systems were the costs are two to two and one-half times larger than assumed in previous work. These updated component cost figures not only change the general level of solar cost, but also influence the shape of the expansion paths relative to previously reported results.

The change in the general level of solar costs between the Phase II(b) study and the present results is reflected in the fact that the Phase II(b) results were presented on coordinates that ranged from 0 - 200 US\$/MWh for the dependent variable and 0 - 100 % for the solar fraction whereas the coordinator for the current study results range from 0 - 100 US\$/MWh and 50 - 100 %.

All generic systems analysed in Phase III showed heat costs of close to or below 50 US$/MWh, for most climates and load sizes, using estimated future cost data. The exception is solar heating systems for small load sizes in northern climates, which are higher. Large generic systems of 1 000 houses can, however, be economically viable, even at current costs.

5.3.1 Solar heating systems

The performance, and consequently the cost effectiveness, of a solar heating system is dependent on both the climatic conditions and the load size.

Figures 5.7 and 5.8 show the solar cost as a function of the solar fraction for solar heating systems supplying 200 houses in four different climates. The cost of the solar heating systems is strongly dependent on climate. Comparing Milano with the more northerly sites, the improvement in performance, and consequently cost effectiveness, can be as much as 30 % moving south.

Further, the water storage systems performe about 10 % better than ground storage systems in northern climates, but the difference between the two storage systems is very small for southern climates. The ground storage systems have exactly the same solar cost in Milano and Madison.

Figure 5.9 shows the solar cost for different load sizes in Milano. The figure shows a strong dependency on the load size, especially going from a 50 houses load to a 200 houses load, for both water and ground storage systems. The solar cost for large ground storage systems is about 35 % lower than the solar cost for a small system in Milano. The same relation for water storage systems is about 25 %.

Figure 5.9 shows also that the solar cost for a large water-filled rock cavern system in Helsinki, is close to the solar cost for a large water pit storage system in Milano. The less favourable climate in Helsinki is compensated by a low investment cost for a cavern compared to a pit with approximatly the same size.

Solar cost for the 200 houses load with the label "today" includes a collector investment cost of 200 US$/m^2, a water pit storage investment cost of 50-60 US$/m^3, a ground storage investment cost of 60 US$/m (high cost) or 30 US$/m (low cost) duct or pipe.

Solar cost for the 200 houses load with the label "future" includes a collector investment cost of 170 US$/m^2, a water storage investment cost of 30-40 US$/m^3 or a ground storage investment cost of 30 US$/m (low cost).

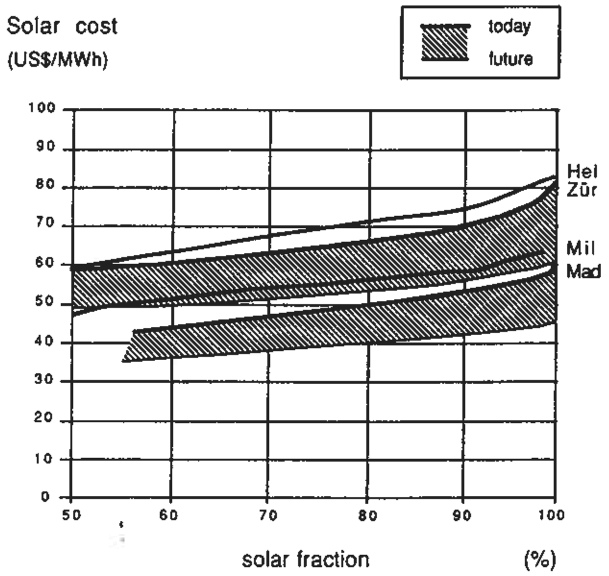

Figure 5.7 Solar cost for **solar heating systems** with HT FP collectors and **water pit storage,** using **different climates.** Load size **200 houses.**

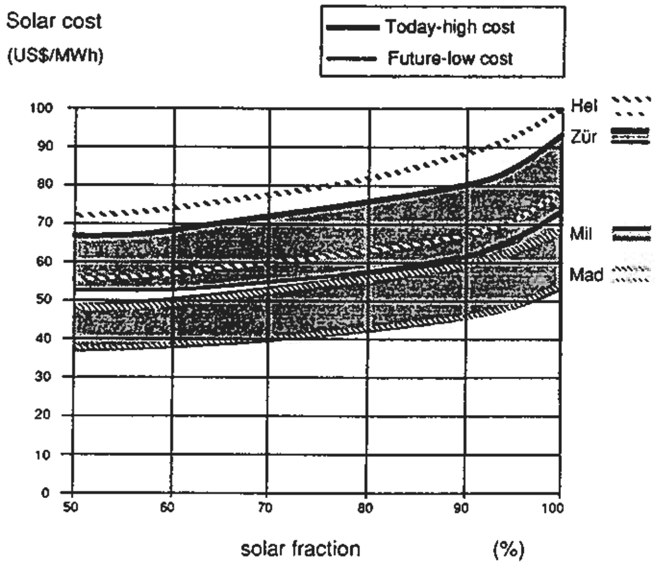

Figure 5.8 Solar cost for **solar heating systems** with HT FP collectors and **ground storage,** using **different climates.** Load size **200 houses.**

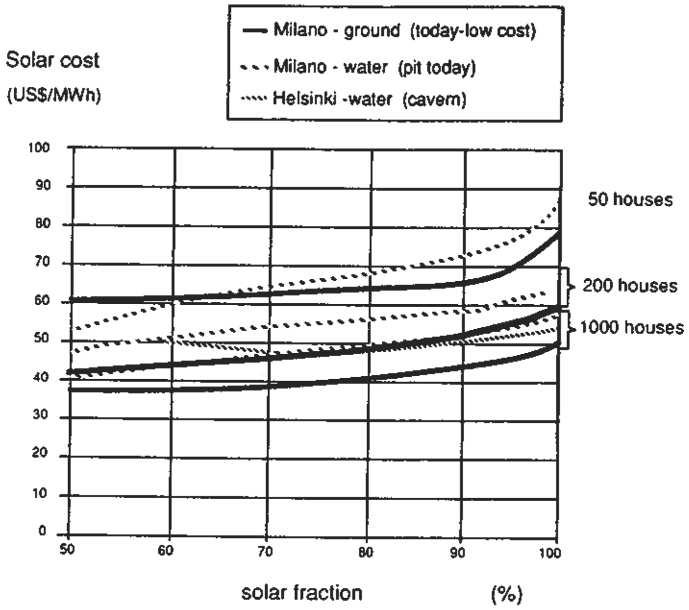

Figure 5.9 Solar cost for **solar heating systems with different storages** and **different load sizes in Milano**, and a **rock cavern** system with a **1 000 houses load** in **Helsinki.**

5.3.2 The solar assisted heat pump system

The solar assisted heat pump system has almost equal costs for different climates, and economics is not as size-dependent as the solar heating system. The system works mainly on the ground water temperature and the specific collector cost is assumed to be constant with system size in this analysis.

Figures 5.10 shows the total cost as a function of the solar fraction for the solar assisted heat pump system supplying 200 houses in four different climates. Figure 5.11 shows the total cost for different load sizes in Helsinki.

Since the solar cost is less than the cost of electrical energy and the aquifer cost is almost constant, the total cost for the solar assisted heat pump system decreases with increasing solar fraction, thus an optimal system is always found close to 70 % solar fraction, determined by the SPF.

Aquifer storage was identified early in Task VII as a promising storage technology due to its low cost and favorable power and energy characteristics. This early outlook has been confirmed by continued successful aquifer storage projects.

The results of the low temperature solar storage system with heat pump confirm the competitive nature of such systems. However, the similarity of these costs with ground water heat pump systems, as indicated by the national analysis of the Canadian national project, among others, lead us to question the comparability of this solar assisted heat pump system with other CSHPSS.

Our analysis of aquifer storage CSHPSS was limited by the combination of simple MINSUN models of aquifer hydraulic and thermal properties and the inadequate solar and economic aspects of standard aquifer models. Also the aquifer projects of participating countries, while successful in delivering cost-effective energy to buildings, do not take full advantage of the CSHPSS concept.

We conclude that the results of the solar assisted heat pump analysis are not directly comparable to other CSHPSS analysis. They reflect more accurately the inherent advantages of ground water heat pump systems.

Recent aquifer projects, plus improvements in the flexibility of aquifer models, give future possibility of evaluating aquifer storage in combination with true seasonal solar storage.

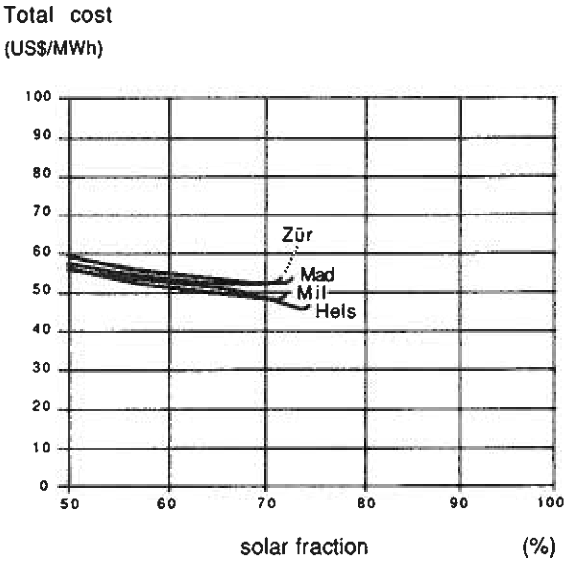

Figure 5.10 Total cost for the **solar assisted heat pump system** with absorbers and aquifer storage, using **different climates.** Load size **200 houses.**

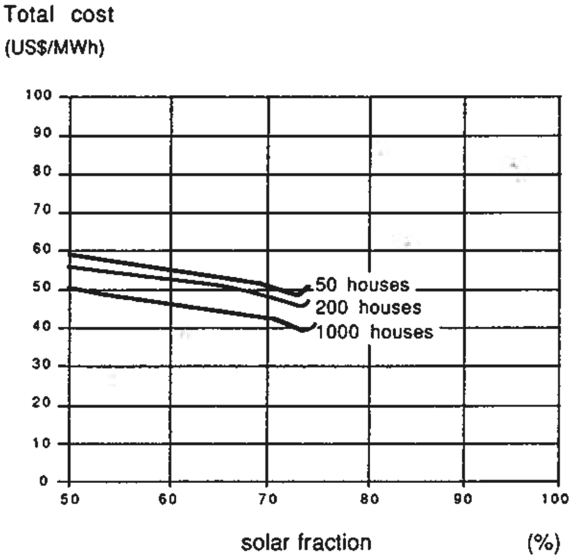

Figure 5.11 Total cost for the **solar assisted heat pump system** with **different load sizes** in **Helsinki.**

5.4 Detailed results for solar heating systems

Figures 5.12-5.15 show the solar cost for solar heating systems with 200 houses load size in the four different climates with different storage types; water pit storage, water and gravel-filled pit and ground storage.

Water storage systems were found to be more cost effective in northern climates than in southern climates as stratified storage systems are able to meet higher distribution temperatures better. The difference between water and ground storage systems is, however, small and one can conclude that the potential for both storage types is about the same. The system with a water and gravel filled pit is in general more expensive than both water pit and ground storage systems, but it is quite close to the other systems in Madison.

The collector area to annual load ratio is higher for ground storage systems than for water storage systems; 2-3 m^2/MWh compared to 1.5-2.5 m^2/MWh, for solar fractions 70-80 %, due to the different relations between collector and storage cost and lower collector performance for ground storage systems.

The storage volume to collector area ratio is also higher for ground storage systems than water storage systems; 4-7 m^3/m^2 compared to 2-3 m^3/m^2, for solar fractions of 70-80 %, mainly due to the lower heat storage capacity for ground storages.

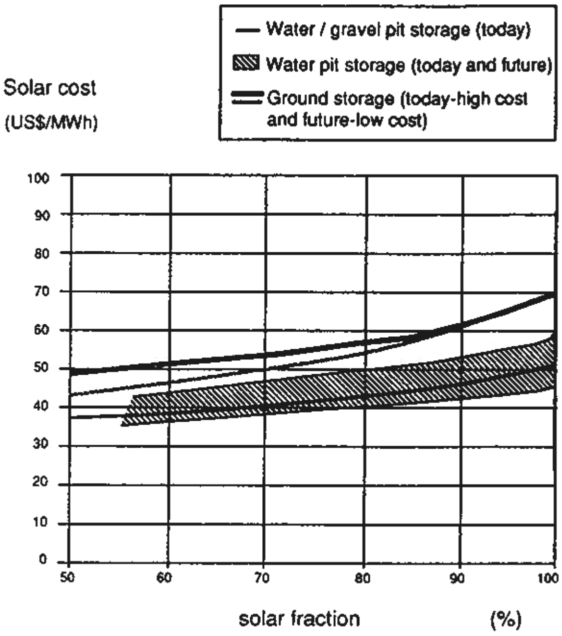

Figure 5.12 Solar cost for **solar heating systems** with different storage types in **Madison**, load size **200 houses.**

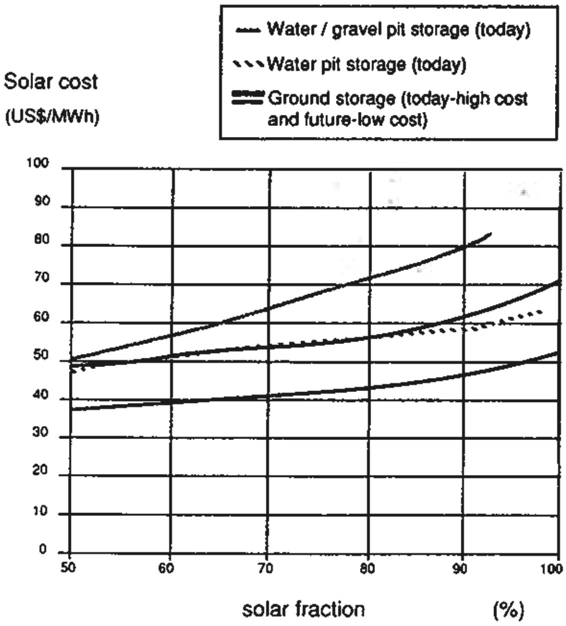

Figure 5.13 Solar cost for **solar heating systems** with different storage types in **Milano**, load size **200 houses.**

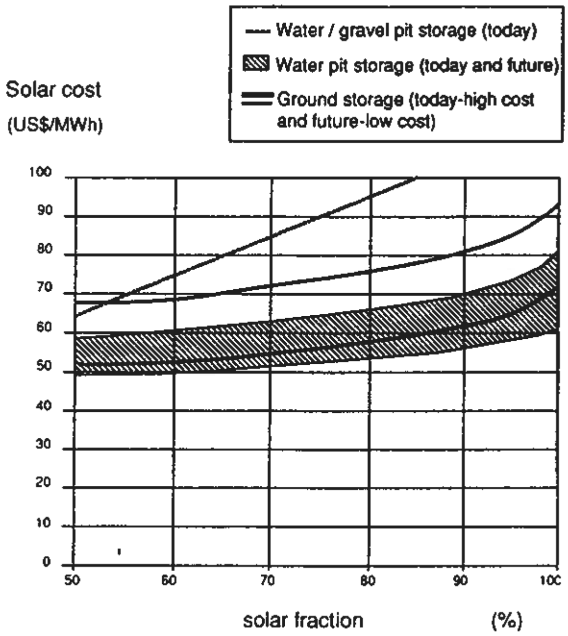

Figure 5.14 Solar cost for **solar heating systems** with different storage types in **Zürich**, load size **200 houses.**

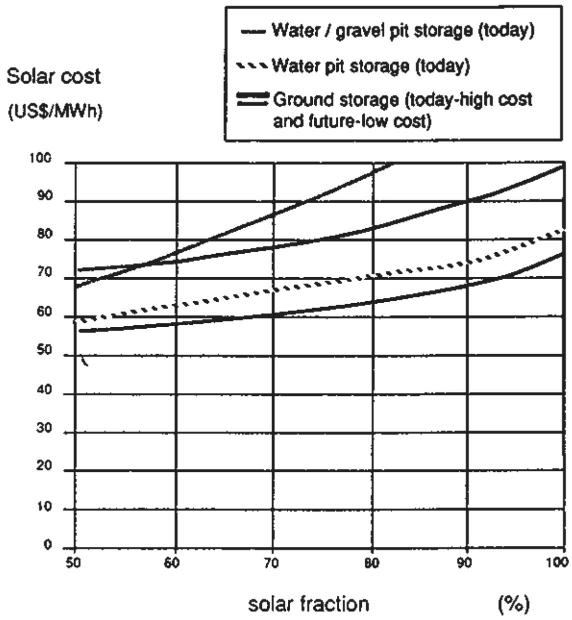

Figure 5.15 Solar cost for **solar heating systems** with different storage types in **Helsinki**, load size **200 houses.**

5.4.1 Systems with water storage

Figure 5.16 shows the collector area needed for the 200 houses load in the four different climates. Typical characteristics for 200-1 000 houses load systems with water storage and 70-80 % solar fraction are shown in Table 5.7.

Figure 5.17 shows as examples the storage volume and collector area needed for two different systems in two different climates, 1 000 houses in Helsinki and 200 houses in Madison.

Table 5.7 Water storage system characteristics

Collector area to annual load ratio:	1.5-2.5 m^2/MWh
Storage volume to collector area ratio: (30-90 °C available storage temperature range).	2-3 m^3/m^2

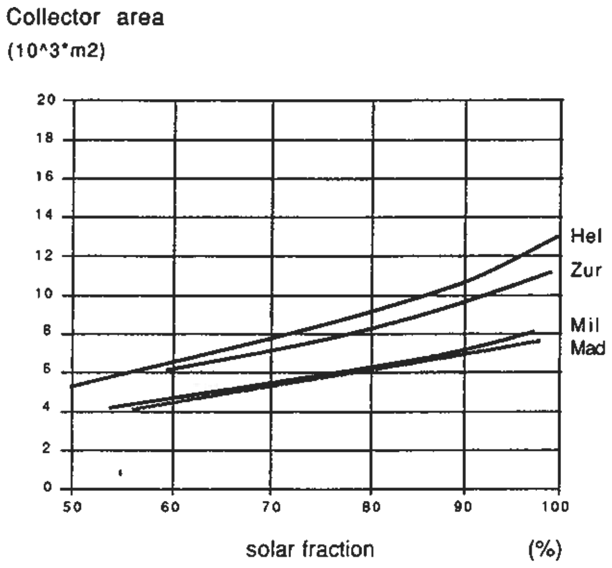

Figure 5.16 Collector area for **solar heating systems with water pit storage,** using different climates, load size **200 houses.**

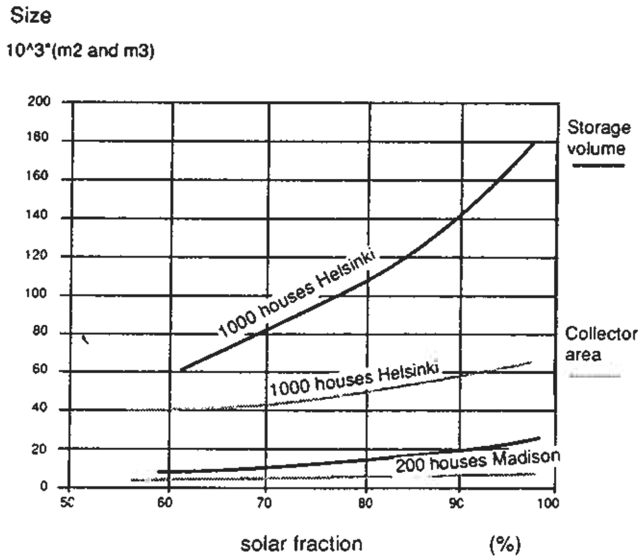

Figure 5.17 Collector area and storage volume for a **solar heating system with water-filled rock cavern storage** in **Helsinki,** load size **1 000 houses,** and for a **solar heating system with water pit storage** in **Madison,** load size **200 houses.**

5.4.2 Systems with ground storage

Figure 5.18 shows the collector area needed for 200 residential units in different climates. Typical characteristics for 200-1 000 load systems with ground storage and 70-80 % solar fraction are shown in Table 5.8.

The results for ground storage systems are always shown for "soil" characteristics. Clay and rock will change the sizing of the storage but it does not influence the cost of the system.

Figure 5.19 shows as examples the storage volume and collector area needed for 200 houses in two different climates, Zürich and Milano.

Table 5.8 Ground storage system characteristics

Parameter	Clay	"Soil"	Rock
Volumetric heat capacity (MJ/m^{3}K)	4.0	2.0	2.0
Thermal conductivity (W/mK)	1.0	2.0	3.5
Collector area to annual load ratio (m^2/MWh):	2-3	2-3	2-3
Storage volume to collector area ratio (m^3/m^2): (35-90 °C available storage temperature range)	4-5	6	6-7
Pipe length to collector area ratio (m/m^2): (borehole diameter of 0.1 m), and	1.5	1.5	1
Borehole (pipe) spacing (m):	1.5	2	2.5

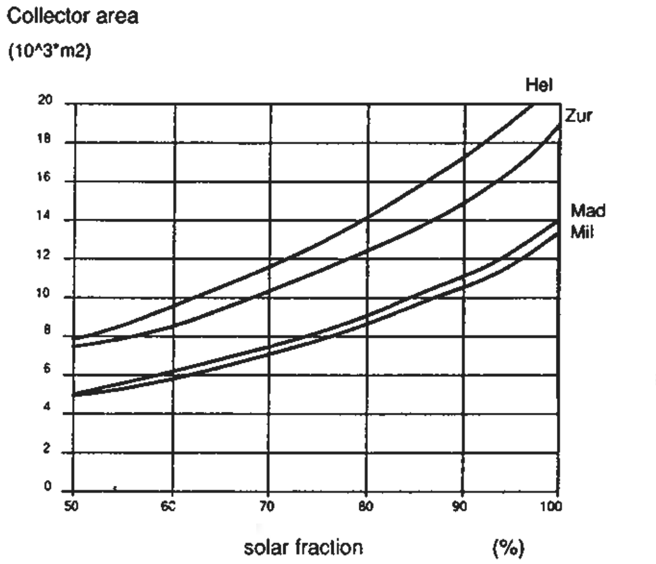

Figure 5.18 Collector area for **solar heating systems with ground storage**, using different climates, load size **200 houses.**

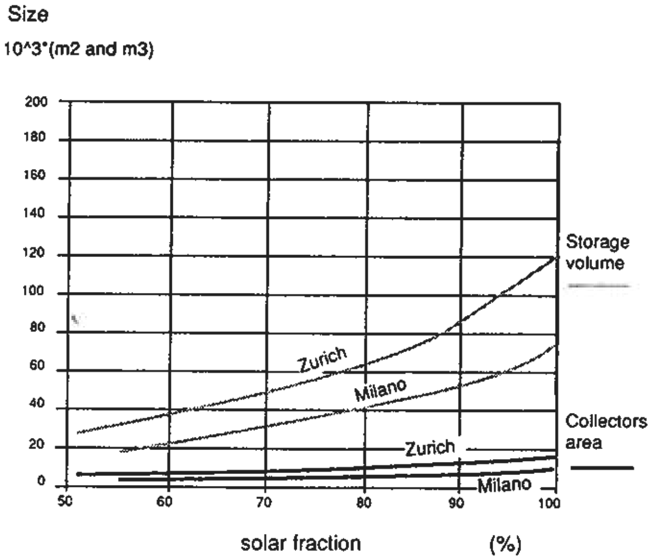

Figure 5.19 Collector area and storage volume for **solar heating systems with ground storage**, in **Zürich** and **Milano,** load size **200 houses.**

5.4.3 Discussion

In order to understand the shape of the solar cost-solar fraction relationship, it is helpful to consider and discuss two aspects that influence it: The relative cost of the major subsystems, and the temperature constraints, if any, that limit the performance of any of the subsystems.

The major subsystems are the collector array, the storage system and the end-use (load) heat exchanger. The simulations and the economic results in the Generic System studies do not include the cost of the end-use heat exchanger, but they are strongly dependent on the relative cost and performance of the collector and storage subsystems as well as the performance of the end-use subsystem.

Stratified Water Storage Systems

The efficiency of the collector subsystem decreases with increasing collector delivery (i.e., average) temperature and, therefore, the cost of the collector per unit of energy delivered is an increasing function of the delivery temperature.

The storage capacity, on the other hand, depends on the product of the volume and the difference between the maximum and minimum average temperatures within the storage volume and, since the maximum storage temperature is limited by the collector delivery temperature, the cost of storage, per unit of energy stored, decreases with increasing collector delivery temperature.

Therefore, there exists an optimum collector delivery temperature which minimizes the combined cost of the collector and storage subsystems. Close examination of the results for systems lying along the expansion path for stratified water storage systems does show that the storage swing is nearly constant and is close to the value predicted by simple linearized cost optimization arguments.

Since the operation of a seasonal storage system is such that the maximum average temperature is achieved only once per year (fully charged condition). It follows that ability of the cost-optimized, perfectly-stratified system to meet the full load requires that the maximum temperatures at the fully charged condition, less any reductions due to heat losses from the storage, is greater than the demand temperature throughout the heating season.

The reduction of the maximum storage temperature due to the heat losses is a function of the size of the store (volume to surface ratio). The larger the load, the larger the fraction that can be met by a cost-optimized system. This explains why the simulation results show minima in the solar-cost vs. solar fraction curves above 50% only for relatively large system, e.g. 1000 units in Helsinki (Figure 5.9).

Minima occur at lower solar fractions for smaller systems, but this may be complicated by the simulation method in which diurnal storage is implicitly included at no cost (daily time steps). Further, since all the cost functions decrease with system size, the absolute minimum solar cost will occur when the load is large enough that the minimum solar cost occurs at 100 percent solar fraction.

The practicality of designing systems for 100 percent solar fraction requires consideration of the stochastic variation of the climatic parameters and the ability of the plant to operate at off-design conditions.

The discussion above also explains some of the differences between the Phase II (b) system analysis results and the present generic system results. In the II (b) study the ratio of storage to collector costs was much lower and therefore, the optimum storage capacities were larger, and the fraction of the load that could be met by a cost optimized system was higher. However, since collector costs were considerably higher (except for small systems) and the same for all sizes, and the collector costs dominate the system costs, the level of system costs for the II (b) study was generally higher than in the present study.

So far, this discussion assumes that all the system temperatures are unconstrained. In fact, recognition of material limitations, thermophysical properties and safety have led to imposing a number of temperature constraints on the MINSUN simulations. The most important ones for purposes of this discussion are the limits on either collector outlet temperature or maximum storage temperature. It is obvious that if the maximum storage temperature is less than the maximum temperature required to meet the load on the coldest day of the simulation, 100 percent solar fractions cannot be achieved.

It is also possible that even though the maximum storage temperature is initially greater than the maximum required temperature at maximum load, the required temperature cannot be maintained within the stratified storage volume from the time when the storage is fully charged until the time that the maximum temperature is required (say from October to February). This is the explanation for the sharp increases in solar cost exhibited by some of the simulated systems as the solar fraction approaches 100 percent (at about 98 percent in Figure 5.7 and about 95 percent in Figure 5.9).

If the simulated collector area and the volume are increased without allowing the maximum storage temperature to rise, the system may still be unable to meet the peak loads that occur late in the season. The average storage temperature will rise and the additional heat losses from the storage will dissipate most of the additional solar energy supplied, but the solar fraction will not increase in proportion to the cost of the added capacity.

In an unconstrained design, the proper engineering solution of the dilemma posed by incompatibility between the heat source (storage temperature) and the load (delivery temperature) is not to limit the solar fraction but to increase the surface area of the end use heat exchanger to make the source and load compatible.

The practicality of changing the end-use heat exchanger size in a retrofit design has not been addressed. It might not be a problem as existing systems often are oversized. Also if solarization of the heating plant were undertaken in combination with a program for reducing the building heat losses, increased end-use heat exchange area might not be necessary.

Ground Storage Systems

The discussion of ground storage systems results such as those shown in Figure 5.8 is somewhat more complicated owing to the heat transfer process between the collector and load heat transfer fluids and the earth or rock. The lack of controllable temperature stratification in ground storage systems, coupled with the inescapable temperature differences between the charging and discharging fluids and the storage media will generally require that the minimum average temperature of ground storage systems be higher than the minimum average temperature of a stratified water storage system resulting in a larger storage volume and high heat losses.

In addition, the maximum temperature of earth storage systems may need to be limited to prevent soil drying and loss of conductivity (temperatures in competent rock storage systems may not be subject to such limits) making it difficult to achieve high solar fractions.

Despite these differences between the stratified water storage systems and the ground storage systems, the results shown in Figure 5.8 (ground) look remarkably similar to those in Figures 5.7 and 5.9 (water), and thus the general arguments regarding cost ratios and temperature limitations discussed above must apply. Although the ground storage systems are not normally designed for temperature stratification, the low thermal diffusivity of the rock or soil means that the temperature in the storage volume is non-uniform and this non-uniformity may occasionally serve the same function as stratification in a water tank. For example, occasional sunny winter days may result in ground temperatures near the pipes high enough to meet the demand during subsequent cold days even when the average earth (storage) temperature is too low.

6 MAJOR FINDINGS

6.1 Evaluation of existing plants

Prior to Phase III most CSHPSS projects were still under design or construction, but today many of these are in operation and have been evaluated. International co-operation has been invaluable in the evaluation of projects and the exchange of information, in the international forum of the IEA, has greatly improved design know-how on a national level.

6.1.1 Planning and design

Ideally the planning and design of a CSHPSS projects would be undertaken along with the planning of a new residential building area, especially if roof-integrated collectors are to be used. Thus, new construction offers the best opportunities for solar heating. Low temperature space heating systems are essential for optimizing performance and are normally used in new buildings.

Correct use of conventional heating technology in solar heating applications is more vital to the performance of a CSHPSS than in a conventional boiler plant.

Validated pre-design tools, such as MINSUN, should be used to ensure proper sizing of new systems. For some early systems proper specific tools were not available. Some of the design problems might have been avoided if less sophisticated system configurations had been employed.

6.1.2 Construction

The development of large module flat plate collectors has been ongoing for several years. This collector type has been developed and is most suitable for large scale on-ground mounting. Roof-integrated collector systems have not yet been developed to the same extent.

Water pits have been built in several countries and development work is continuing. The top of the pit may float on the water or have a separate support structure. Filling the pit with gravel, as in the Stuttgart project, reduces the structural requirements for the lid.

Pits in soft clay or unconsolidated earth must be built with rather shallow side slopes to meet building requirements and safety standards. Such pits are relatively shallow with large surface to volume ratios and upper surface areas, which must be insulated. Deeper pits with steeper sides may be constructed in rock or hard ground, but the excavation cost is usually greater.

Rock caverns can be built were the rock is suitable, and the same technology that has been used to excavate crude oil storages can be used.

Duct storages can be very inexpensive in areas where the geological conditions are favourable. Favourable conditions are found in very soft clays that can be penetrated easily by vibrating lances or pile driving techniques, or in competent bed-rock formations where the holes can be drilled and heat can be transferred without casings or linings. Loose soil or mixed soil and rock present greater difficulties for the installation of duct storages.

The knowledge about construction of high temperature ground storages and aquifer storages is limited.

6.1.3 Performance and operation

Solar collector arrays have generally performed as expected, but incorrect use of conventional heating technology has sometimes caused problems such as incorrect flow distribution in collectors, etc.

Larger storage heat losses than expected have been observed in some cases. Some of the unexpected storage losses are due to inadequate knowledge about the thermal loss mechanisms in subsurface environments (insulation techniques).

The maintenance of high temperature stratification in water storages has complicated the operation in some installations, although it has been successful and increases the performance.

Heat pump seasonal performance factors are lower than expected because the heat pumps were originally designed for conventional heating plants (lower evaporator temperatures). Redesigned electrical heat pump systems have, however, shown improved performance factors.

6.2 Generic systems study

The analyses in Phase III, unlike that in Phase II, reflect the fact that collectors have become both cheaper and operationally more efficient with advances in technology. This has undoubtably an important influence on the results obtained.

All generic systems in this analysis show a cost of heat close to or below 50 US$/MWh, for all climates and 200 residential units or larger load sizes, using estimated future costs. Site and system specific cost-effective CSHPSS configurations do already exist.

CSHPSS incorporating high temperature flat plate solar collectors and storages are most suitable to supply heat to 200 houses or more. Increased system size reduces unit thermal losses and the cost of net produced energy. Systems smaller than 100-200 houses, or equivalent load, are not economically attractive at present and would need more R&D.

The generic system analysis also supports the conclusion that a better thermal and economic performance based on a common cost base is always obtained when moving climatically southwards with the same system. Up to 30% improvement is noted for solar heating systems between the most northern and southern locations in this analysis.

It has not been possible to make a more detailed analysis of the solar assisted heat pump system with aquifer storage than previously was done in Phase II.

7 CONCLUSIONS AND RECOMMENDATIONS

CSHPSS technology has advanced sufficiently to be introduced onto a broader market. Taking anticipated global pollution costs of fossil fuels into account, CSHPSS is already cost-effective.

The confidence in the CSHPSS technology has come so far that a comprehensive design study of a large solar heating plant of 56 GWh/a load has been completed for the town of Kungälv in Sweden. Operation of the plant is planned to begin in the 1990's, if financing can be arranged.

With realistic assumptions of further collector cost reductions in production and marketing, solar heating systems would become even more cost effective. Rational manufacturing techniques for large ground mounted, as well as roof-integrated, solar collectors do exist and it should be possible to bring the cost per m^2 down to 130 US$, through a more industrial manufacturing.

The system aspects of a CSHPSS are now better understood and there is increased confidence in design tools. However, designing a CSHPSS heating system requires expertise from many fields not involved in conventional heating plants. A new installation designed and built with present solar technology expertise, together with correct application of conventional heating technology, would perform much better than most existing plants.

Future systems should employ less complicated system designs. All CSHPSS benefit from the use of a low temperature heat distribution system. The use of heat pumps in CSHPSS should be more carefully considered in conjunction with other design options using heat pumps.

Lessons from plants in operation show that system design and operation should be as simple as possible. This gives the high level of security that is necessary to achieve many years of operation with a minimum of supervision. Continued emphasis on control and maintenance of CSHPSS together with education of operating personnel is a continuing requirement.

There is an effort in most Task VII countries to identify opportunities to plan and build new projects using some or all of the components of CSHPSS. Since these projects are inevitably large and expensive, they must be built for real heat loads and generally must produce revenue for their owners. It is therefore critical that such projects benefit from the experience available in the Task VII countries. As new projects are proposed and designed, there is great value in having these proposals reviewed and constructively criticized by an international expert group.

In general, CSHPSS technology is a non-polluting technology that, during a period of 10 years, has become a realistic heat supply alternative for applications located between latitudes 40° and 65°. Comprehensive knowledge about design, construction and operation of various types of CSHPSS exist in all participating countries at present.

Widespread adoption of these systems would be facilitated by:

- co-ordinated technology exchange between different participating countries, including circulation of relevant market information;
- greater awareness among engineers, architects and energy planners of the technical and economic solutions that are available;
- support for continued experimental development of the technology to reach general cost-effectiveness and eventually become the space heating technology of choice.

7.1 Storage subsystem development

The key issue for the further development of CSHPSS is the storage technology. Low temperature ground storages and water-filled rock caverns in large sizes are the most developed components for CSHPSS. High temperature ground and water storages in moderate sizes are needed in order to create broad applications for CSHPSS. These need further development, both in construction techniques and cost effectivness, in order to be cost competitive in all countries.

There is a need for international research and development with common goals to improve the competitiveness of high temperature (95°C) pit, duct and aquifer storage subsystems for CSHPSS. The appropriate goal for the storage subsystem in a CSHPSS is to allow a temperature high enough to meet the load temperature demand without augmentation and to do so at a construction cost of 20 to 30 $US per m^3 of water equivalent.

Water pits with polymer liners can be operated at temperatures up to 80°C for long periods without serious degradation or leaking. In order to make pits more cost-effective for CSHPSS applications, the maximum operating temperatures need to be increased by replacing the plastic liners with metal or improved polymers. The geometry and insulation techniques must also be improved.

The experience from high temperature ground storages is limited. Research efforts ought to be directed at improving the knowledge about these constructions in various ground materials. Research efforts are currently directed primarily at improving the heat transfer and reducing the cost of drilling and lining the holes.

New drilling technologies, such as thermal drilling techniques that simultaneously form a hole and a glass-like lining or jet drilling, could have an impact on the economics of duct storage in the future.

Thermal energy storage in low-temperature aquifers is now established technology. Storage of high-temperature water in deep aquifers is under investigation in several countries. If successful, it could open new opportunities for cost effective CSHPSS without heat pumps.

7.2 Development of pre-design tools

MINSUN has been valuable as a tool for preliminary studies including sensitivity studies and subcomponent sizing. These functions have been the primary basis for our understanding of the potential of various systems in different climates and economic conditions.

Both improvement of detailed modelling capabilities for design and performance analysis, and analytical or empirical methods for redesign and optimization are required.

The simulation models and techniques that have been developed so far, in conjunction to Task VII, have concentrated on accurate descriptions of the individual components such as the storage or collectors, and have not provided much insight into the best way to arrange and control these components. However, detailed simulations have been performed within some national evaluations.

MINSUN cannot at present handle direct connection of the collectors to the load, alternate connections of the heat pump, non-solar heat sources, hybrid storage or collector subsystems (more than one type in the same installation), distributed storage or collector subsystems, or a variety of other options that designers and researchers might like to evaluate further. More flexible modelling tools should be used for detailed simulation of alternatives and for detailed design studies.

For many preliminary studies, however, sufficiently accurate results can probably be obtained by simpler methods based on analytical solutions of simplified models and empirical equations. Such methods may be especially powerful when packaged in an expert system and combined with a knowledge base derived from the international experience with design, construction, and operation of CSHPSS and their components.

One of the distinguishing characteristics of a CSHPSS as compared to other solar and non-solar heating plants is that, because of their large size and coupling with the ground, they respond very slowly to changes in operation. It usually takes a very long time to evaluate their performance and to determine experimentally the most effective control strategies.

In most plants it will be impractical to attempt to develop the best operational strategy, based on observations of the plant operation, because of the very slow rates of change and the susceptibility to stochastic variables such as the weather. It is, therefore, cost effective to study the response of CSHPSS to control strategies by the use of accurate dynamic system models.

GLOSSARY

CSHPSS

Central Solar Heating Plant with Seasonal Storage (pronounced as "chips"). Solar radiation is converted to thermal energy in a solar collector and stored as sensible heat in a centralized plant. The stored heat is then used to supply space heating during the cold season and heating of DHW in connected buildings, aiming at a high solar fraction (50-100 %) with or without the use of a heat pump. The heat is distributed using a hydronic pipe network.

Solar heating system

Solar heat, whether stored or not, is used direct to supply space heating and heating of DWH in connected buildings.

Solar assisted heat pump system

Solar heat, whether stored or not, is used as the heat source for a heat pump. The condensor heat is then used to supply space heating and heating of DHW in connected buildings.

SPF

Seasonal Performance Factor. The relation between the annual condensor heat from and the annual drive energy to a heat pump. The Coefficient of Performance (COP) is the relation between the condensor power and the drive power for a certain operation period.

HT FP collector

High Temperature Flat Plate collector. A well insulated large module flat plate solar collector. Typical operating temperature range 40-100 °C.

LT FP collector

Low Temperature Flat Plate collector. A conventional flat plate solar collector. Typical operating temperature range 20-60 °C. Typical application DHW.

UG collector

Unglazed flat plate solar collector (solar absorber). Typical operating temperature range 10-30 °C.

ET collector

Evacuated Tube collector, including heat pipes. Typical operating temperature range 40-200 °C.

CPT collector

Concentrating Parabolic Trough collector. Typical operating temperature range 40-400 °C.

Water storage

The storage medium is water contained in a tank, excavated pit or rock cavern. The tank and the pit are fully or partly insulated. The heat is transferred to and from the storage volume by pumping the water in and out.

Ground storage

The storage medium is the ground material; soil or rock. The heat is transferred to and from the ground with the help of a pipe or duct system imbedded in the ground.

Aquifer storage

The storage medium is the ground water, and partly the aquifer material. The heat is transferred to and from the aquifer by pumping the water from supply wells to recharge wells.

DHW

Domestic Hot Water.

Heat load

Space heating and heating of DHW, including distribution losses, in one or more buildings.

Solar fraction

The part of the heat load that is supplied by solar heat in a solar heating system, and the relation between the heat gained in the heat pump evaporator and the total heating load in a solar assisted heat pump system.

Solar cost

The annualized cost of solar heat per MWh supplied to the heat load, or to the evaporator in a solar assisted heat pump system, including capital cost for the collectors, the heat storage and the heat pump, where applicable.

Solar cost (US$/MWh):

$$\frac{\text{Solar system annualized investment cost (US\$)}}{\text{Solar fraction * Heat load (MWh)}}$$

Total cost

The total annualized cost of heat per MWh supplied to the heat load, including operating and all capital costs, except for the distribution pipes to the load.

Total cost (US$/MWh):

$$\frac{\text{Total annualized investment + auxiliary heat cost (US\$)}}{\text{Heat load (MWh)}}$$

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APPENDICES

A: CANADIAN NATIONAL EVALUATION SUMMARY

Based on the evaluation of the Aquifer Thermal Energy Storage field trial at the Scarborough Canada Centre Building. *E. L. Morofsky*

B: FINNISH NATIONAL EVALUATION SUMMARY

Based on the evaluation of Kerava Solar Village. *S. Peltola*

C: EVALUATION SUMMARY OF THE STUTTGART UNIVERSITY PROJECT (FRG)

M. Hornberger, N. Fisch

D: ITALIAN NATIONAL EVALUATION SUMMARY

Based on the evaluation of Treviglio system. *L. Mazzarella*

E: NATIONAL EVALUATION SUMMARY OF THE NETHERLANDS - THE GRONINGEN CSHPSS

J. Havinga

F: SWEDISH NATIONAL EVALUATION SUMMARY

Based on the evaluation of four CSHPSS with water storage. *J-O. Dalenbäck*

G: SWISS EVALUATION SUMMARY

Based on the evaluation of the Vaulruz project with an underground earth storage. *P. Jaboyedoff*

APPENDIX A: Canada - Scarborough

CANADIAN NATIONAL EVALUATION SUMMARY

Based on the evaluation of the Aquifer Thermal Energy Storage field trial at the Scarborough Canada Centre Building.

Dr. E. L. Morofsky
Public Works Canada

1 INTRODUCTION

Completed in 1985, the Scarborough Canada Centre Building is the major federal government building in the eastern section of Metropolitan Toronto. It has been designed for the conservation of heating and cooling energy and for research into the effective use of the latest energy conservation technology. (Arthurs et al., 1985)

One of the technologies which is being investigated is Aquifer Thermal Energy Storage. (Hooper and Angus, 1986) Aquifer Thermal Energy Storage involves the injection of cold or hot water underground into a permeable layer of sand (the aquifer). The water is later retrieved to supply the building heating or cooling load. Cold water can be obtained from cooling towers or heat pumps during the winter. Hot water can be obtained by recovering waste heat from summer heat pump operations or from solar collectors.

The purpose of this field trial is to monitor and evaluate the problems, performance, and economic viability of installing and operating a system for seasonal energy storage in an aquifer under Canadian climatic conditions. The field trial is also the Canadian national project selected for the IEA Solar Heating and Cooling R&D Program, Task VII on Central Solar Heating Plants With Seasonal Storage, Phase III. (Arthurs, 1986; Bankston and Chant, 1986; Boysen and Chant, 1986; Boysen, 1987)

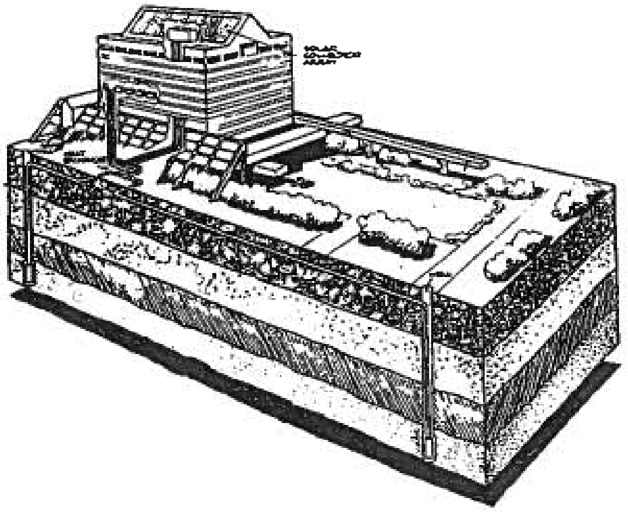

Figure 1: Scarborough Canada Centre Building

2 DESCRIPTION

2.1 Building

The Scarborough Canada Centre Building is 14 stories with 30,470 m^2 of usable floor area, including two floors of underground parking. Construction is of concrete and double glazed windows cover 35% of the wall area. The building and underlying aquifer are shown in Figure 1.

The site is at latitude 43.8° North. There are 3939 heating degree days and 236 cooling degree days (relative to 18° C) annually. The average January temperature is –6.3° C and the average July temperature is 20.8° C. The climate is strongly moderated by Lake Ontario.

Figure 2 shows the annual profile of the heating and cooling loads as calculated by the Merriwether program. The annual heating load is 2279 MWh (8.2 TJ) and cooling load is 3332 MWh (12 TJ). Because of the building's low surface area to volume ratio and large amount of insulation, the cooling load is greater than the heating load. Because of internal heat gain at the core and heat loss from the building shell, there is often a simultaneous heating and cooling load.

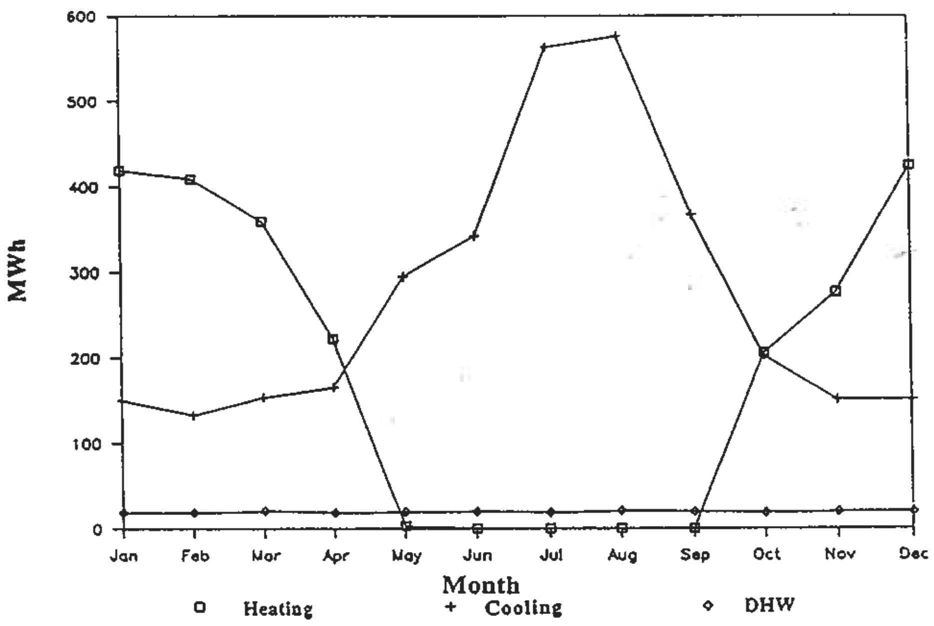

Figure 2: Building Loads

2.2 Aquifer

The Scarborough site stratigraphy includes two aquifers; an upper aquifer of fine sand separated by a 10 m layer of clay from a lower aquifer of medium sand. The lower aquifer has superior hydraulic properties and is the one being used for energy storage.

In 1982–83, tests were performed on the Scarborough Aquifer using a 150 mm diameter test well near the middle of the property. Aquifer properties include:

Natural Temperature	9°C	Regional Flow	24 m/year
Thermal Conductivity	1.56 W/mK	Density	2670 kg/m^3
Heat Capacity	2.41 MJ/m^{3}K	Porosity	0.28
Thickness	7.5 – 10 m	Piezometric Head	30 m
Yield (two wells)	83 – 100 l/s	Transmissivity	150–200 m^2/day
Storativity coefficient	10^{-4}	Dispersivity	0.02–0.26

Analysis of the groundwater chemistry showed it was slightly alkaline and hard, with rather high concentrations of dissolved iron and manganese, and very high levels of dissolved methane. The high iron content dictated the use of a closed system of pumping.

Due to the limited size of the property, two pairs of production wells were used, one near each corner of the rectangular property. Production wells are 130 m apart, with the pairs 65 m apart. Each well is 355 mm in diameter and packed with gravel. A variable speed pump transfers 18 to 40 l/s of water at a head of 760 kPa. In addition to the four production wells, there are 14 observation wells spread over the site. (Mirza et al., 1985) Each is 65 mm in diameter and contains two pressure transducers for measuring water level and five temperature sensors. The positions of the production and observation wells are shown in Figure 3.

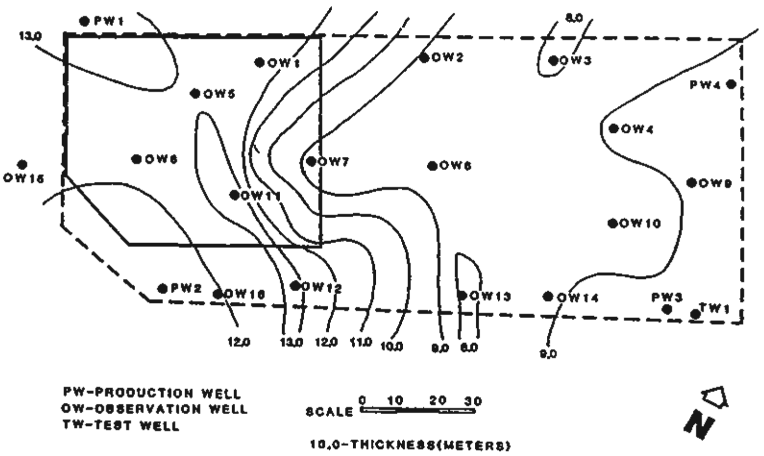

Figure 3: Scarborough Aquifer Well Locations and Thicknesses

2.3 Heating and Cooling System

The following major components are available for the heating and cooling of the building: heat pumps, cooling towers, solar collectors, boilers, short-term storage tanks, and the aquifer for long-term energy storage. Operation of components is performed by a computerized energy monitoring and control system. (H.H. Angus, 1985)

The Scarborough building configuration is shown in Figure 4. The figure depicts the interaction of the building's energy components.

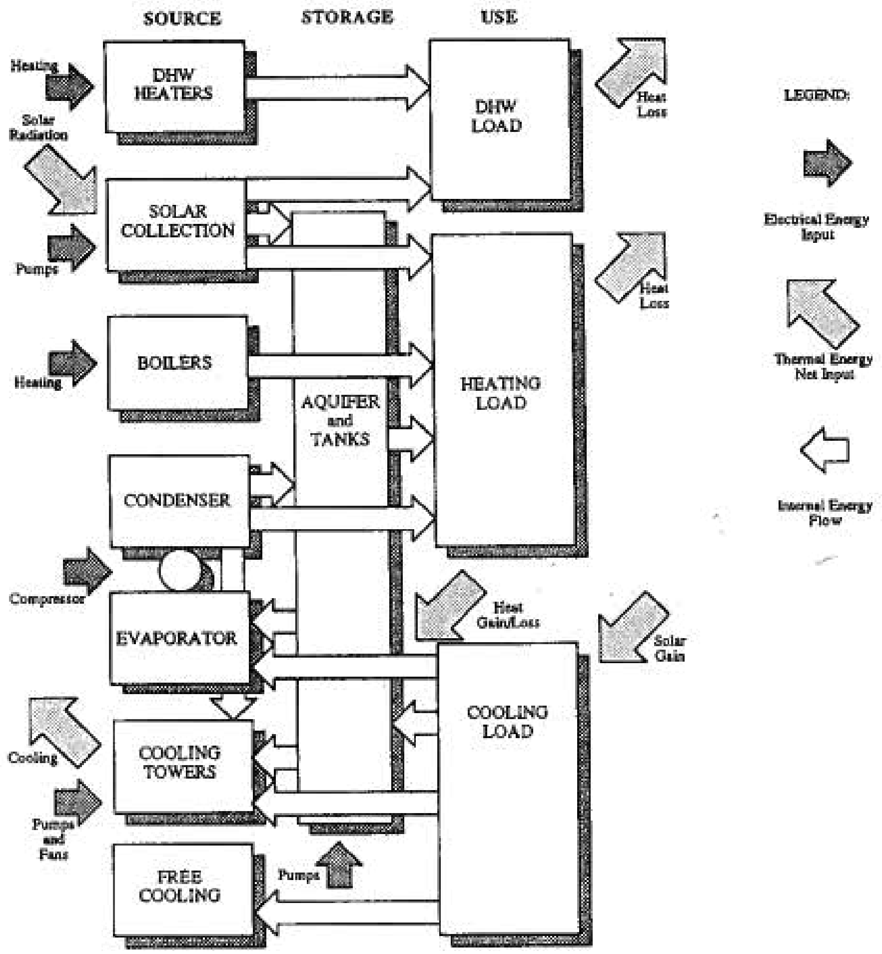

Figure 4: Schematic Diagram

3 OPERATION

3.1 Theoretical

The theoretical optimal operation of the heating and cooling system relies heavily on the use of the aquifer in conjunction with the heat pump on a seasonal basis. (Arthurs et al., 1987) Selection of individual components at any particular time depends on the conditions, but in general the interaction of the heat pump and aquifer is as shown in Figure 5.

In the winter, the net heating demand is met first by direct heating from the aquifer. Later, when the temperature of the aquifer has fallen, the heat pump is used to extract additional heat, thereby cooling the aquifer in preparation for summer cooling. In the summer, the net cooling demand is met first by direct cooling from the aquifer. Later, when the temperature of the aquifer has risen, the heat pump is used to extract additional 'cold', thereby heating the aquifer in preparation for winter heating.

Use of the aquifer and heat pump together, therefore, provides two distinct advantages:

- The heating and cooling demand are balanced at all times (because of seasonal storage), resulting in high heat pump efficiencies; and
- Storage temperatures can be maintained near ambient ground water temperatures, resulting in high storage efficiencies.

Use of the aquifer and heat pump in this way is subject to a suitable building energy demand profile. (Arthurs et al., 1988a) Auxiliary heating or cooling from boilers or cooling towers may be needed at some points. Also, the heat pump may be required to improve the quality of energy stored in the aquifer at times when the theoretically optimal operation indicates that the heat pump will not be used. Various problems have prevented this optimal seasonal operation from being used so far.

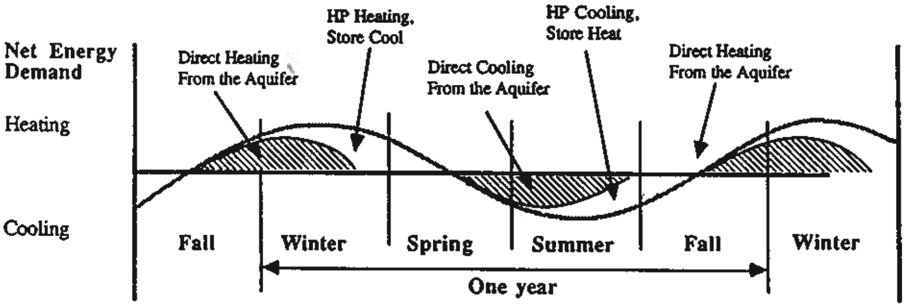

Figure 5: Optimal Heat Pump and Aquifer Interaction

3.2 Experience

The aquifer at Canada Centre has been operational since January 1986, but automated monitoring began only in January 1987. Results to date indicate that the aquifer is operating close to expected performance. The aquifer has been utilized for both heating and cooling during the first year and a half. (Arthurs et al., 1988b; Strata, 1986a, 1986b, 1987)

The aquifer field trial at Canada Centre was intended to be experimental and, not surprisingly, problems have been encountered. Experience with aquifer operation is one of the areas where information is being shared internationally as part of the IEA cooperative effort identified above. The more significant problems have been:

- Canada Centre occupancy levels have been only one half of those anticipated in design calculations.
- The aquifer was added after the original design of the building, with the result that the heat pump was improperly sized to interact with the aquifer. The heat pump has been modified so that storage and extraction of energy from the aquifer using the heat pump is possible.
- The data acquisition system is not fully operational. Choice of data points and data recording algorithms were designed for building operation and not experimental analysis purposes. Presently data collection is less complete than would be desirable.
- Public Works Canada is the sponsor of these aquifer field trials, but leases, rather than owns the building. Although the building owners have been cooperative, useful experimental operational strategies are limited. In particular, strategies which would result in increased energy consumption are resisted by the building owners.
- Due to temperature calibration problems with the building's computer system, all measurements and monitoring of the aquifer have been carried out manually.
- Leakage due to large water rises at injection wells has limited pumping speeds to 70% of capacity. This is not an injection related problem, but rather one of system design and integrity.
- Lightning strikes destroyed 65% of the initially installed pressure transducers. These are now protected with lightning arresters.

In spite of the problems, the field trial has provided useful experience:

- Charging of the aquifer with cold has been proceeding using the cooling towers and cooling of the building using the aquifer is occurring. The building operators feel that the aquifer is beneficial and easy to use; and
- No hydro–geological problems have developed. The need for frequent backwashing has not developed. No appreciable clogging (either chemical or biological) has occurred and the wells are continuing to operate efficiently.

4 COMPUTER SIMULATION

4.1 Simulation Program

A computer program called ABES (Aquifer Building Energy System) has been developed by the project team. (Angers, 1988) This program simulates the energy flows associated with heating and cooling a large building in order to analyze the costs and benefits of energy storage using aquifers. The program is currently tailored to the Scarborough Canada Centre Building. With some adaptation, the program can be used to simulate any building of similar conception.

The program simulates one year of building operation from January to December in monthly time steps. It consists of a Lotus 123 spreadsheet and a Pascal program. The spreadsheet is used to facilitate input to the model and display final results. The Pascal program does the actual simulation of the energy flows.

The model produces a breakdown by month of the energy flows between components and the flows from components to loads. If any loads remain at the end of a month, they are flagged. A month-by-month value for electrical energy consumption is also given.

For each component, the utilization percentage by month is output along with a total pumping energy consumption and electrical energy consumption. Finally, an analysis of the capital, operating and maintenance costs by component is output. This is used to calculate the energy unit cost of heating and cooling the building.

Preliminary results from the application of the ABES program to the Scarborough Canada Centre Aquifer Field Trials show it to be a flexible, fast, easy to use, and useful tool. It is not overly sophisticated, but its results have been validated for use in comparing the relative strengths and weaknesses of alternative system configurations and operational strategies.

4.2 Results

The annual heating, cooling, and domestic hot water loads for the Scarborough Canada Centre Building are shown in Figure 6. The cooling load has already been reduced by the amount which can be met through free cooling (bringing cold outside air into the building). In the figure, each load has been divided into its winter (October to April) and summer (May to September) components. It can be seen that there is a simultaneous heating and cooling load during the winter because of internal heat gain at the core of the building combined with heat loss to the environment at the perimeter.

When simultaneous heating and cooling loads exist, the heat pumps can be used to transfer heat internally. Figure 7 shows the loads after taking advantage of possibilities for balancing heating and cooling requirements. The ABES program has been used to examine alternative ways of meeting these loads.

The following five operational strategies for meeting loads were considered:

Base - the aquifer is not included in the heating and cooling system;

HP Cool -the aquifer, assisted by the heat pump, is used only for cooling;

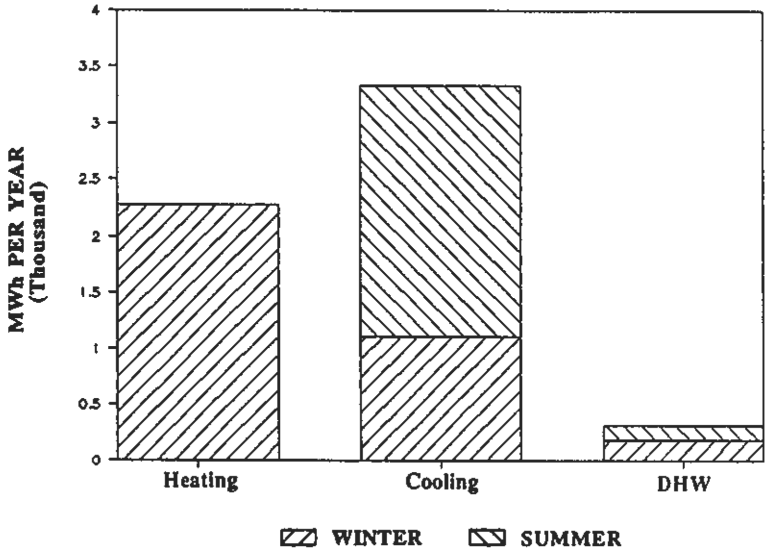

Figure 6: Loads

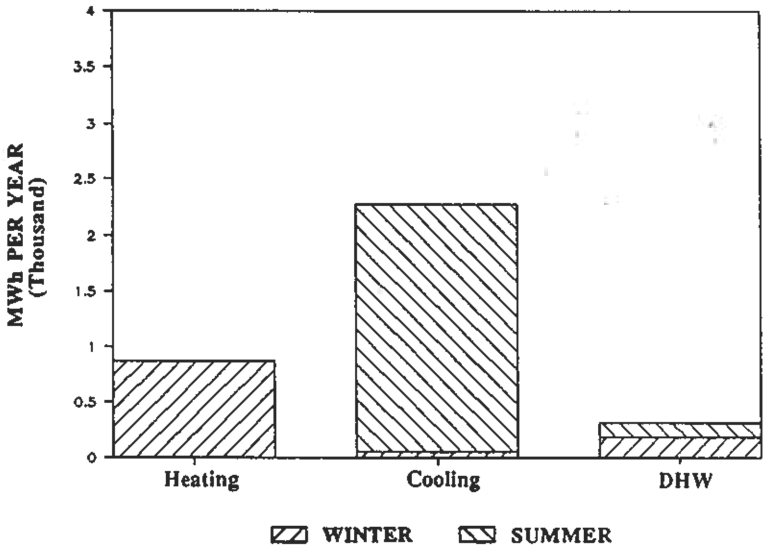

Figure 7: Loads After Balancing

AQ Cool -the aquifer, without assistance by the heat pump, is used only for cooling;

AQ Heat -the aquifer is used for heating only using solar energy stored during the summer; and

AQ H&C -the aquifer is used for heating and cooling, balancing total annual heating and cooling loads. The net cooling requirement is met by the heat pumps with the cooling towers.

The proportional energy flow diagram for the 'AQ H&C' operational strategy is shown in Figure 8.

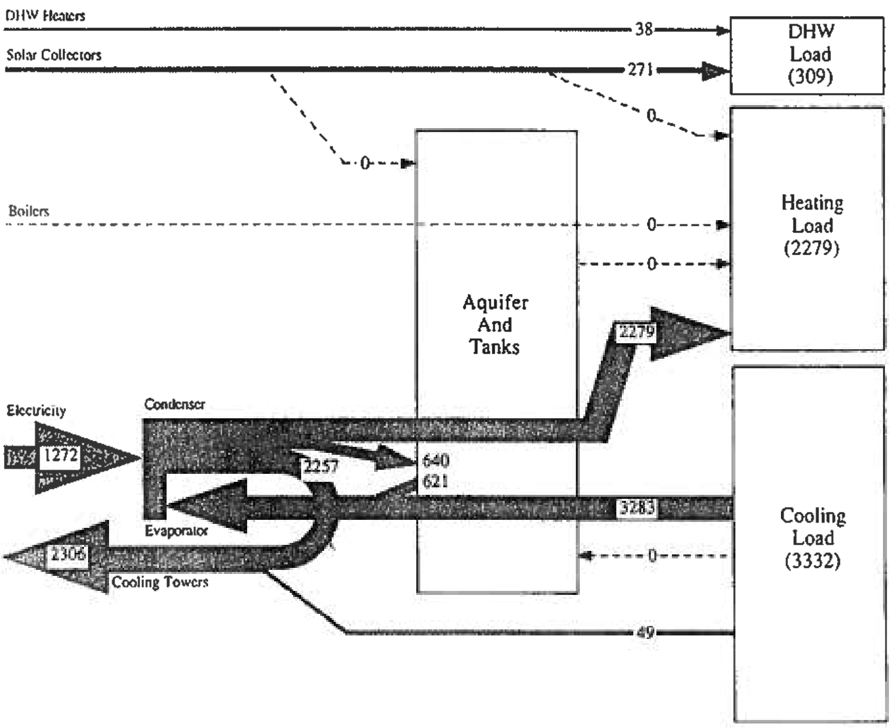

Figure 8: Proportional Energy Flow Diagram

Figure 9 compares the heating and cooling energy contribution to the load of each component under each of these five operational strategies.

Figure 10 then compares the electric energy utilized by each of the five operational strategies in providing the heating and cooling energy. All strategies, except heat pump cooling, are more energy efficient than the base strategy. Low energy utilization implies low operating costs.

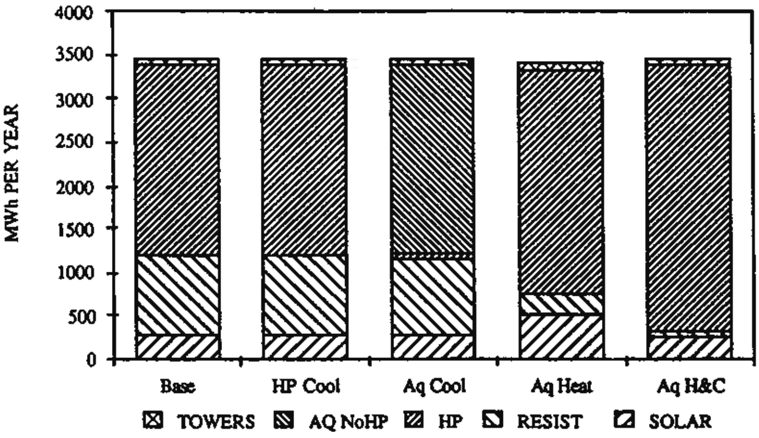

Figure 9: Meeting the Loads

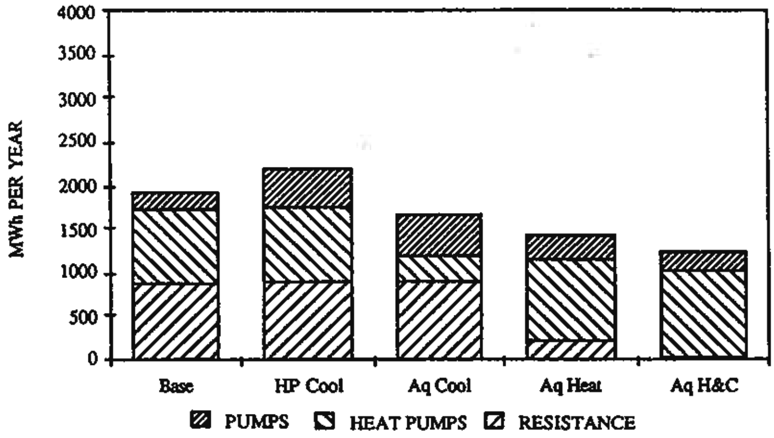

Figure 10: Use of Electrical Energy

The effect of capital costs, however, is substantial. Figure 11 compares the cost of meeting the heating and cooling loads under each of the five operational strategies. The overall cost of energy includes amortized investment costs, energy costs and maintenance costs. Even though most strategies are more efficient than the base strategy from an energy perspective, only the aquifer heating and cooling strategy has lower overall cost than the base strategy because of the high capital cost of the aquifer.

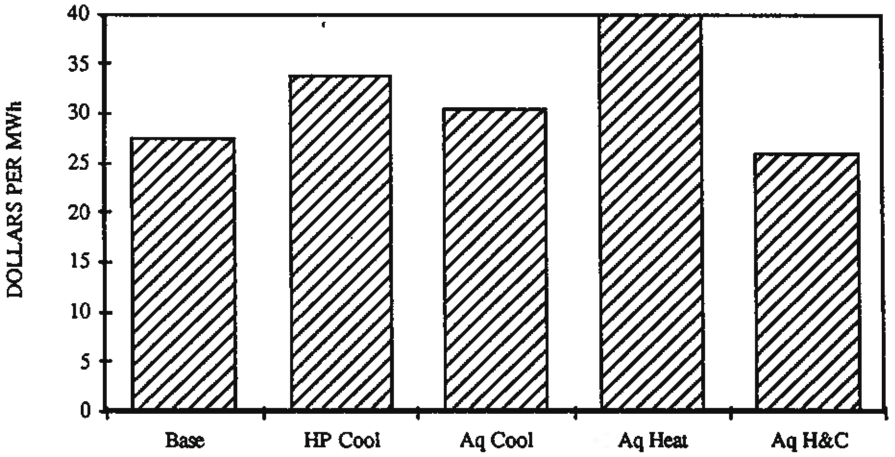

Figure 11: Average Unit Cost to Load

The efficiency of use of the aquifer heating and cooling operational strategy depends on the balance between heating and cooling loads on an annual basis. This characteristic has been examined using the model by varying the ratio of heating and cooling load while keeping the total load constant.

As shown in Figure 12, the operating cost of the building goes through a minimum as the relative amounts of heating and cooling are varied. The minimum cost point is where the annual heating load is 44% of the total (heating plus cooling) load. This ratio of cooling to heating of 1.25 is greater than unity because of the use of the heat pump — when used for heating, heat pump input energy is delivered to the load, but when used for cooling, the input energy is a loss.

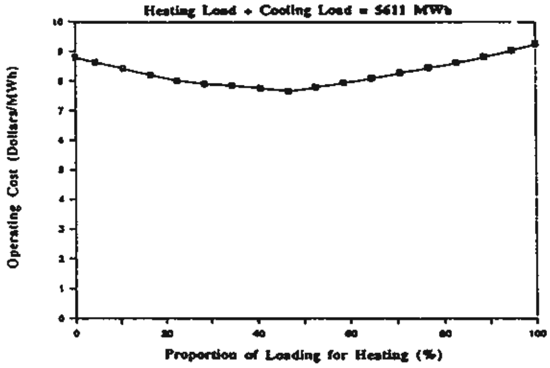

Figure 12: Aquifer Used for Heating and Cooling

4.3 Comparing Operating and Simulation Experience

In order to validate computer simulation results it is necessary to compare them with actual building operating experience. The electrical energy used for heating and cooling is an effective statistic for making such a comparison. The ABES model and the Merriwether program both include monthly values for electrical energy used for heating and cooling as a part of their output. The actual operating values were more difficult to extract. The electrical energy used for heating and cooling was estimated monthly by subtracting the amount of electricity thought to be used for non-heating/cooling purposes from the total monthly electrical consumption for the building's operation. The results of the comparison are shown in Figure 13. Despite the approximate nature of the calculations the results are comparable.

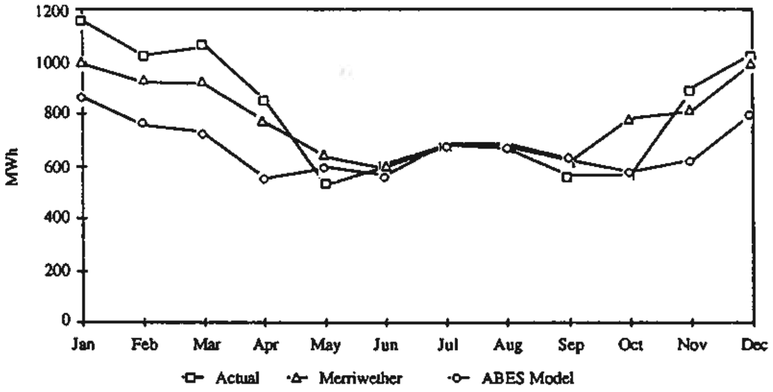

Figure 13: Energy Use Comparisons

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APPENDIX B: Finland - Kerava

FINNISH NATIONAL EVALUATION SUMMARY
Based on the evaluation of Kerava Solar Village

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1 INTRODUCTION

Kerava Solar Village (KSV) is the first, and thus far, the only experimental CSHPSS plant in Finland. It was designed in 1980-81 and built during 1982-83. The initial goal of the project was to test new energy technologies including solar energy collection, seasonal heat storage and large heat pumps. As the KSV is a pilot plant, it has primarily been designed for research purposes and no economic or technical optimization has been performed.

The village is located 30 km north from Helsinki (60° 24'N). The average weather conditions at the nearby Helsinki-Vantaa airport, some 15 km NW from KSV are given in Table 1.

Table 1. Average weather conditions in KSV.

	Annual	June	December
Mean ambient temperature°C	+5.4	+14.3	-3.2
Global rad. on hor., MJ/m^2	3421.8	640.4	15.9
Diffuse fraction,%	39.8		
Average wind speed, m/s	<6.0		
Heating deg.days	4377.0	18.0	637.0

2 SYSTEM DESCRIPTION

The KSV comprises 44 flats with a total heated floor area of 3756 m^2. The heating system has four major components: combined water and duct storage, solar collectors, electric driven heat pump and electric boilers.

The solar collectors are non-selective, single glazed flat plate collectors with a unit size of 2.5 to 3 m^2. The total collector area is 1100 m^2. They have been installed on the southern facades and roofs of the buildings with tilt angles of 70° and 90°. A 50% water-glycol mixture is used as the heat transfer fluid.

All the energy collected is transferred into a central 1500 m^3 water storage excavated in bed rock. The stratification in water storage is maintained with a movable return pipe. Additional storage capacity is provided by 11 000 m^3 of rock surrounding the water storage. The rock storage can be cooled or heated by 54 boreholes drilled around the water storage in two concentric cones with 18 ducts in the inner and 36 in the outer cone. The total length of boreholes in the inner circle is 400 m and in the outer 860 m.

An electric driven heat pump is used for upgrading the temperature of the stored heat. Lower parts of the water storage are used as a heat source and the uppermost few meters serve as the short term storage for high temperature heat from the heat pump condenser. The heat pump has thermal power of 400 kW at the nominal operating point (leaving temperatures 10 °C for the evaporator and 70 °C for the condenser).

Two 200 kW electric boilers have been installed for back-up purposes. They can meet the entire heat load. System schematics illustrating various operating modes are indicated in Figure 1.

3 THERMAL PERFORMANCE

The original design goal was for solar energy to provide 75% of the energy requirements. The design work was done by a private consulting company. The models employed were relatively simple and input values partly erroneous resulting in rather optimistic results. Later on, the theoretical performance characteristics of the KSV system have been re-calculated at the Helsinki University of Technology. Figure 2 summarizes the original design values (Vuorelma, 1982) and Figure 3 the results from re-calculation (Lund & Peltola, 1987). The recalculation reflects both the expected performance of the plant as built and the intended operational mode.

The Kerava Solar Village has been in operation since May 1983. A comprehensive monitoring and evaluation programme has also been in place during this period. In Fig. 4, energy balance data are given for the year 1984 (Lund & Peltola, 1987), as it best reflects the system operation. Several component failures, mainly related to the heat pump, marred the system behaviour during the other years.

The theoretical energy balance of Fig. 3 indicates the expected thermal performance of the KSV plant under faultless operating conditions. Full utilization of the duct storage has been assumed. Accordingly, the available storage capacity is larger than that used in practice during 1984 (Fig. 4). The duct storage was not actively charged during the first years of operation. The ducts were used only for collecting the water storage heat losses.

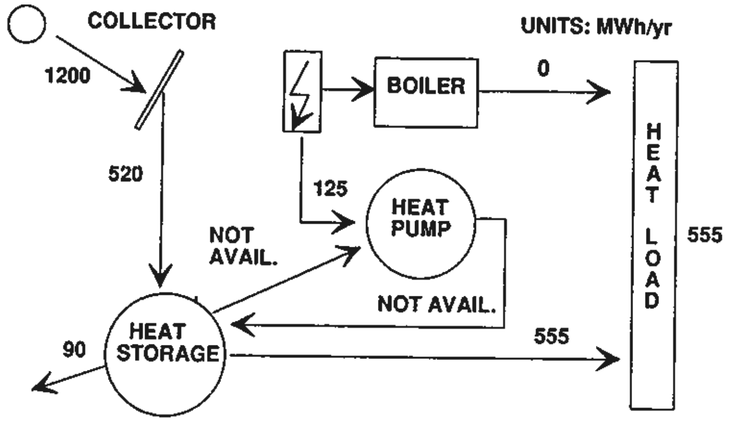

Figure 2. Thermal performance of the Kerava Solar Village according to the original design.

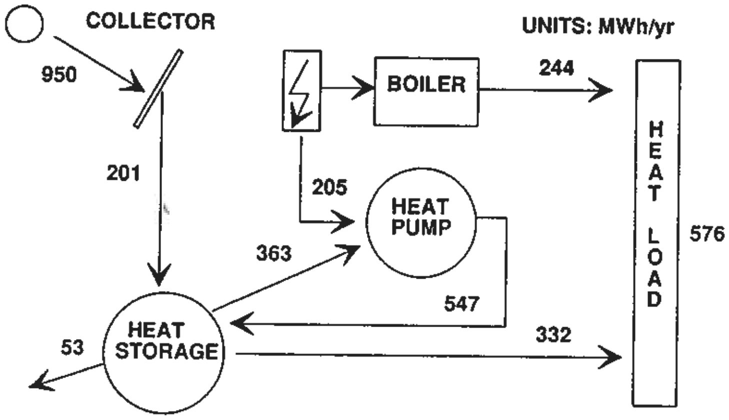

Figure 3. Recalculated theoretical energy balance of the Kerava Solar Village. Note that the solar radiation indicated corresponds to the average total horizontal radiation.

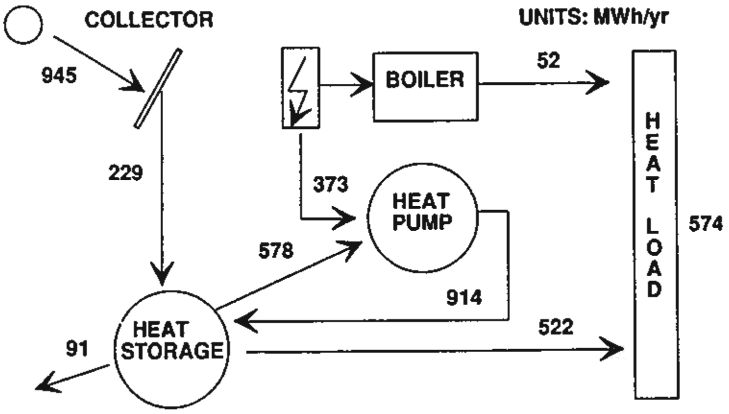

Figure 4. Measured energy balance of the Kerava Solar Village (1984). Note that the radiation indicated is the measured total radiation on the collector surface.

Figures 2 to 4 indicate that the original design goal was too optimistic. The village was designed before proper design tools were available and experience with other CSHPSS's was available. The simulation models used during the design phase employed only simple energy balance methods and not enough attention was paid to energy quality problems or temperature limitations. Furthermore, the heating system controls were neglected.

During the evaluation program, improved simulation models have been developed. The accuracy of these computer codes is good. They have been used for finding the bottle necks in the system operation and to analyze some practical improvements in plant operation.

An example of such a calculation is the analysis of the KSV thermal performance under optimal control strategy and enhanced duct storage utilization. By activating the duct storage usage, one can increase the available seasonal storage capacity. When at the same time, the control system is revised so that the losses in energy quality are reduced, a substantial improvement can be gained. Figure 5 indicates the annual energy balance under these conditions.

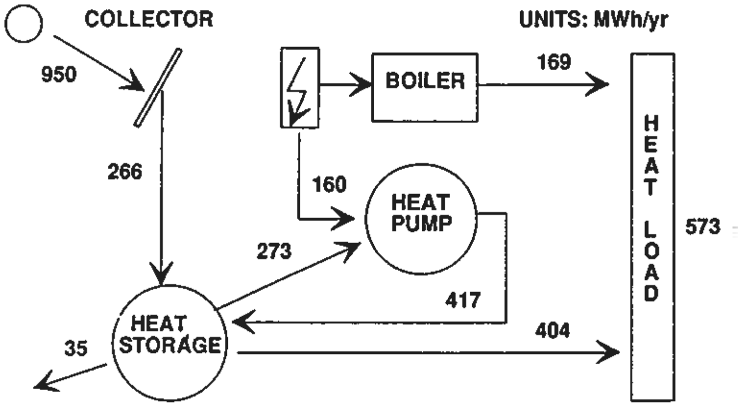

Figure 5. Energy balance of the Kerava Solar Village with enhanced duct storage utilization and optimized control strategy.

The models have also been used for more fundamental re-design of the system. Calculations have been performed to determine the optimal main system sizing parameters with the original basic configuration. As the KSV system configuration with combined water and duct storage cannot be properly described by the MINSUN model (Chant, Håkansson, 1985), the thermal performance has been evaluated with the SUPERSOL model (Lund,1987). The economic analyses have been done with SUPECON code (Lund, Keinonen,1985).

Three load sizes have been considered in the optimization. In addition to the original village load (44 flats, 0.55 GWh annual load), we used 5 and 20 GWh loads.

The main results are shown in Fig. 6. For the original load size, no optimum point could be found but the energy cost was steadily rising with solar fraction. For the larger load sizes, a very flat optimum is obtained. The minimum energy cost was obtained with a 4000 m^2 collector area and 10 000 m^3 of storage for the 5 GWh annual load. The corresponding parameters for the 20 GWh annual load were found to be 20 000 m^2 and 50 000 m^3 , respectively. However, in the solar fraction interval from 20 to 50 %, the energy cost rises at a maximum of 5 % above the overall optimum cost. Accordingly, the actual sizing can be based on parameters other than the final energy cost, if the sizing is close to the optimal configuration.

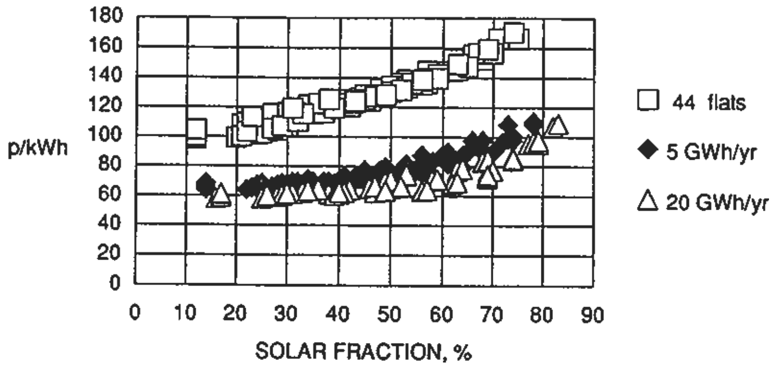

Figure 6. Total energy cost vs. solar fraction for KSV type CSHPSS systems of three sizes. 1 US$ = 4 FIM, 1 FIM = 100 p.

4 CONCLUSIONS

The Kerava Solar Village is a pilot plant, in which several new energy technologies have been tested under actual operating conditions. It has served as a valuable source of practical knowledge and has provided experimental data needed in the development of theoretical models.

The practical experiences with the operation of the KSV heating system components has been mainly satisfactory. For example, no major collector problems have been detected. The seasonal heat storage efficiency has been above 80%. Also, the short term storage of heat in the uppermost parts of the water storage has made it possible to benefit from off-peak electrical rates.

The biggest problems have been with the heat pump, which has failed several times. As the system performance is very closely connected to the heat pump operation, the problems have strongly influenced the system performance. A fundamental problem in the KSV system design is the low storage volume tocollector area ratio. According to simulation studies, an optimized system would have a ratio of at least double that of the actual system.

Experiences from the KSV have indicated the importance of energy quality aspects. As the solar energy is collected at a relatively low temperature, one should avoid the mixing of different temperatures for as long as possible. For example, in the original heating system, a common return pipe was used for both the collector and distribution loops. This resulted in the mixing of water at different temperatures.

In the KSV heating system, as in many other experimental projects, several new ideas were tested simultaneously. Accordingly, the control system has a variety of different operating modes. It now is evident (Lund, 1987) that simple systems are preferred. This would possibly result in slightly decreased theoretical performance indices, but would offer better operational characteristics because of improved availability and ease of maintenance.

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APPENDIX C: FRG - Stuttgart University

EVALUATION SUMMARY OF THE STUTTGART UNIVERSITY PROJECT

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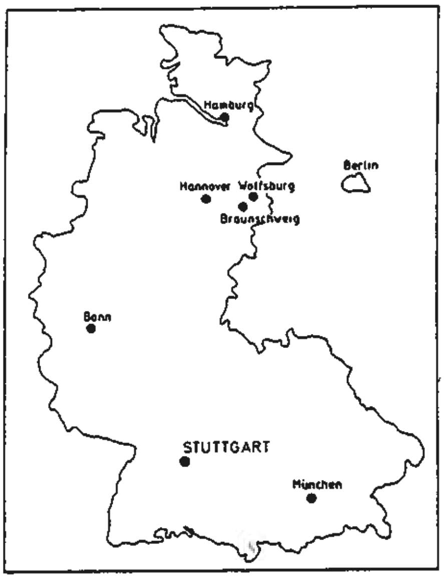
1 INTRODUCTION

The Stuttgart University plant is the first solar-assisted long-term thermal energy storage project in the Federal Republic of Germany (FRG). The storage is a water/gravel-filled pit with a volume of 1050 m^3. The project is located on the campus of the university of Stuttgart in Stuttgart-Vaihingen at latitude +47° 47', longitude 9° 10'E and at an elevation approximately 460 m above sea level (Figure 1).



Climate:

Global radiation on a horiz.surface (yearly)	938 kWh/m^2
Diffuse portion	48 %
Sunshine hours (yearly)	1560 h
Average ambient temper.	10.1 °C
Degree days (VDI 2067)	3432 DD
Average wind speed	1.7 m/s

Figure 1. Location.

2 DESCRIPTION

2.1 Overall System

Figure 2 shows the interconnections between the components of the heating system. The system consists of 211 m^2 unglazed collectors, an electric heat pump with 66 kW_{th}, a long-term heat storage with a volume of 1050 m^3 and a low-temperature (50/40 °C) distribution heating system. Two different storage concepts are combined: an artificial aquifer with loading and unloading by direct water exchange (right part of storage in Figure 2) and heat exchange by a register of horizontal polyethylen (VPE) coils (Fisch, 1986).

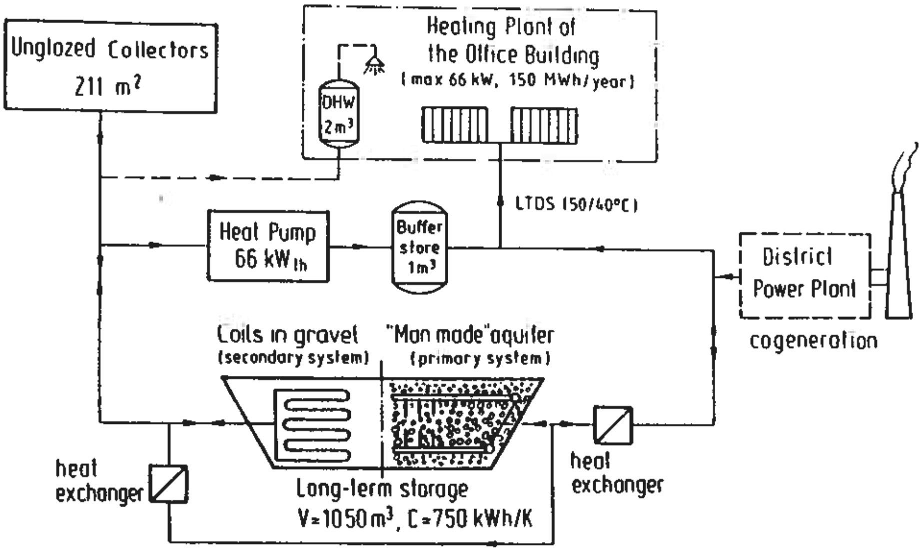


Figure 2. System schematic.

2.2 Solar Collector Subsystem

The unglazed collectors (absorbers) are mounted on four nearly south-facing shed-type roofs (45° tilt angle) on the building. A combination of three types collectors of two different brands are used. The net collector area is 211 m^2. The area-weighted intercept and slope of the entire collector field efficiency curve are $F' \cdot \alpha_A^*$ = 0.634 and $F' \cdot U_L$ = 15.8 $W/(m^2 \cdot K)$, respectively.

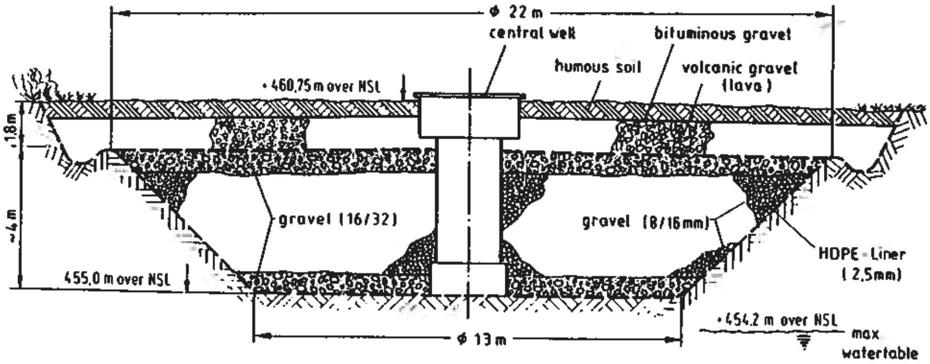


Figure 3. Cross section of the storage.

2.3 Storage Subsystem

The truncated cone-shaped store has a gross volume of 1050 m^3 and a water flooded volume of about 956 m^3 The (Figure 3). The gravel filling has a porosity of 37 %. A 2.5 mm thick high density polyethylen (HDPE) liner was applied to the store basin as a water-proofing layer. The store was insulated at the top only by a 0.9 m volcanic gravel (lava) layer. Heat can be exchanged by way of direct water exchange (aquifer) or, as used during the long-term cycles, by eight coils of polyethylen (VPE) tubes with an entire length of approximately 4600 m.

2.4 Building and Heating Load

The building is an office of a University Institute. It has two storeys and a floor area of 1375 m^2. The total heat demand was estimated to be 150 MWh/a and the yearly consumption of domestic hot water was estimated to be 25 MWh/a.

2.5 Heat Pump

The electric heat pump uses R12 refrigerant and was designed for ϑ_{evap} = 0 °C, ϑ_{cond} = 55 °C, P = 66.5 kW_{th}, COP = 3.4. Real heat pump operation yielded much lower COP values.

A new heat pump has been in operation since March 11, 1988. Performance data are available, which are appropriate to the real operating conditions of the system and the store (highest, lowest storage temperature). Measured performance data in terms of the coefficient of performance (COP) of the new heat pump are compiled in Table 1.

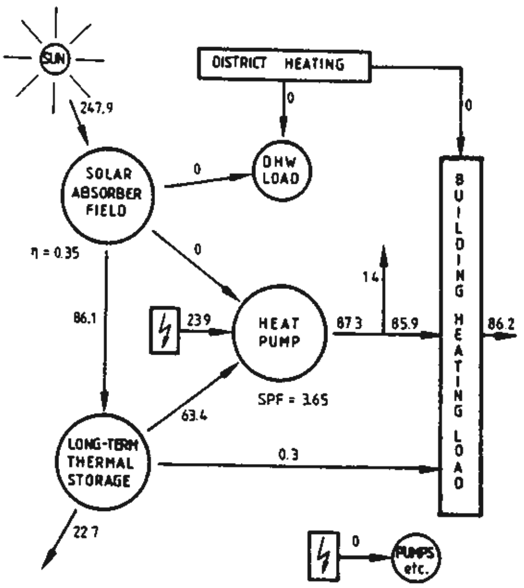
Heating Temperature	Heat Source Temperature			
	0 °C	10 °C	20 °C	30 °C
35 °C	3.2	3.9	4.7	5.5
45 °C	3.0	3.5	4.0	4.5

Table 1: COP values of the new heat pump (measured) for various operating conditions.

3 Performance

3.1 Original System Design

The simulation was performed with the simulation program "MINSUN" based on hourly weather data from a "Test Reference Year" for Würzburg, which has a climate similar to Stuttgart. Figure 4 shows an energy flow diagram of the yearly heat balance of the original system design.
Almost the total heating load of the building can be covered by the heat pump. Only a small part of the heating demand can be delivered directly from the storage. The predicted thermal performance factors on annual basis are:



Collector field effectiveness	0.35
Heat pump SPF (seasonal performance factor)	3.65
Storage effectiveness	0.74
Solar fraction	0.74

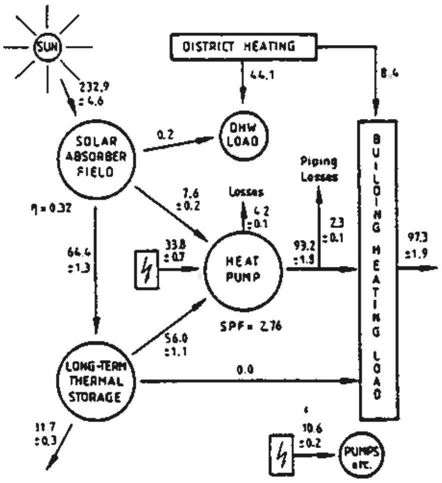
The storage temperature varies between 0°C and 32.5°C, net storage heat losses are 26 % of the charged heat.

$$\Delta Q_{St} = -0.3 \text{ MWh}$$
$$\vartheta_{min} = 0 \ ^\circ C$$
$$\vartheta_{max} = 32.5 \ ^\circ C$$

Figure 4. Original system design, calculated with MINSUN, Test-Reference-Year.

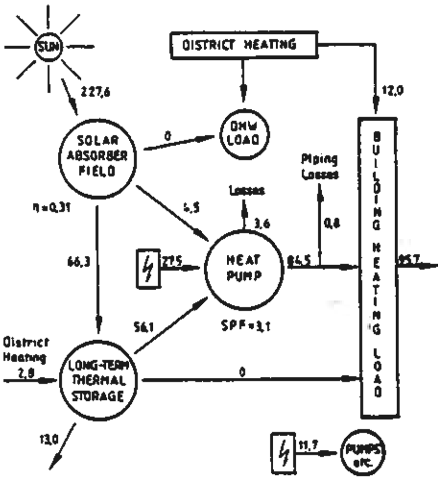
3.2 Measured values for the real system

The system has been operating since April 18, 1986 as a solar heating plant with seasonal storage. Results can be presented for two years of seasonal operation from April 18, 1986 to April 17, 1987 (1^{st}-cycle) and from April 18, 1987 to April 17, 1988 (2^{nd}-cycle). Figures 5 and 6 present the first and second cycle results as flow diagrams. The heat pump covers most of the total heating load of 97.3 MWh in the first cycle. The district heating had to meet nine per cent of the load, and there were no direct contributions to the load from the collectors and the storage. The average store temperature varied from 0 °C to 32.9 °C. In the second cycle the heat pump supplied 87.5 per cent of the total heating load (95.7 MWh). The high amount of district heat fed to the load (12 MWh) was caused by the installation of the new heat pump in the period of low outdoor temperatures (February 17 to March 11, 1988). About 2.8 MWh of district heat were fed to the store in experiments in order to perform heat transfer measurements from coils to the gravel/water-filling. No heat was delivered directly from either the collectors or the store to the load. The average store temperature varied between 1.7 °C and 31.3 °C. In both cycles the circulating pumps registered high energy consumption. For more information about results see Fisch, 1987 and Fisch, 1988.



$$\Delta Q_{St} = -3.3\ \text{MWh}$$
$$\vartheta_{min} = 0\ °\text{C}$$
$$\vartheta_{max} = 32.9\ °\text{C}$$

Figure 5. Measured energy flows in 1986/87 for real system design



$$\Delta Q_{St} = 0\ \text{MWh}$$
$$\vartheta_{min} = 1.7\ °\text{C}$$
$$\vartheta_{max} = 31.3\ °\text{C}$$

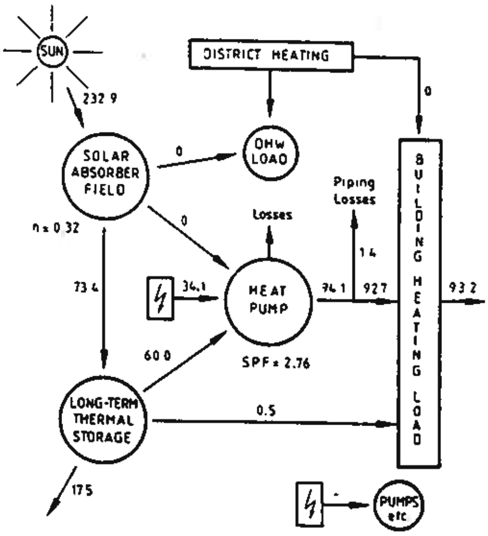
Figure 6. Measured energy flows in 1987/88 for real system design

Table 2 presents the thermal performance factors of the system.

	1st cycle	2nd cycle
Collector field effectiveness	0.32	0.31
Heat pump SPF	2.76	3.1
Storage effectiveness	0.82	0.8
Solar fraction	0.6	0.59

Table 2: Thermal performance factors

3.3 Recalculated performance



$\Delta Q_{St} = -4.6\ \mathrm{MWh}$

$\vartheta_{min} = 0.1\ ^{\circ}\mathrm{C}$

$\vartheta_{max} = 33.2\ ^{\circ}\mathrm{C}$

After the first cycle a simulation has been performed with the real parameters of the system and measured weather data of the first cycle. The energy flow diagram is shown in Figure 7. The performance factors are:

Collector field effectiveness	0.32
Heat pump SPF (seasonal performance factor)	2.80
Storage effectiveness	0.75
Solar fraction	0.63

Figure 7. Recalculated performance (MINSUN), measured weather data, 18.4.86 - 17.4.87.

4 Discussion

The measured seasonal performance factor (SPF) in both years was lower than the predicted (3.65). The reasons for the unsatisfactory SPF of the heat pump were: a) the heat pump was designed for too low heat source temperatures, and a temperature level above 12 to 15 °C in the store cannot be used and b.) there was an extremely high pressure drop in the evaporator. A failure in the control system, which sets the partial load switch of the heat pump, was detected in November 1987. Disregarding the heating demand of the building the heat pump always ran with a load of 100 per cent. With the elimination of this failure, the SPF improved slightly to 3.1 in the second year.

The storage effectiveness was higher than expected in both cycles. Good results are achieved by insulating the top of the store. As neither side nor bottom walls were insulated, much of the heat loss to the surrounding soil was regained. The recalculated performance shows good agreement with the measured performance.

5 Redesign

Redesign studies performed for the Stuttgart aquifer project include:

- investigation of a system with variable mass flow in the collector circuit;
- optimization of the heat pump;
- variation of the unglazed collector area and the storage volume; and
- investigation of a system with high efficient flat plate collectors.

The results are:

- With variable mass flow in the collector circuit, the system performance increases only slightly.
- A higher heat transfer capacity in the condenser and evaporator improves SPF and solar fraction and decreases solar cost.
- The Stuttgart project has relatively high storage cost. An optimization of this system to obtain minimum solar cost yields a higher collector area and a lower store volume than the actual system.
- With high efficient flat plate collectors (100 m^2), the same solar cost and solar fraction as in the actual system can be obtained. For higher solar fractions (>80%) however the flat plate collectors are advantageous.

6 Conclusions

The new heat pump has a higher electric power (old: 22 kW_{el}, new: 26 kW_{el}) and an evaporator with an extended heat exchanging area and lower pressure drop within the refrigerant flow. This resulted in an improved value of COP compared to the old heat pump. In April and May 1987, the old heat pump worked with COPs of 2.7 and 2.9, respectively. In April and May 1988 the new engine worked with COPs of 3.6.
The control strategy for heating the building was changed in April 1987 (the beginning of the 2nd seasonal cycle). The overnight room temperature setdown was cancelled, yielding lower building peak loads in the morning and increasing the partial load operation of the heat pump.

The man-made aquifer has worked well without failures. There were no problems with the chemical and biological water quality of the storage during both cycles.

Good thermal and economic performance is expected for a man-made aquifer combined with high efficient flat plate collectors, which work at a higher temperature level. Scaling up such a system improves storage efficiency and decreases solar cost.

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APPENDIX D: Italy - Treviglio

ITALIAN NATIONAL EVALUATION SUMMARY

Based on the evaluation of Treviglio system

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1 INTRODUCTION

The Italian National Project for Task 7 of the IEA Solar Heating and Cooling Programme on "Central Solar Heating Plants with Seasonal Storage" or CSHPSS is located in Treviglio, Italy. It is referred to as the Treviglio Project. This system was constructed privately. The design was completed in 1980 by GELDIN, a private engineering firm. The financing was shared equally between the owners and the government through a grant. The system has been in operation since the summer of 1982. Partial monitoring was installed in the Spring of 1985 and complete monitoring in November of 1986. A public research group, unrelated to the owners or the designers, is responsible for the performance evaluation.

The town of Treviglio is located near Milan, in the northern part of Italy, at longitude 9° 30' east, latitude 45° 31' and at an altitude of 120 m . The average weather conditions are given in Table 1 .

Table 1. Average weather conditions

Average Yearly Temperature	14.1	°C
Average June Temperature	19.7	°C
Average December Temperature	3.3	°C
Yearly Solar Radiation on Horizontal Surface	1.3	MWh/m^2
Solar Radiation on Horizontal Surface, June	190	kWh/m^2
Solar Radiation on Horizontal Surface, December	27	kWh/m^2
Yearly Average Wind Speed	0.4	m/s
Degree Days	2150	DD
Heating Period	180	days

2 SYSTEM DESCRIPTION

The Treviglio Project consists of five apartment buildings each heated by solar-assisted heat pumps with seasonal ground storage located below the buildings. Three heating plants, **CT1**, **CT2** and **CT3** (Centrale Termica), supply different buildings. Heating plant (CT2) supplies centralized hot water for all of the buildings.

The buildings are positioned such that the principal surfaces face East-

West.

- Building 1 : 3 floors 12 apartments 4681 m^3
- Building 2 : 3 floors 24 apartments 8265 m^3
- Building 3 : 3 floors 6 apartments 2463 m^3
- Building 4 : 6 floors 30 apartments 10153 m^3
- Building 5 : 6 floors 30 apartments 9500 m^3

Each heating plant consists of a separate solar collector system, ground storage, heat pump, and conventional gas burner to meet the peak heating demand. Heating plant **CT1** and **CT2** employ vertical bore holes in the ground and heating plant **CT3** employs horizontal coils (see Figs. 1 and 2). Neither the horizontal coils nor the vertical bore holes employ insulation or water barriers.

All buildings are heated by low temperature hydronic piping embedded in the floors.

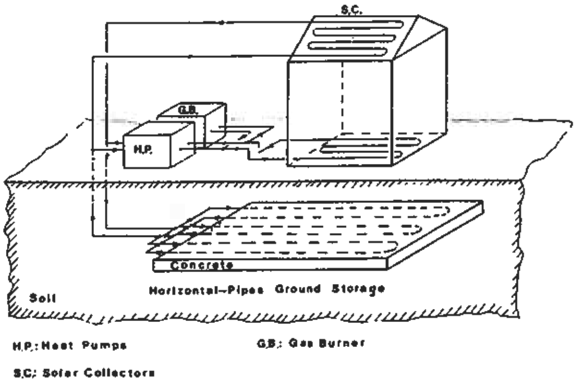

Figure 1. Schematic of the system with horizontal coils.

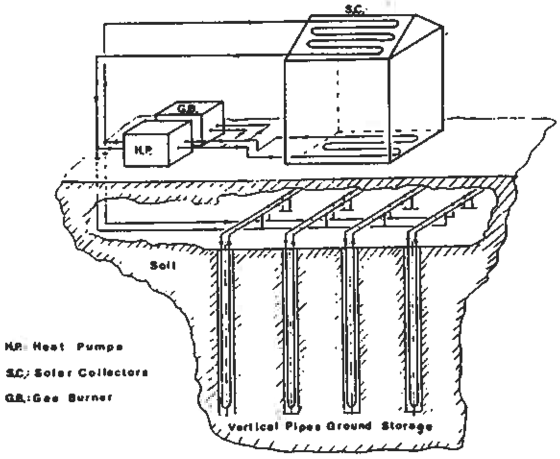

Figure 2. Schematic of the system with vertical bore holes

The horizontal coils ground storage (see Fig.1) is located 4 m below the ground surface beneath the building and a garden area. It has an area of 3,500 m^2 and a volume of approximately 14 000 m^3. The ground storage contains 55 U-shaped, flexible, high density polyethylene tubes (25 mm inner diameter, 2 x 54 m length with 0.6 m spacing) enclosed within a 150 mm thick concrete slab.

The vertical bore holes ground storage (see fig.2) consists of 220 bore holes for the heating plant 1 (**CT1**) and 194 holes for the heating plant 2 (**CT2**). The bore holes have a diameter of 300 mm and are under the garage. The garage floor is located at 3 m below the ground surface. The bore holes extend to a depth of 11 m. This results in storage volumes for **CT1** and **CT2** of 14 191 m^3 and 15 216 m^3. Each bore hole contains a U-shaped polyethylene tube of 14 mm inner diameter inserted in a sand-concrete mixture.

The solar collectors are integrated in the building roofs with the absorbers placed directly over the concrete structure. The absorbers are then covered with corrugated Polyacryl slabs. The area and orientation of these collectors is as specified in Table 2. The absorbers are made in black rubber and manufactured by PIRELLI.

Table 2. Solar collector areas and orientations.

Heating Plant		Area m^2	Orientation Degr.[1]	Tilt Angle Degr.
CT1	S	67	15	19
	E	219	105	19
	N	48	195	19
	W	192	285	19
CT2	S	146	15	19
	E	685	105	19
	N	122	195	19
	W	256	285	19
CT3	S	78	15	19
	E	184	105	19
	N	114	195	19
	W	180	285	19
CT2 Tap Hot Water	W	436	285	19

Each heating has four 60 kW, water + glycol to water heat pumps. Each heat pump is comprised of three hermetic compressors, three condensers, and one evaporator. With R22 refrigerant and a T evaporator of 7 °C and T condenser of 54 °C the heat pump can supply 60 kW at a COP of 3.9.

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[1] solar azimut measured counter-clockwise form the South

The solar collectors have direct connections to the evaporator of the heat pump and the ground storage, as shown in Fig. 3. The destination of collected solar energy depends upon the season and the mode of operation being employed. Heat to the buildings is supplied by the heat pump and the boiler.

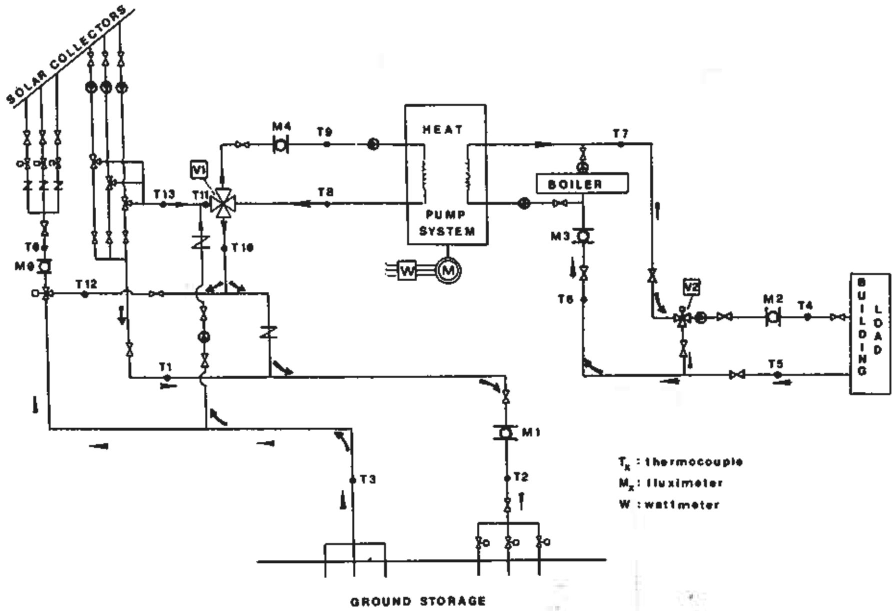

Figure 3. Generic heating system schematic

The gas boiler is activated whenever the inlet distribution temperature falls below 30 °C with the heat pumps on. Required energy is supplied to the evaporator, whenever is possible, from solar collectors. Any surplus is goes into the storage. When the solar energy is insufficient to supply the evaporator ground storage is used as the energy source.

3 THERMAL PERFORMANCE

The overall annual thermal energy requirement was estimated by the designers at 963 MWh for heating and 252 MWh for tap water . Figure 4 , 5 and 6 show how this heating load was divided among the three plants ,**CT1**, **CT2** and **CT3**, and how it was planned to meet it with the CSHPSS system.

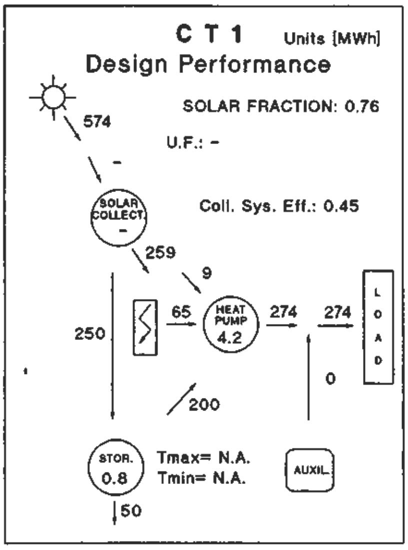

Figure 4. Design annual energy balance for CT1

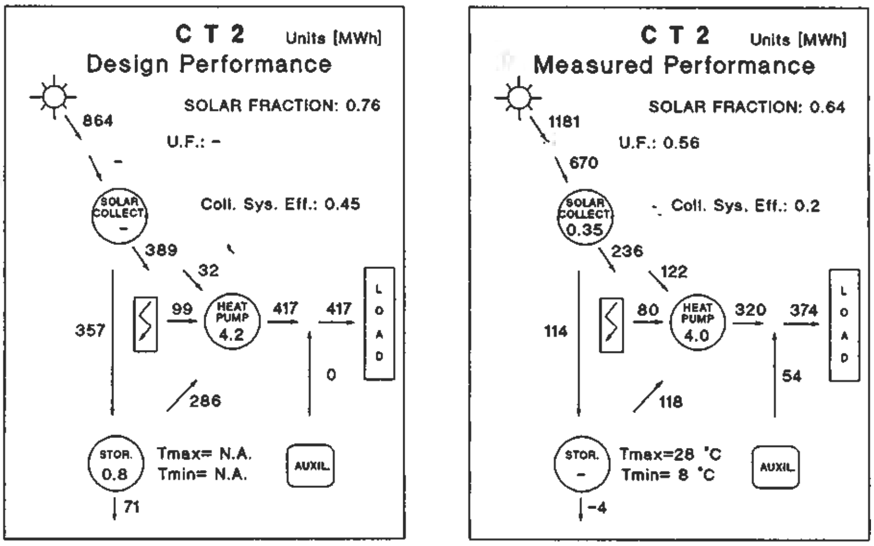

Figure 5. Measured and design annual energy balance for CT2

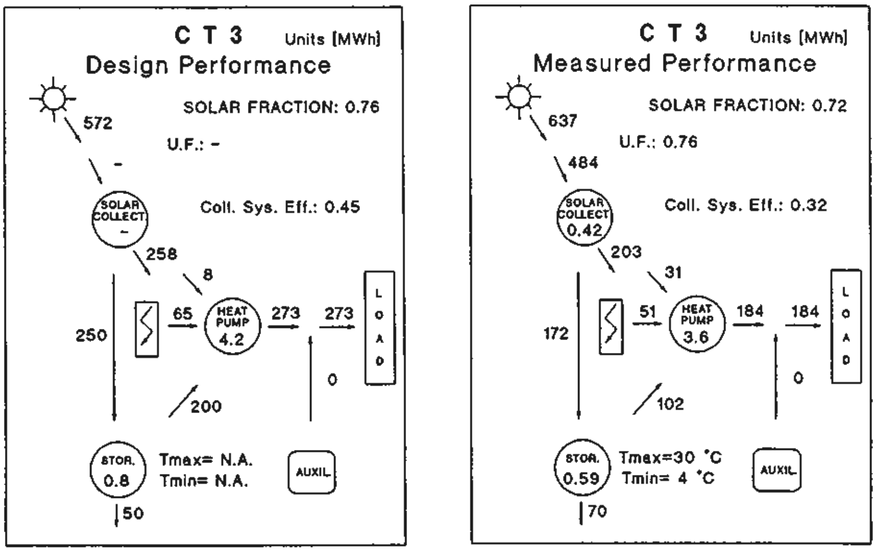

Figure 6. Measured and design annual energy balance for **CT3**

To simplify the evaluation procedure it was decided to monitor only two of the three plants (**CT2** and **CT3**) and thereafter to neglect the tap water.

Figure 5 compares the measured performance of **CT2** plant (related to the time period from April 1987 to April 1988) with the design one.
In Figure 6 the measured performance of **CT3** plant (averaged over three years, 1985/86 through 1987/88) is plotted together with the design one.

In all the energy balances the pumping energy for the storage and collector systems has been neglected , because it is a small percentage of the electrical energy required by the heat pumps, and the solar collector system performance is characterized by the use of the following ratios:

$$\text{U.F.} = \frac{\text{Avail. Solar Rad. when Coll.Sys. is ON}}{\text{Available Solar Rad. on Solar Collectors}}$$

(UTILIZATION FACTOR)

$$\text{S.C.E.} = \frac{\text{Therm. Energy delivered by Sol. Coll.}}{\text{Avail. Solar Rad. when Coll. System is ON}}$$

(SOLAR COLLECTOR EFFICIENCY)

$$\text{C.S.E.} = \frac{\text{Therm. Energy delivered by Sol. Coll.}}{\text{Available Solar Rad. on Solar Collectors}}$$

(COLLECTION SYSTEM EFFICIENCY)

The **S.C.E.** ratio rates the component performance, while the **U.F.** and **C.S.E.** ratios account better for all the influences of the control system and of the other linked systems.

In these figures the minimum and maximum temperatures reached in the storage are also reported , with a great difference in the meaning: for the horizontal system it is the temperature in the core of the coil system ; for the vertical system it is an average temperature of the storage volume.

Neither plant can be simulated by MINSUN; therefore simulation results are not reported.

4 CONCLUSIONS

The comparison between the measured and design performance indicates large differences both in aggregate and component values. These differences are due to the design tool used by the consultants which gave unrealistically optimistic figures in the energy balance. A negative consequence of these incorrect figures was an incorrect sizing of various thermal components leading to a worsened overall performance.

The **CT2** plant reduces the temperature in the ground storage by several degrees below its natural level in winter and restores the temperature level in summer with solar energy. This explains the high storage efficiency close to 100%, as there are essentially no net losses through the storage boundaries. The ground heat exchangers are undersized compared to the low thermal diffusivity of the ground. This undersizing results in lower than expected heat carrier fluid temperatures in winter and necessitates the heat pumps to be operated at a lower evaporation temperature than intended. Thus the solar collectors supply more solar energy directly to the heat pump evaporator than for the **CT3** plant, due to the lower average temperature of the solar collectors. This also explains the higher than anticipated temperature in the solar collector loop in summer, which increases the heat losses and lowers the efficiency.

The **CT3** plant acts essentially as a ground-coupled heat pump with summer regeneration of the heat store and some solar assistance in winter. A larger exchanging surface (three times greater than in **CT2**) reduces the specific heat flux across the pipe wall. It is possible to operate the heat pump at higher evaporation temperatures, thus reducing the solar energy supplied directly to the heat pump evaporator. Other differences between the performances of the two plants are explained by a badly designed control system, which degrades the overall performance.

The objective of an economically competitive system has not been achieved, since the cost of the energy delivered to the users is some three times the standard cost.

In spite of all these drawbacks, the solar fractions are relevant (64% for CT2 and 73% for CT3); after accounting for the energy used for heat pump operation, the figures of net energy saved are still remarkable.

Further system performance improvements are possible and studies have been performed to assess their feasibility. The private owners are not presently willing to invest more into the project.

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APPENDIX E: The Netherlands - Groningen

NATIONAL EVALUATION SUMMARY OF THE NETHERLANDS
THE GRONINGEN CSHPSS

1 INTRODUCTION

In Groningen, a town in the northern part of the Netherlands, a central solar heating plant with seasonal storage (CSHPSS) in the soil has been realized. It has been in operation since the autumn of 1984. The climate at the site is moderate with a strong maritime tendency. This moderating influence results in cool temperatures in summer and warm temperatures in winter, except for colder winter periods of a few weeks in which north-eastern and eastern winds from the continent and polar region may occur.

The objective of the project was to gather practical experience from realisation of such a system in the field, to monitor its overall behaviour, and to gather data for model validation. The project was financed from the Dutch National Solar Energy Research Programme and by the Commission of the European Communities.

2 SYSTEM DESCRIPTION

The Groningen CSHPSS consists of 96 solar houses divided in 9 blocks grouped around the seasonal earth store and the central boiler house. Figure 1 shows the total system in a schematic form. Each house has a solar heating system consisting of about 25 m^2 Philips VTR-261 evacuated tubular solar collectors (total collector area 2,400 m^2). The solar heat system contributes to both space heating and domestic hot water preheating. For space heating there is a central auxiliary plant. Each house has its own back-up system for domestic hot water.

The houses are well-insulated (heat demand at the design conditions: 6.3 kW; total system heating load: 1200 MWh). The space heating system in the house is a low temperature hydronic radiator system with 42.5 °C supply temperature at design conditions.

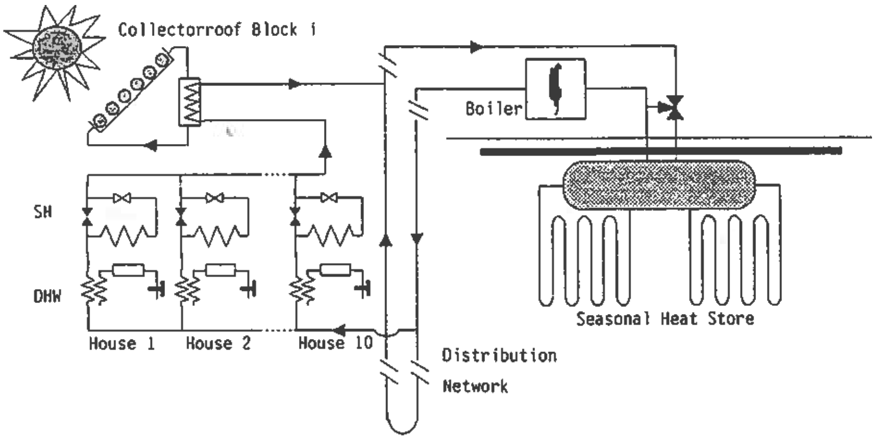

Figure 1 Schematic representation of the total system.

The storage system consists of a short term (daily) and a long term (seasonal) store. The short term store is a 100 m^3 water tank buried in the centre of the seasonal heat store. The volume of the seasonal store is 23,000 m^3 of soil (38 m diameter, 20 m deep), which can be described as water saturated sand with thick layers of clay and some thin layers of peat. The ground water level is about 1 m below the surface.

Only the top of the seasonal store is insulated. The heat exchanger is made of 360 flexible polybutene "U-shaped" tubes which are vertically inserted in the ground. The distribution network between the solar houses and the seasonal heat store has a total length of 1900 m. To avoid corrosion problems the soil circuit has been separated from the distribution network by a water to water heat exchanger.

3 PERFORMANCE

3.1 Projected solar contribution

For the design work on the system a specially developed computer simulation programme has been used.

The solar contribution of the system after 3 or more years of operation is expected to be 732 MWh, which is 63% of the projected total load. In Figure 2 an energy flow diagram is given for the projected system performance (pumping energy not included).

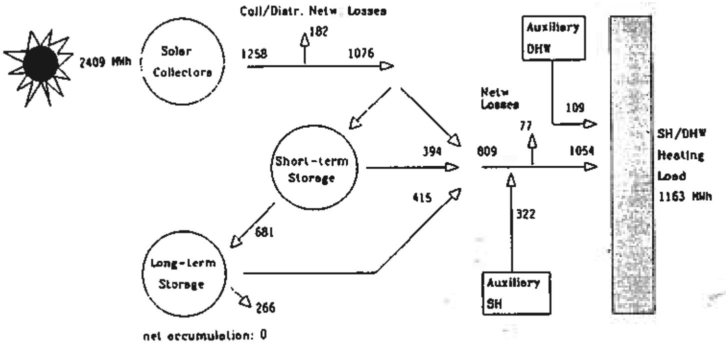

Figure 2 Projected system performance.

The net solar contribution is 310 kWh per m^2 of solar collector. The annual efficiency of the collector roofs is 48%. The seasonal heat store will operate between 30 and 60 °C. The electricity consumption of this system (for pumps) is 77 MWh, i.e. 800 kWh per house.

3.2 Monitoring results

The system performance was monitored extensively for the first two years of operation (1985 to 1987) (Wijsman, Kortschot, 1987). The monitoring programme consisted of measurements on individual houses, on blocks of houses, of central measurements and of detailed measurements on the seasonal heat store. A low level monitoring programme started in early 1987. It consisted of the same measurements as mentioned above, except for the detailed measurements on individual houses and on the seasonal heat store. Data are now collected as monthly totals from meter read-outs. The low level monitoring programme will last until the beginning of 1990.

In Figure 3 the measured system performance is given for the first year of monitoring (February 1, 1985 through January 31, 1986).

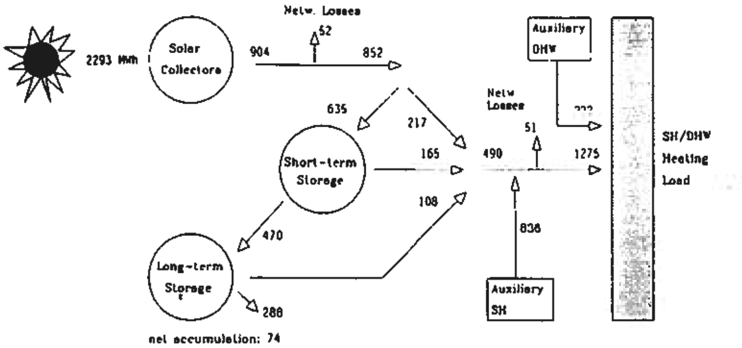

Figure 3 Measured system performance (first year)

The solar contribution of the system was 439 MWh: 217 MWh via direct use, 165 MWh via short term storage, 108 MWh via seasonal heat storage and minus the heat losses of the distribution network towards the houses (51 MWh). The annual efficiency of the collector roofs was 39%. The net heat accumulation in the seasonal store was 74 MWh, the heat losses of this store were 288 MWh. In Figure 4 a energy flow diagram is given for the second year of monitoring

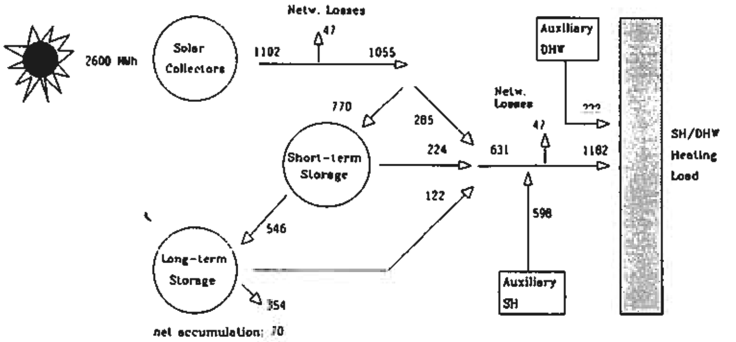

Figure 4 Measured system performance (second year).

The solar contribution of the system was 584 MWh. Of this total solar contribution 285 MWh were used directly at the time of collection, 224 MWh were used via short term storage, and 122 MWh were used via seasonal storage. The distribution heat losses were 47 MWh. The annual efficiency of the collector roofs was 42 %. It was observed that several blocks showed differences in collector performance ranging from 39 to 45%. The net heat accumulation of the seasonal heat store was 70 MWh, indicating a "steady" year cycle had yet to be reached. The heat losses of the seasonal store were 354 MWh.

In Figure 5 the system performance is given for the third year of monitoring (February 1, 1987 through January 31, 1988).

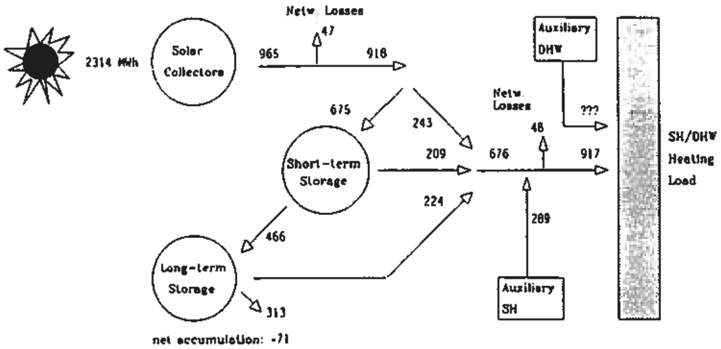

Figure 5 Measured system performance (third year).

The solar contribution of the system was 628 MWh. Of this total solar contribution 243 MWh were used directly at the time of collection, 209 MWh were used via short term storage, and 224 MWh were used via seasonal storage. The distribution heat losses were 48 MWh. The annual efficiency of the collector roofs was 41 %. The net heat accumulation in the seasonal heat store was -71 MWh. The heat losses of the seasonal store were 313 MWh.

During the second year there was a net temperature increase in the seasonal store from 32 to 36 °C. This was caused by improper functioning of the central control system. The control system was modified at the end of the second year and has functioned properly since that time. As a result, the net temperature in the seasonal store decreased from 36 to 32 °C during the third year.

In Figure 6 the mean temperature in the seasonal heat store is shown for the first three years of monitoring.

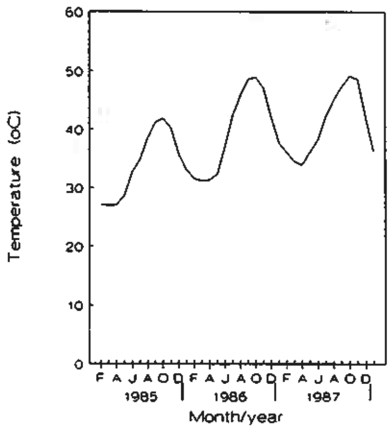

Figure 6 Mean temperature in the seasonal heat store during the three years of monitoring: February 1, 1985 through January 31, 1989

The space heating system in the houses did not function optimally during the second year. This led to demand for space heating during summer. Correction of this problem resulted in relatively higher input to the seasonal heat store during the third year.

Electrical consumption of the total system was 112 MWh and 103 MWh for the second and third years, respectively.

4 DISCUSSION OF THE RESULTS

In the first year the solar contribution of the CSHPSS plant was 439 MWh, in the second year 584 MWh, and in the third year 628 MWh. Compared to the design value (732 MWh), the solar contribution for the third year was 14 % lower.

The lower solar contribution is due to the lower than expected efficiency of the solar collector roofs and the higher than expected heat losses of the seasonal heat store. In the first year the efficiency of the collector roofs was 39 %, during the second year 42 %, and during the third year 41 %. During the Spring of the first year part of the collector roofs were out of operation due to frost damage. The assumed design efficiency was 48 %. Therefore, the measured efficiency for the third year is approximately 13 % less than design.

An additional study yielded the causes of the lower than expected performance. The measured heat losses of the seasonal store are 1.6 times higher than calculated. Heat flow measurements through the top insulation indicate that both the top losses and losses to the surrounding soil are 1.6 times greater than calculated. This greater than expected storage heat loss is due to a larger U_l -value of the top insulation than expected, a slightly higher than design minimum useful temperature in the system, and greater than assumed ground water movement in the store.

Modification of the central control resulted in a decrease of the net temperature in the seasonal heat store during the third year. Modification of the heating system in the houses resulted in a lower heat consumption during the summer and so to a better seasonal storage function.

The electrical consumption of the plant during the second and third years was higher than projected at 112 MWh and 103 MWh, respectively. This is due mainly to electrical consumption of valves, control equipment, and other equipment than by extra consumption of the pumps.

5 EVALUATION AND REDESIGN STUDY WITH THE MINSUN SIMULATION PROGRAM

With the Minsun program an evaluation and redesign study was done for the seasonal duct heat store under Dutch climatological conditions. This study is an update (Havinga, Wijsman, 1988) of the Dutch contribution to the IEA Task VII subtask II(b)-report, entitled "Central Solar Heating Plants with Seasonal Storage -Evaluation of Concepts" (Bankston, 1986). Three system concepts have been considered:

- a gas-driven heat pump and unglazed solar collectors;
- an electrical heat pump and unglazed solar collectors; and
- no heat pump and evacuated tubular solar collectors.

The evaluation was done for a total load of 4.4 TJ, which corresponds with the total load of the Groningen system. The DHW-fraction is 16 % (0.7 TJ). Requested distribution temperatures are indicated in Figure 7.

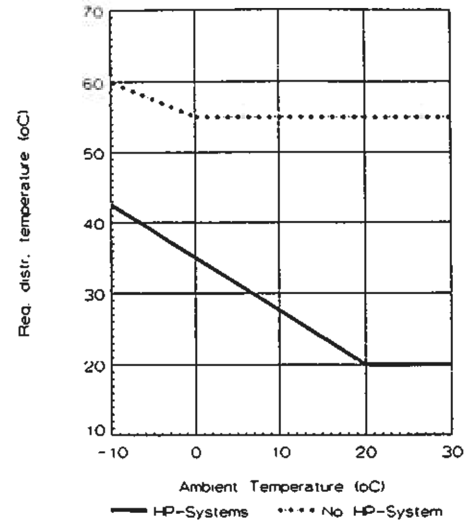

Figure 7 Requested distribution temperature for heating system

The evaluation used actual data from the Groningen project wherever possible. Cost data were based on a special study done by Bredero Energy Systems. In order to simulate a gas-driven heat pump, the Minsun model for an electrical heat pump was modified. Also the definition for solar cost in the Minsun model has been modified to take into account non-identical cost for electricity and auxiliary (natural gas). Fuel prices per 1-1-88 (for small consumers): electricity: 0.24 Dfl/kWh, natural gas: 0.06 Dfl/kWh.

The results are presented in a 'Solar costs versus solar fraction' Figure (see Figure 8). From this figure, lowest solar cost systems are derived. For these optimal systems, characteristics and total system heat fluxes are given (see Table 1, Figures 9-11).

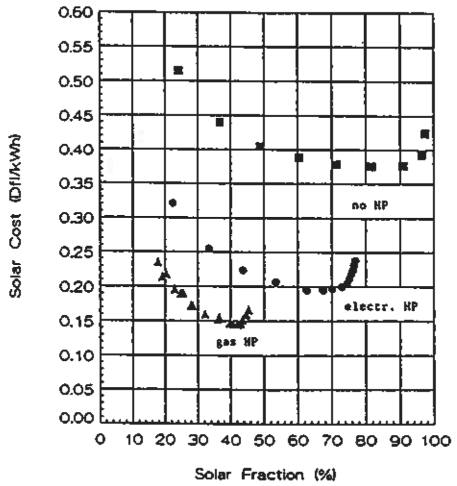

Figure 8 Comparison between the three system concepts.

Table 1 Optimal system characteristics

System		no HP	elec. HP	gas HP
collector area	(m^2)	3500	1750	1250
storage volume	(m^3)	20000	58000	41500
number of boreholes	(-)	1750	1250	900
solar costs	(Dfl/kWh)	0.377	0.195	0.145
solar fraction	(%)	81.5	68.0	42.2
COP	(-)	-	3.64	1.76

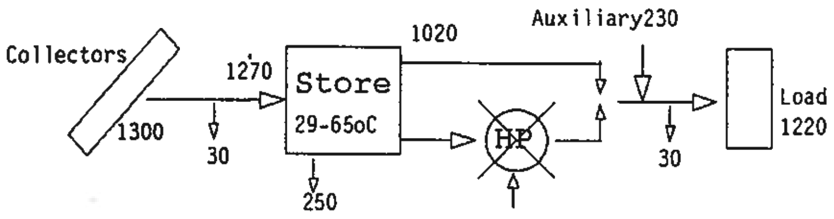

Figure 9 Heat fluxes in the total system (MWh), no HP, evacuated collectors.

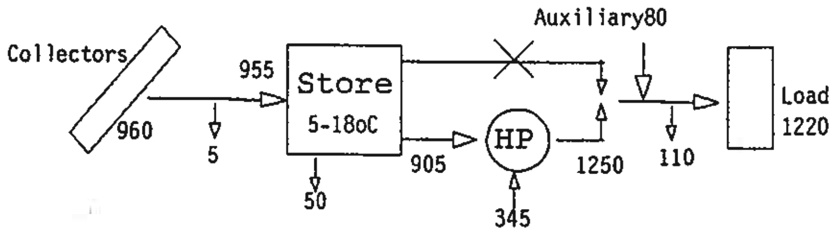

Figure 10 Heat fluxes in the total system (in MWh), electrical HP, unglazed collectors

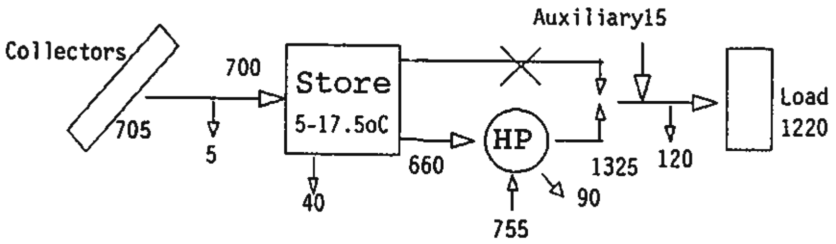

Figure 11 Heat fluxes in the total system (in MWh), gasdriven HP, unglazed collectors.

It is shown that the solar unit costs for both heat pump systems are not very sensitive to the solar collector costs. However, the solar unit costs for the system without a heat pump is highly sensitive to solar collector costs. The solar unit costs for the optimum system (0.377 Dfl/kWh) include 0.29 Dfl/kWh for solar collectors. The solar unit costs for the gas driven heat pump system could be equalled by the actual system provided the cost of evacuated tubular collectors were the same as for unglazed solar collectors (300 Dfl/m2).

It should be noted that the fossil energy savings for the optimum system with an electrical heat pump are only 13 % (in the Netherlands electricity is generated by gas turbines with an efficiency of about 33 % at the consumers). Therefore, such a system does not provide significant energy savings. For all system concepts the storage part of the solar unit costs is approximately equal, 0.04 - 0.07 Dfl/kWh.

CONCLUSIONS

During the three years of monitoring of the Groningen plant considerable operational experience was gained. As the Groningen project was the first CSHPSS in the Netherlands and it included many research aspects, it is likely that future CSHPSS in the Netherlands would have substantially lower costs.

Using updated cost data and Dutch circumstances, the Minsun evaluation study showed that duct storage systems with gas-driven heat pumps and unglazed collectors give the best economy.

A duct system with high performance collectors (without a heat pump) can reach a much greater solar fraction, but solar collector unit costs must be reduced to the range 400-500 Dfl/m^2 (200-250 US\$/m^2) for this system concept to be attractive. Some other countries have already attained such a solar collector unit cost, e.g., Swedish collector costs are approximately 250 US\$/m^2 for flat plate collectors with a performance comparable to evacuated tubular collectors.

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APPENDIX F: Sweden - Ingelstad I, Lyckebo etc

SWEDISH NATIONAL EVALUATION SUMMARY

Based on the evaluation of four CSHPSS with water storage

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ABSTRACT

This paper summarizes the Swedish research program for solar heating systems with seasonal heat stores. It describes existing plants and gives the essential basis for new designs - based on experience from and research related to existing plants.

Based on today's knowledge, these solar heating systems should be designed and rated to provide a heat coverage of about 75 per cent of the heat requirement of the load. They should be realized using flat plate collectors in large modules - mounted on ground or integrated in the roof - with a basically simple system design.

Smaller systems, intended to supply heat to hundreds of users, require the use of thermally insulated heat stores. Larger systems, intended to supply heat to thousands of users, can use water-filled uninsulated rock caverns.

1 INTRODUCTION

Several solar heating plants incorporating seasonal heat stores have been built in Sweden for experimental purposes. In order to achieve the maximum benefit in terms of knowledge and experience relating to different types of plants, a mix of designs and sizes has been built, with performance and other aspects being monitored closely. The experience obtained from these plants, together with that from other larger plants, has resulted in the accumulation of an internationally unique experience.

This paper summarizes experiences concerning pure solar heating plants (i.e., without heat pumps) as documented earlier in the Swedish national report (Dalenbäck, 1988a). The evaluation of Ingelstad I is used as an example, instead of the evaluation of Lyckebo (Swedish main contribution to phase III of Task VII). The evaluation of the Ingelstad I plant has, in practice, been made according to the evaluation guide-lines that were drawn up within phase III. It has only been possible to follow these guide-lines in theory for the Lyckebo plant (Walletun). In general, however, the conclusions are valid for a system like the one in Lyckebo, and the feasibility study for the Kungälv project (Jilar, 1988) is a redesign of the Lyckebo plant.

A large part of the collector array in Lyckebo is simulated with an electric boiler. It was not possible to imitate a full collector array with the boiler, which caused some evaluation problems. The collector performance, however, is as expected, while the heat losses from the cavern differ from the design study due to convection losses through the old access tunnel that was used during construction (Brunström et al, 1988).

2 DESIGN AND PERFORMANCE

2.1 Existing plants

Table 1 summarizes the main components and design data in four solar heating plants with seasonal heat stores, using water as the storage medium. The connected annual loads vary from about 40 MWh (130 GJ) in Studsvik to more than 8,500 MWh (30 TJ) in Lyckebo. The solar heat coverage given for each plant is the intended design coverage.

Table 1 Main components and design data in existing plants

Plant name ------- First year of operation	Collector area and type (m²)	Heat store volume and type (m³)	Solar coverage (%)	Annual load (MWh)
Studsvik 1979	120 partly concentrating	640 insulated excavated pit	100	37
Ingelstad Ia 1979	1,320 conc parabolic	5,000 insulated concrete tank	50	1,160
Ingelstad Ib[a] 1984	1,425 flat plate high-temperature	"	50	[e]920
Ingelstad Ic[b] 1987	2,425 flat plate high-temperature	"	70	[e]920
Lambohov[c] 1980	2,700 flat plate roof-integrated	10,000 insulated rock pit	85	900
Lyckebo [d] 1983	28,800 flat plate high-temperature	105,000 uninsulated rock cavern	100	8,500

[a] Ingelstad Ia rebuilt with flat plate collectors.
[b] Ingelstad Ib with increased collector area.
[c] Heat pump in the system design.
[d] The full collector array has not yet been installed, but is simulated by an electric boiler.
[e] Based on measured load 1980-83.

Figure 1 shows schematic diagrams of the existing systems (except Ingelstad Ic). Some plants have separate charging and discharging circuits, while in others it is possible to by-pass the store and supply heat from the collectors directly to the load. System designs in which constant and variable flow rates through the collector and storage circuits are combined with heat supply to the store at one or more levels are represented, as are designs with abstraction from one or more levels.

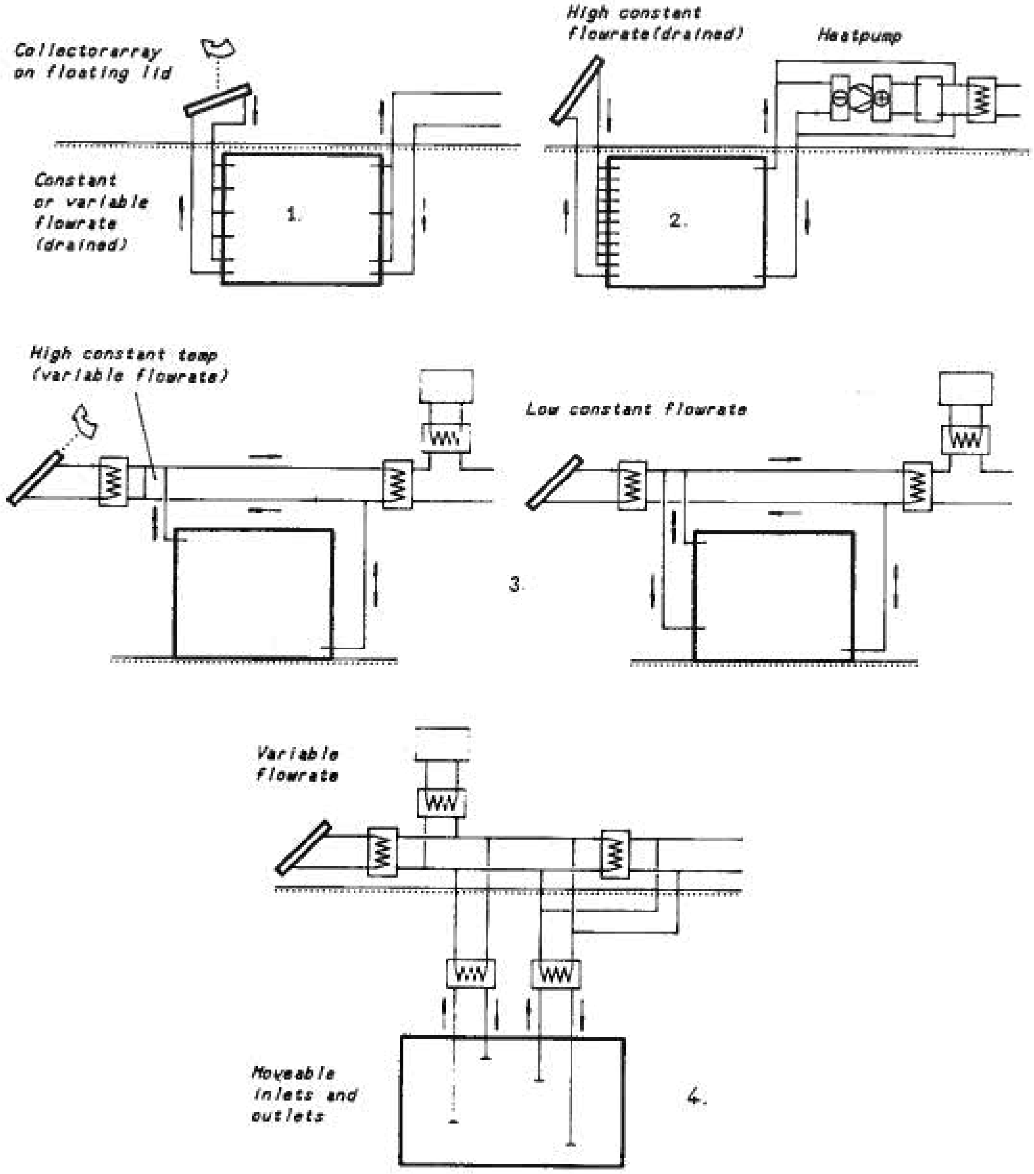

Figure 1 Schematic diagrams of the existing systems.

1. Studsvik, 2. Lambohov,
3. Ingelstad Ia and b, 4. Lyckebo.

Figure 2 shows a comparison of the measured annual heat balances in the plants. The quantities of solar heat and supplementary heat have been related to the magnitude of the heat load, making it possible to compare the measured degree of heat coverage with the intended design coverage (see Table 1). It is also possible to see the magnitude of the heat losses from the store in proportion to the yield from the collectors. In making such a comparison, it is important to bear in mind the relative sizes of the systems. The Ingelstad and Lambohov plants, for example, are about 10 times larger than the Studsvik plant, while Lyckebo is larger again by an additional factor of 10.

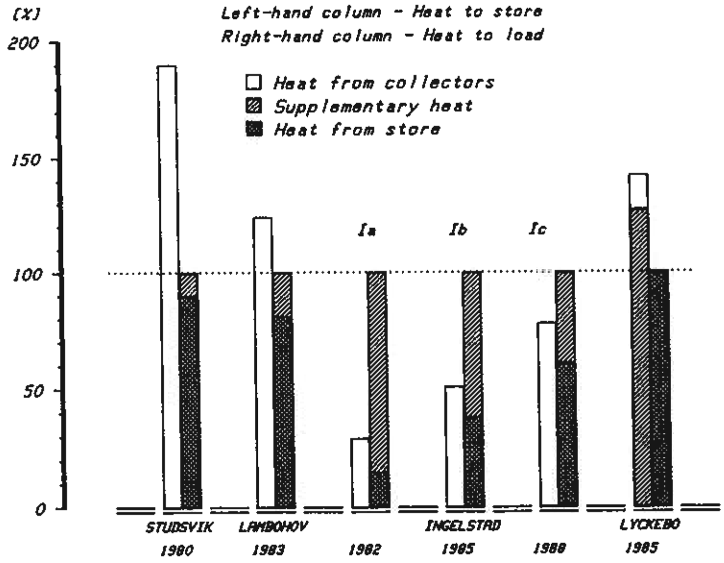

Figure 2 Measured annual heat balances in the existing plants.

The as-measured degree of heat coverage was close to the design coverage for all installations except Ingelstad Ia. Consequently, the concentrating collectors were replaced with flat plate high-temperature collectors (Ingelstad Ib), which brought the yield up close to the expected value. Heat losses from the stores, however, differ considerably from the design losses for Lambohov (insulated) and Lyckebo (uninsulated). The deviations are mainly related to untried constructions in both cases.

2.2 The Ingelstad example - First design.

The design work for Ingelstad Ia was carried out during 1978 (Finn, 1979) without any particular knowledge about large solar heating systems in practice. Athough the evaluation showed that the real performance was far from the design performance, it did show that the design performance was realistic if collectors with better performance were used (Jilar, 1984).

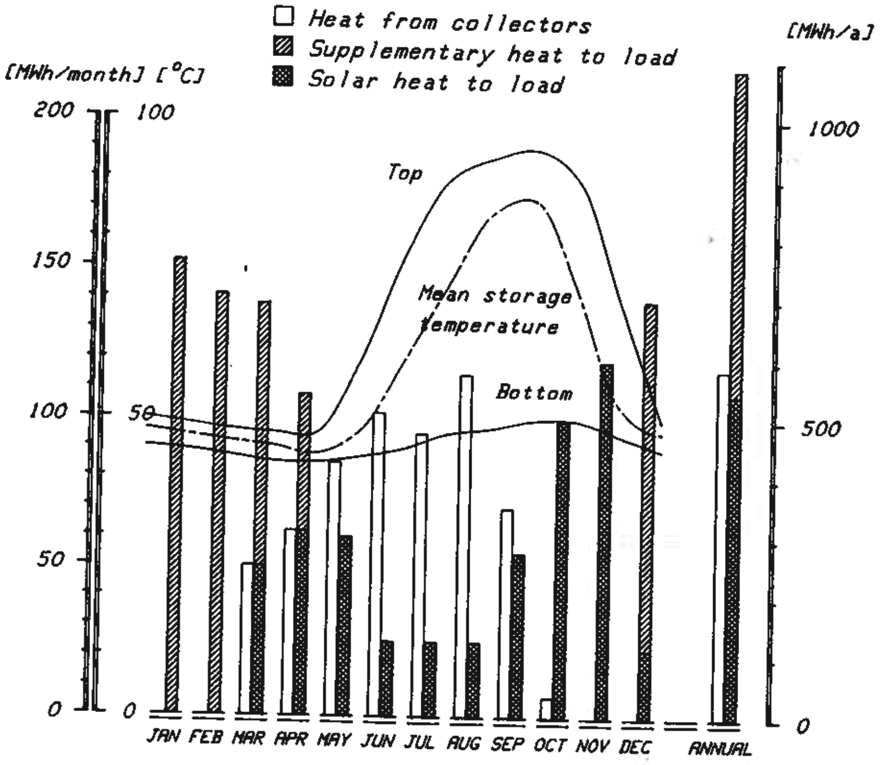

Figure 3 Design performance for Ingelstad Ia.

The major reasons for the large deviation between design and measured performance are as follows:

- The beam solar radiation was overestimated due to an incorrect calculation method, and

- the collector performance was less then expected mainly due to incorrect focusing of the collectors.

Together with some other minor important malfunctions these factors brought the solar coverage down to 15 per cent instead of the expected 50 per cent.

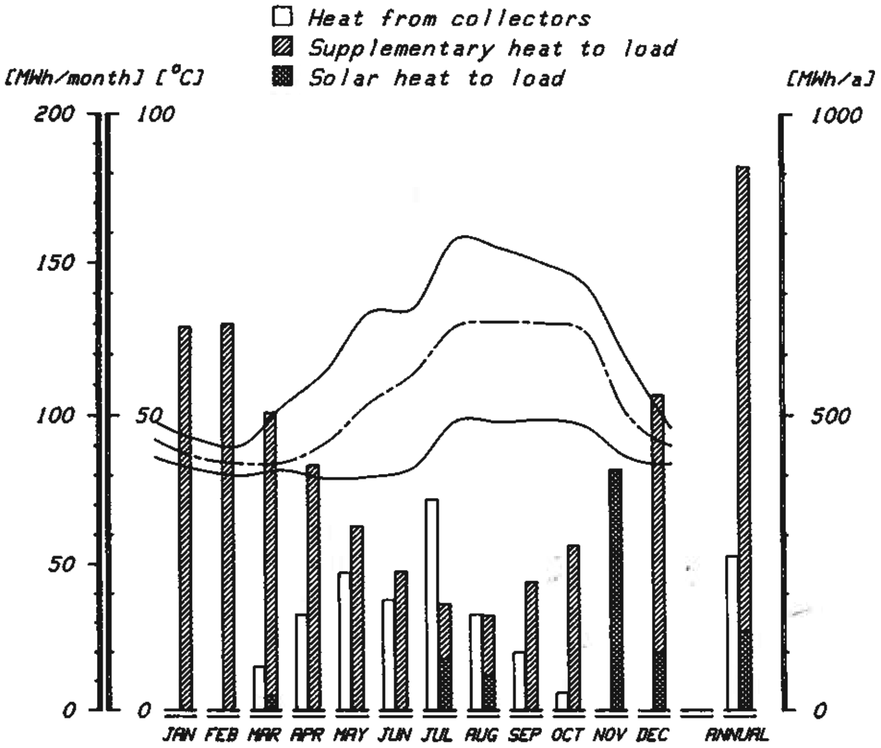

Figure 4 Measured performance (1982) for Ingelstad Ia.

3 DISCUSSION

3.1 Evaluation and redesign

To a greater or lesser degree, design calculations were made for the first of the existing plants before they were built. These calculations were made without any possibility of comparison with actual results. Performance measurements, together with new computer simulations, provided opportunities to isolate the effects of particular system design features, such as collector and store type, as well as, opportunities to rate these elements.

Computerized simulation models, the results of which were confirmed by comparison with measurements from existing plants, have been used exclusively during the work on the feasibility studies carried out for new projects in recent years. The results of these feasibility studies are, therefore, much more closely linked to reality than was previously the case.

3.2 The Ingelstad example - First redesign.

The Ingelstad plant was rebuilt with newly developed flat plate collectors (the same as those used in Lyckebo) and the system configuration was redesigned in order to make better use of flat plate collectors. The real performance (40 per cent solar coverage, 1985) was analyzed with the simulation model SIMSYS.

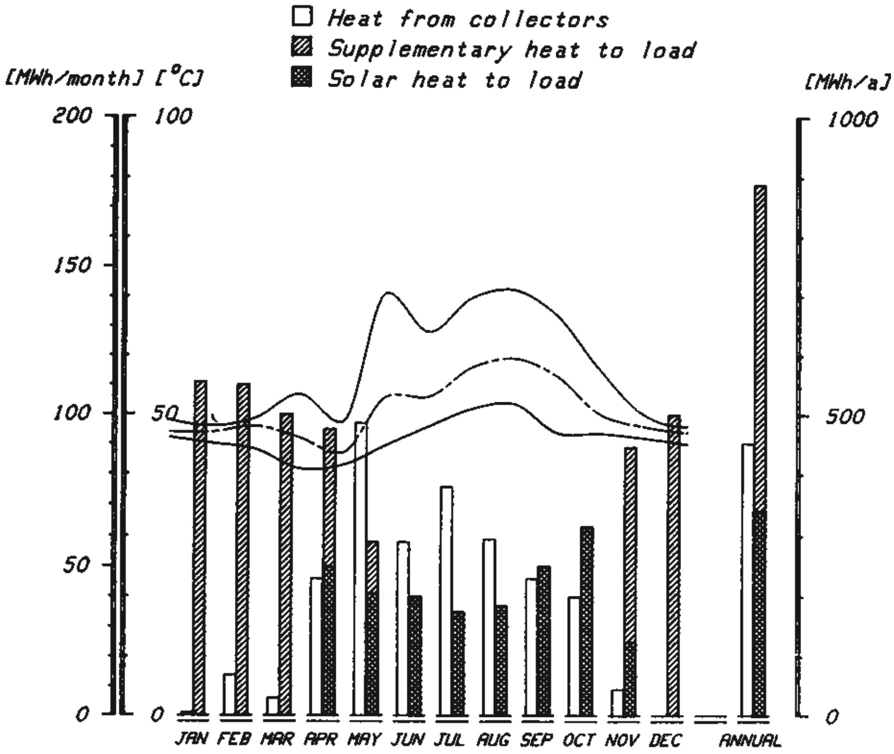

Figure 5 Measured performance (1985) for Ingelstad Ib.

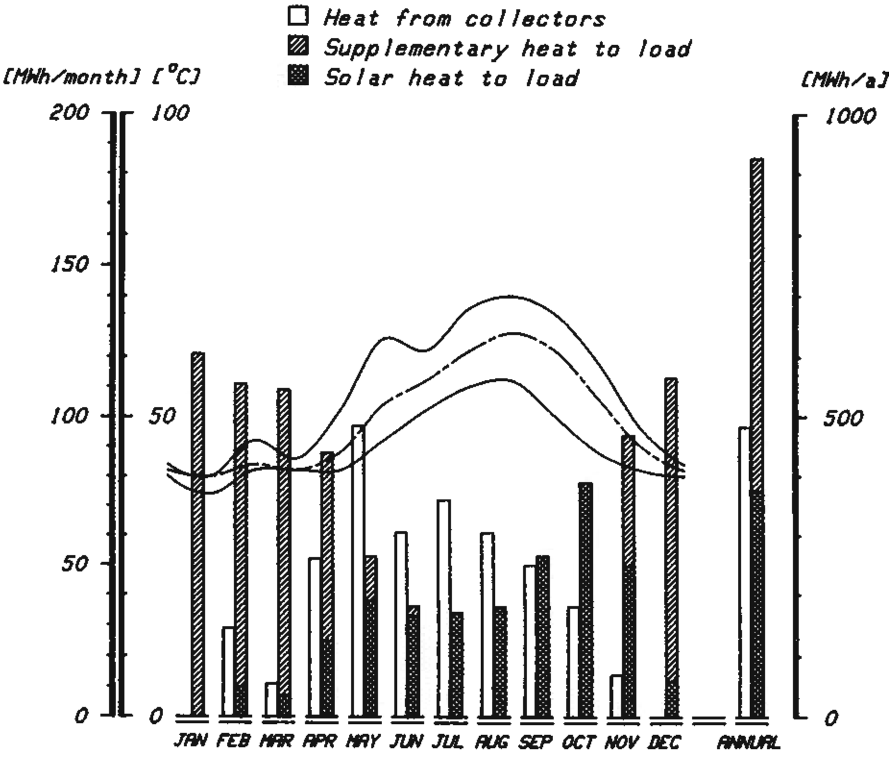

Figure 6 Calculated performance (1985) for Ingelstad Ib.

The performance during an average year was then estimated (45-50 per cent) with the same model and compared with design performance (50 per cent average year).

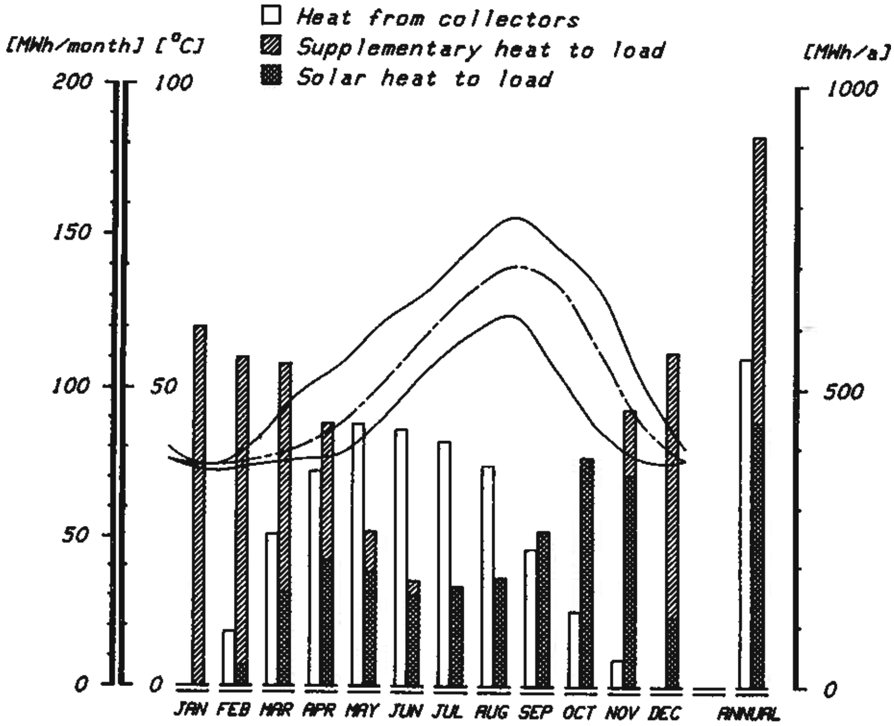

Figure 7 Calculated performance - average year for Ingelstad Ib.

4 CONCLUSIONS

4.1 System design and rating - New plants

Based on Swedish current knowledge, solar heating systems with seasonal heat stores in water should be designed and rated to provide a heat coverage of about 75 per cent of the heat requirement of the connected load for an average year. The rest, varying from year to year, should be covered by a supplementary boiler. The systems should be built using flat plate solar collectors in large modules, with a basically simple system design incorporating separate heat charge and discharge circuits, as shown in Figure 8. The solar collector and the storage charge circuit should be designed for a low, constant flow rate.

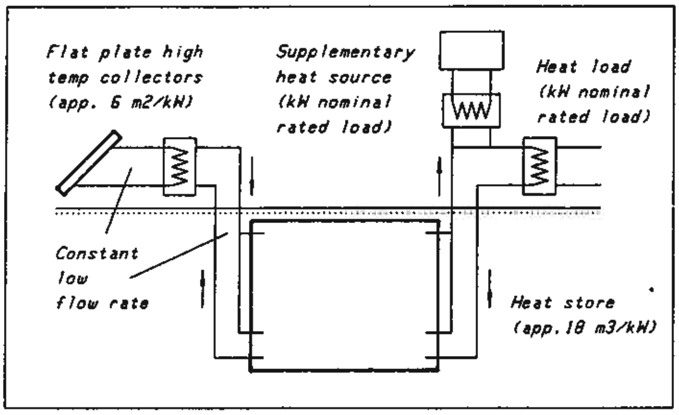

Figure 8 Schematic diagram of new systems.

When roughing out the initial design of district heating plants for operation in southern Sweden, the following guide values can be used to provide a 70-80 per cent heat coverage of the connected load by means of solar heat.

- 6 m^2 of solar collector surface area per kW of nominal connected load power demand (equal to 670 m^2/TJ annual load), which requires a ground surface area of 15 m^2 per kW (4,000 m^2/TJ).
- 18 m^3 of store volume of water per kW of nominal connected load power demand (equal to 2,000 m^3/TJ annual load), which gives a volume/area ratio of 3 m^3/m^2.

Smaller systems, i.e., those intended to supply heat loads of the order of 100-3,000 kW (1-30 TJ/year), require the use of insulated heat stores ranging in size from 2,000 to 60,000 m^3 of water. These types of heat stores still require a lot of research. Water pits or coil systems in shallow ground are suitable store concepts.

Larger systems, intended to supply loads of 5 MW or more (40 TJ/year or greater), can use water-filled, uninsulated rock caverns (100,000 m^3 in size or more) as their heat stores. In this case, extensive experience is available from crude oil storage.

A new pilot plant, Kronhjorten (Dalenbäck, 1988b), has recently been built and is under evaluation. It is a smaller installation having a new type of insulated heat store. Two similar pilot plants are also under construction in Malung (Studsvik, 1986) and Särö (Gräslund, 1988), and a feasibility study for a large system with rock caverns in Kungälv (Jilar, 1988) has been carried out.

4.2 The Ingelstad example - Second redesign.

According to the recommendations above, the Ingelstad Ic collector area was increased by 1000 m^2 (1987) and the system was further simplified (according to Figure 8). The heat store type (concrete tank above ground) is not considered to be a future solution. It was, however, possible to increase the collector area as the heat store capacity was large enough, making it possible to further evaluate an existing solar heating plant properly designed and rated with today's knowledge.

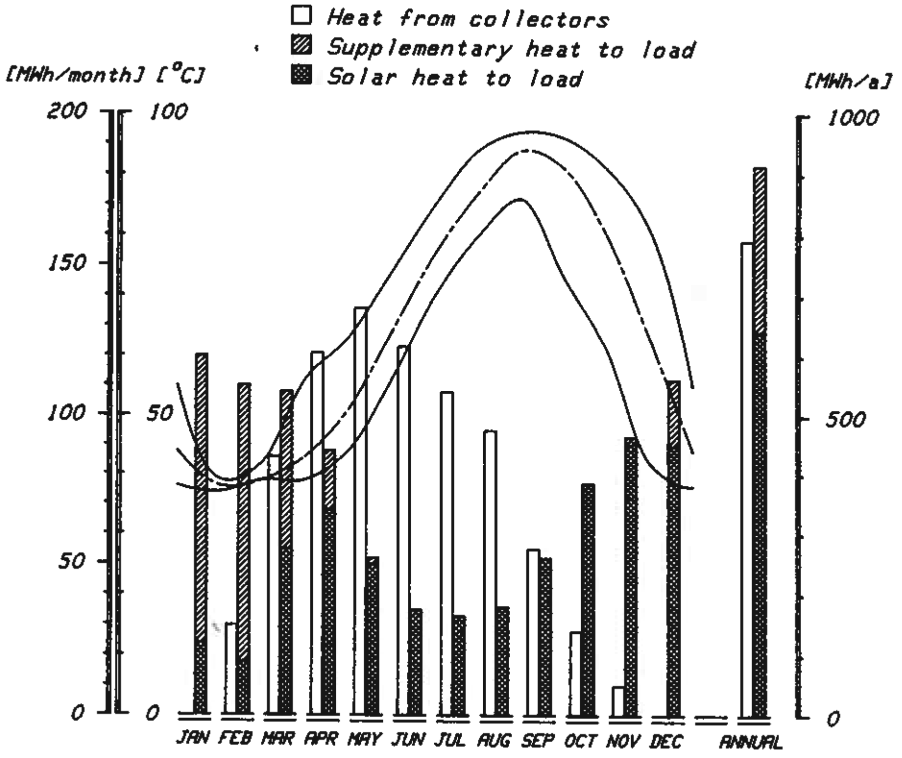

Figure 9 Design (average year) performance for Ingelstad Ic.

A preliminary evaluation for Ingelstad Ic (April 1988 to March 1989) shows that the measured solar coverage is about 60 per cent, compared to the design coverage of 70 per cent (average year). The deviation is, however, more strongly related to the operation of the plant and the deviation from an average year, than it is to the use of an incorrect design tool.

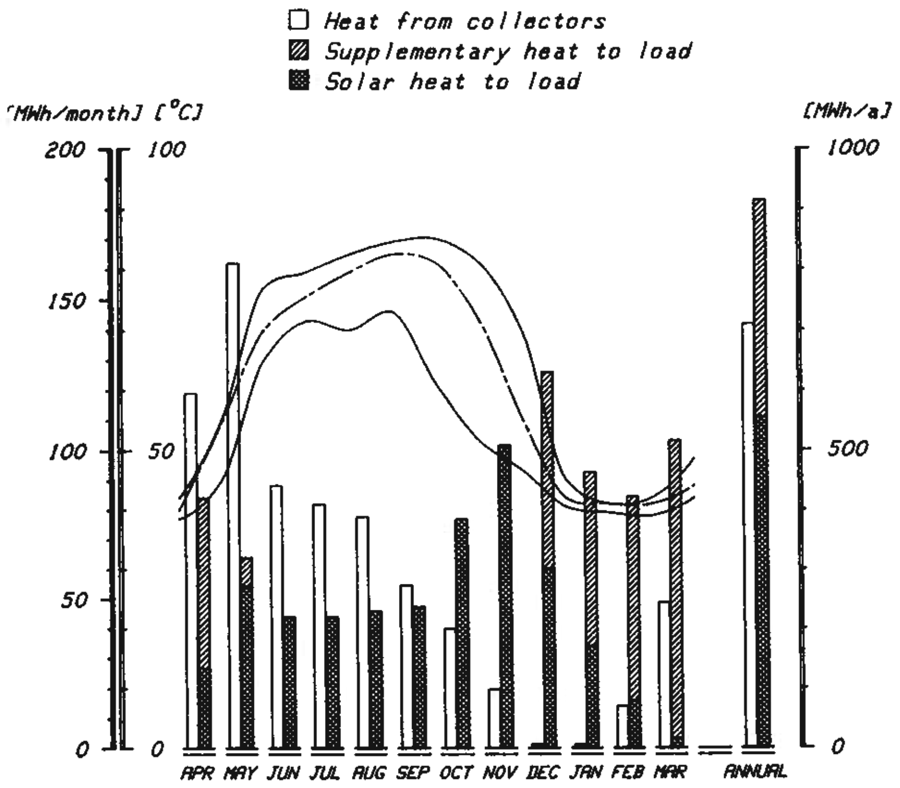

Figure 10 Measured performance (1988) for Ingelstad Ic.

One interesting observation is that the measured temperature profile is different from the calculated temperature profile during the spring. The reason is that the inlet valve in the charging circuit was connected in the wrong way during the reconstruction from Ib to Ic. The upper inlet was open when it should be closed and vice versa, thus mixing warm and cold water. This was corrected in June.

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APPENDIX G: Switzerland - Vaulruz

SWISS EVALUATION SUMMARY

based on the evaluation of the Vaulruz project
with an underground earth storage

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1 INTRODUCTION

In Vaulruz, Switzerland, a motorway maintenance center (with truck garages and office buildings) has been equipped, with a solar plant consisting of 510 m2 solar collectors, a 3500 m3 underground earth storage, and a 44 kW electric heat pump.
This system was put into operation in 1983. It was the first system of this kind in Switzerland.

1.1 Site description

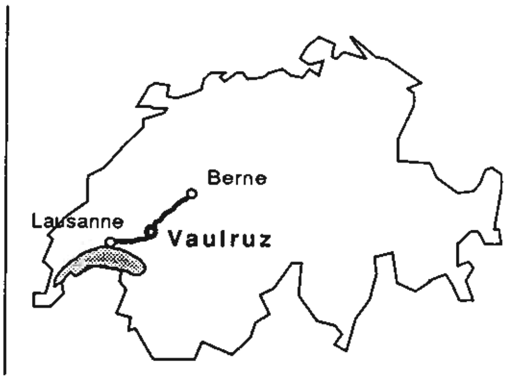
Vaulruz is in the canton of Fribourg, and is situated in front of the Alps (the longitude is 6°58' and the latitude 46°38'). The solar plant lies 847 m above sea level. The soil in this area consists of clay, sand and stones.

1.2 Climate description

Vaulruz has a typical continental climate where rapid changes of temperature may occur rapidly. The maintenance center is particularly under the influence of the north-eastern continental wind (Bise) coming from Germany, which is very cold even on sunny days. This wind may blow throughout the year. The first snows are expected in October, and can last until April.

Climate characteristics :

Global irradiation on a horizontal plane : 4238 MJ/m2 year
Diffuse proportion : 55%
Degree days 18/12 3886
Sunshine 1854 hr/year
Average yearly outdoor temperature : 7.3 °C
Average relative humidity : 78%



2 SYSTEM DESCRIPTION

2.1 Overall system

The Vaulruz plant consists of a 510 m2 solar collector field which furnishes energy to the heating loads . These can be separated into two categories: high temperature (radiator heating, ventilation, DHW) and low temperature loads. The energy furnished by the solar collectors in excess of the heating demand is transferred to the 3500 m3 underground duct storage, where heat is stored for a long duration (figure 1).

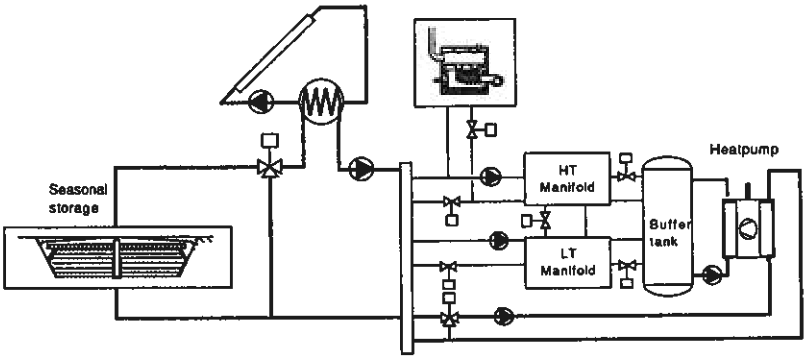


Figure 1

2.2 Solar collectors

The collector array is roof integrated and was built on site; its tilt angle is 33°, and it faces south. Its thermal characteristics are as follows :

$\tau\alpha$ value : 0.6
UL : 3.8 [W/m2K]

2.3 The earth storage

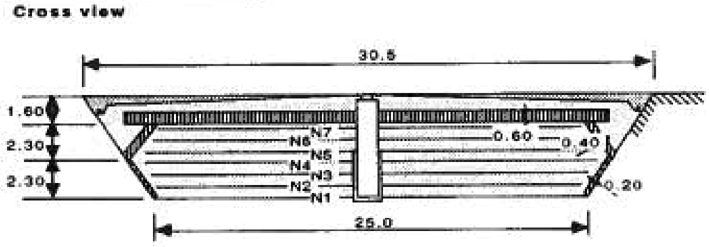


Figure 2

The earth storage is a horizontal type duct storage with earth as storage medium. It is insulated on top (60 cm of expanded polystyrène) and on the side (with 20 and 40 cm) (figure 2).

The heat exchanger consists of seven layers of polyethylene pipe of 20 mm diameter. The total length of the buried heat exchanger is 7000 m. It was built by excavating the whole volume, then placing each of the seven layers one after the other, with earth filling in between.

2.4 Heat pump

In this system, the heat pump provides thermal energy to the heating loads via a buffer tank. Its cold source can be the heat store or the solar collectors, depending on operating conditions.

Initially a 44 kW electric heat pump was installed. Because of its poor performance, it was replaced by a new model in 1987. The newer model gives much better results than the original one.

2.5 Heating loads

The heating loads are separated into two categories and supplied by two different manifolds. This has been designed to make better use of the temperature levels of both loads.

3. SYSTEM PERFORMANCE

The Vaulruz plant was designed in 1981 with a computer code specifically developped for this purpose. The predicted solar fraction was 50 per cent. The measured performance of the system (figure 3) shows that the design was quite realistic, even though operating conditions have been

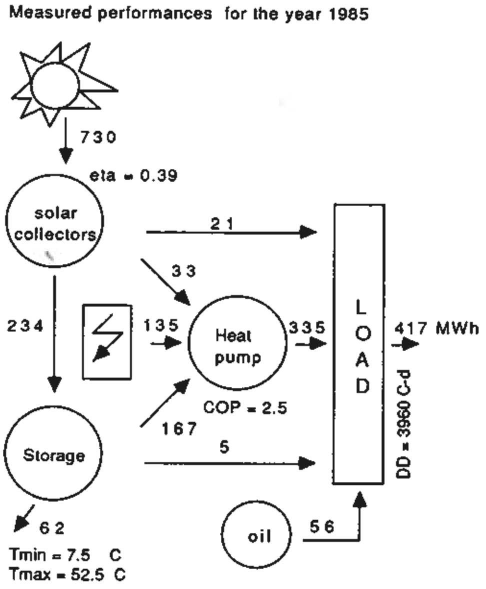


Figure 3

slightly different from the predicted one.
The actual load has been 11.5 per cent higher than expected. The measured solar fraction was of 54 per cent, which is slightly higher than expected. It is important to note the poor behavior of the heat pump which has obtained a seasonal performance factor of 2.5, instead of 3.0 as expected.
The monthly behaviour of the plant is shown below (figure 4). One should note the seasonal behaviour of the storage. The fuel boiler produces energy during the months of january to march only. During the rest of the year, the heat requirement is met completely by the heat pump, using the store or the solar collectors as cold source and by the solar collectors directly during the months of april to december. The contribution from the storage directly to the load is very small.

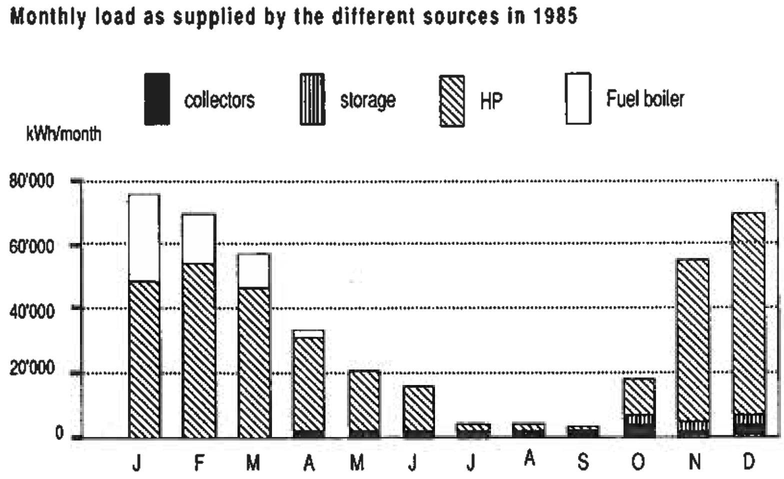


Figure 4

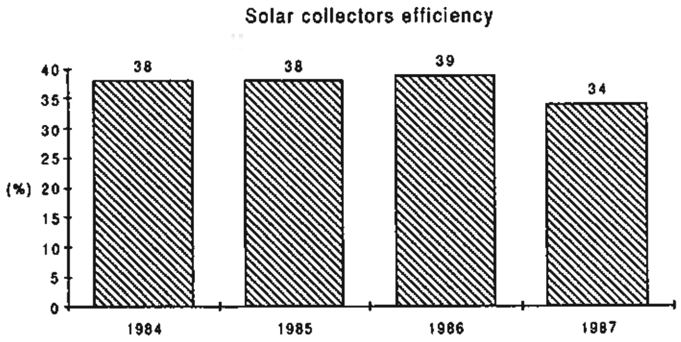


Figure 5

The most important results obtained are :

- the storage has behaved as expected since the beginning of the operation in 1983. The extreme temperatures are 5°C minimum and 50-54° C at the maximum
- the solar collector array has kept a very high yearly average efficiency during the years 1983 to1987 (figure 5).

The lower efficiency measured in 1987 was not due to a degradation of the array, but to the fact that the heat pump was in the process of being replaced during the summer, and the average storage temperature was higher, therefore leading to a lower collector efficiency.

In 1987, the heat pump was replaced by another with better characteristics. It resulted in a much better performance factor (figure 6).

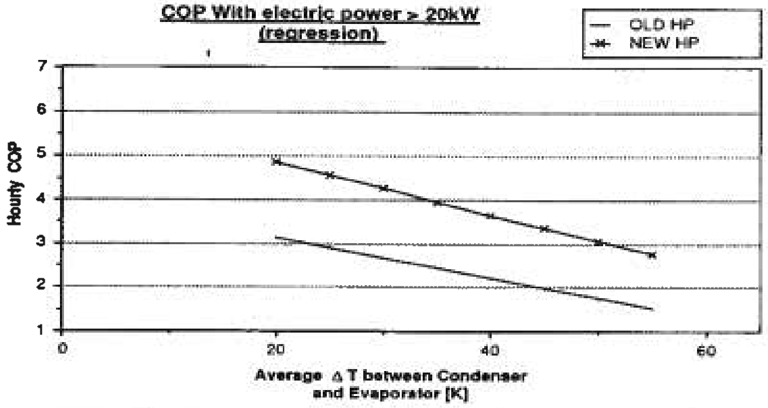


Figure 6

With this new heat pump, the seasonal performance factor was raised from the disappointing value of 2.55 for 1986/87 to 3.91 in 1987/88. Its monthly performance are shown on figure 7.

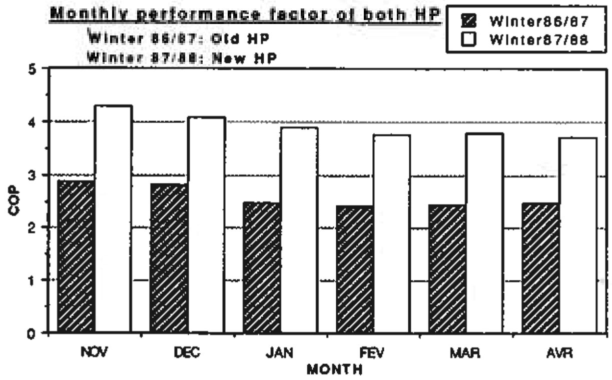


Figure7

4 EVALUATION OF THE PLANT WITH THE MINSUN CODE

Based on the actual system characteristics, and with an adjusted load, the Vaulruz system was simulated for the year 1985, with the Minsun code.
The results obtained (figure 8) are in good agreement with measured performances (figure 3), even though the Minsun code does not take into account the direct connection between the collectors and the load.

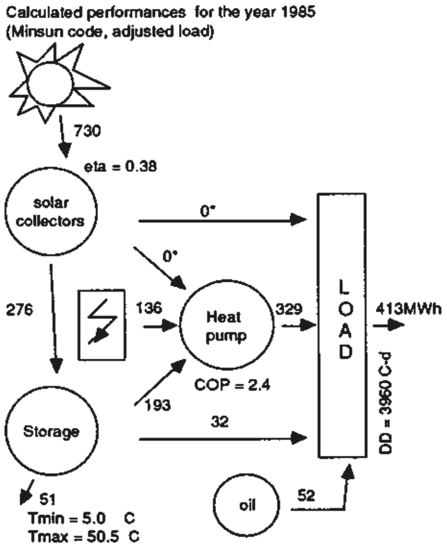


Figure 8

4.1 Reoptimization

Based on that, a reoptimization of the Vaulruz system has been carried out with an enhanced heat pump. The results can be summarized as follows :
with a 3500 m3 store :
- the solar costs curve function of the collector area shows an optimum between 500 and 700 m2

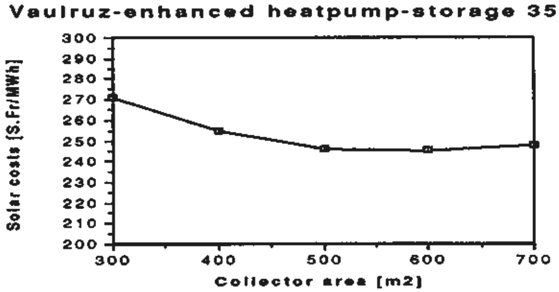


Figure 9

-the chosen solution of storage insulation is among the best possible (figure 10)

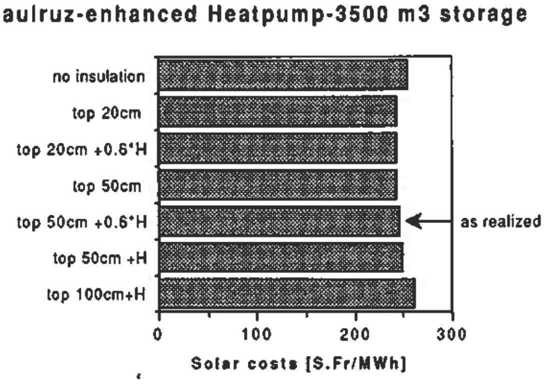


Figure 10

with 500 m2 collectors area :
-when varying the storage volume from 2500 m3 to 7500 m3, no optimum is seen, the solar costs increases with storage volume (figure 11).

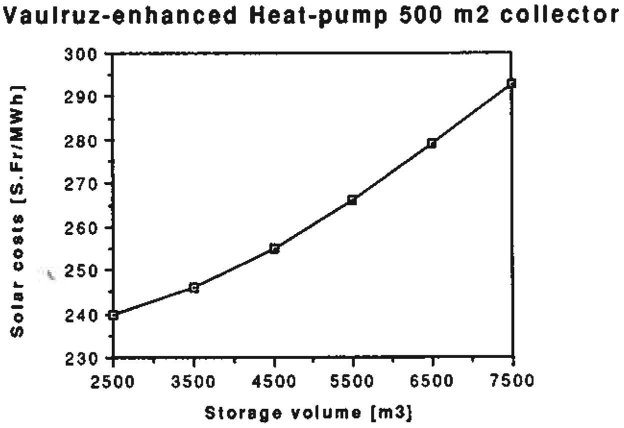


Figure 11

These calculations show that for a given storage volume of 3500 m3, the system, as realized, was close to the optimum solution.

5 THE VAULRUZ SYSTEM COMPARED TO A TRADITIONAL ONE

If one compares the Vaulruz project with a traditional system one can see that the real energy savings amount to approximately 60 %.

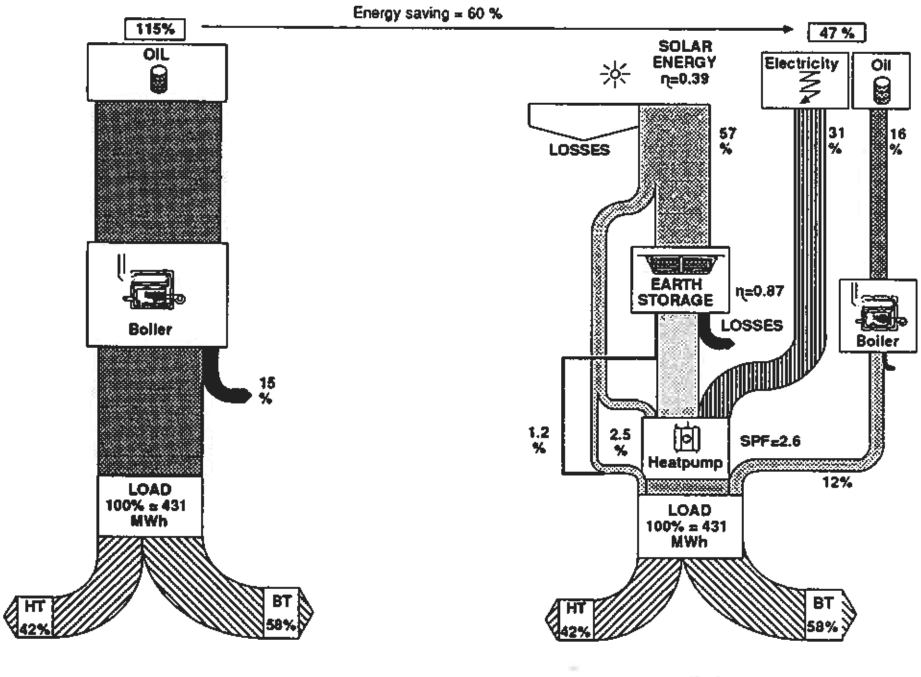


Figure 12

6 USE OF THE VAULRUZ PROJECT

The main interest of the Vaulruz project is that predicted performance matches monitored performance. Indeed, the Vaulruz project is too small to be an economicaly promising system. However, based on the experience gained with such a project, one can now look for projects 10 to 50 times the size of the Vaulruz project, without the use of a heat pump. Such large projects could not be undertaken without the experiences of the Vaulruz project.

7. REFERENCES

The Vaulruz project has been intensively monitored from 1983 until 1988. A detailed description of the plant performance can be found in the following reference :

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