



STATENS GEOTEKNISKA INSTITUT  
SWEDISH GEOTECHNICAL INSTITUTE

# Parameter Study of Solar Heating Systems with Seasonal Ground Storage in Moraine

MARTI LEHTMETS

Report 51

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**Rapport** Report **No 51**

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in Moraine

**MARTI LEHTMETS**

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# Foreword

This report constitutes the documentation of a theoretical design project performed in 1995. The project concerns solar heating with seasonal ground storage in moraine. Potential applications are residential heating and heating of domestic hot water in small and medium sized units of district heating.

The Swedish Geotechnical Institute (SGI) has broad experience of ground heat storage in soft clay at high temperatures. This storage technique, together with ground heat storage in rock, has proved to be most competitive. However, there has been a shortage of design proposals when alternative types of geology, such as moraine and sand, have been considered for ground heat storage.

The project has been made possible through the financial support of the Swedish Council of Building Research and the SGI within an on-going research programme dealing with questions of energy geotechnics. It was decided, unlike the normal publication procedure, to write the report in English in order to enable the institute to enlarge the field of application and to obtain international feedback.

In the project work, feedback of experience regarding seasonal heat storage in moraine has been utilised from a similar realised plant in Switzerland, the Vaulruz project (Hadorn, 1986), and from a Swedish project for monitoring a heat store for the combined purpose of heating and cooling, situated in Hofors (Lehtmets & Bergdahl, 1995).

The project leadership as well as the main workmanship has been conducted by Marti Lehtmets at the SGI. Also Anna Gabrielsson at the same institute has been active in the project.

I wish to thank the members of the reference group of the research programme Björn Sellberg of the Swedish Council of Building Research, Heimo Zinko of ZW-energiteknik, Jan-Olof Dalenbäck of Chalmers University of Technology

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Linköping, October 1995

Marti Lehtmets

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# Summary

A seasonal solar heating system must utilise a heat store to equalise the gap between supply and demand of heat during the season. Water heat storage has been used for a wide range of geotechnical conditions. Ground heat storage has mainly been developed for vertical duct systems in rock and soft clay, especially in Sweden. International experience of ground heat storage in moraine is limited to two plants in Switzerland (Hadorn, 1986) and (Pahud, 1994).

The objective of this simulation project has been to identify the current level of the solar heat cost for a small sized district heating unit covering the heat demand of 200 dwellings. The solar heating system comprises a solar collector array, a ground heat store in moraine and an auxiliary boiler. In the study, a simulation model of a solar heating system (MINSUN) has been used to calculate the heat balance of various system solutions. From the heat balance results and the cost calculations, the specific solar heat cost has been specified in ECU/MWh on an annuity basis.

Two different types of ground heat store have been investigated in the study. One store is based on a conventional technique, similar to the construction of ground heat stores in rock. The second type of ground heat store is a combination of a water filled pit and a ground heat store with a horizontal duct system. The first store is constructed by drilling wells and the second by excavating, lining, duct system installation and gradual refilling of the excavated soil.

A total of 300 simulations have been undertaken in the parameter study. An identified lowest level of the solar heat cost versus the solar fraction is estimated at approximately 130 ECU/MWh, independent of the choice of ground heat store concept. The solar heat cost is relatively stable versus the solar fraction. If attention is given to the cost of auxiliary heat, the total end price may be increased. The commercial introduction of a solar heating plant with seasonal heat store requires a reduction in the solar heat cost clearly below the expected level, 75 ECU/MWh, of supplied conventional heat, i.e. oil and electricity.

In accordance with the results of the presented sensitivity study, efforts to reduce the solar heat cost should be focused on a reduction in the investment costs. This requires an improved cost-effectiveness with regard to the installation of ground heat exchangers and manufacturing of solar collectors. Changes in thermal properties of the industrial manufactured insulation and the natural ground seem to have a minor impact on the solar heat cost.

Further research and development in the area of seasonal storage in moraine should be concentrated to the borehole heat store concept. The economic performance of the two heat store concepts is fairly similar. Since no relevant experience of very large excavated heat stores is available, the potential of the technique should be judged with caution. However, the borehole drilling technique has proved to be successful in other applications than heat storage in moraine.

# Chapter 1.

## Introduction

The heat load of a residential unit is normally covered by heat from a conventional heating plant using fossil fuels. To find more environment-friendly applications, much attention is being given to the potential of solar heating. A seasonal solar heating system must be incorporated with a heat store to equalise the gap between supply and demand of heat and to achieve an acceptable solar fraction at a reasonable solar heat cost. Unfortunately, the economic competitiveness of seasonal solar heating is often found to be limited by the high investment costs. In Sweden, seasonal solar heating is usually demonstrated in the area of small sized district heating units, 1-2 GWh/year.

A seasonal heat store uses the ground or/and water as storage medium. Water heat storage has been developed for a wide range of reservoirs (pit, tank and rock cavern) and different geologies, for example rock and moraine.

In a ground heat store, a system of tubes/ducts, ground heat exchangers (GHE), is installed in the ground to maintain the heat transfer. To increase the output capacity, a water buffer store is integrated between the ground heat store and the heat load. Ground heat storage has mainly been developed for vertical duct systems in rock and soft clay, especially in Sweden. Under these geological conditions, the technique has been found to be successful and competitive. However, there is a lack of experience of ground heat storage in moraine and sand in spite of the dominant distribution of these soils. The land area of Sweden consists of about 75 % moraine, but this is found most frequently outside the urban areas. The design of ground heat stores in friction soils (moraine/sand) and soft rocks may also be interesting in an international perspective.

The general design of the proposed storage system is based on the use of a flexible unit solution applied for different geologies and technical prerequisites. The demands on environmental design, free of objections, are met through the principle of natural recycling. The environmental impact is limited by flexibility, the local anchoring in the choice of services duties and transports, the use of natural

recyclable construction materials and the use of waste products. Even the operation of the seasonal solar heating system is advantageous compared to a conventional heating systems due to the reduced demand on fossil fuels which not only reduces the amount and impact of the air pollution but also the production of carbon dioxide ( $\text{CO}_2$ ).

## Chapter 2.

# Objective of the Study and the Method Used

The objective of this simulation project has been to:

- Identify the current level of the solar heat cost for a small sized district heating unit covering the heat demand (2 GWh/year) of 200 dwellings. Except for the cost calculations, based on Swedish conditions, the study has a general technical approach. The study concerns, a solar heating system comprising solar collectors, a ground heat store in moraine and an auxiliary boiler.
- Investigate the influence on the solar heat cost in a sensitivity analysis through variations in technical and economic parameters. The parameter study has been carried out in order to identify where research and development should be focused.

A simulation model of a solar heating system (MINSUN) has been used to calculate the size dependent heat balance of various system solutions in accordance with the studied concepts. Based on the heat balance results and size dependent investment and operation cost calculations, the specific solar heat cost has been specified in ECU/MWh on an annuity basis.

# Chapter 3.

## Design of the Ground Heat Store Concepts

The fictive ground of the site consists of 20 metres of moraine and a ground water level a few metres below the ground surface. The present ground water level impacts not only on the choice of input data for the simulation model, but also on the method of construction of the heat store.

Two different types of ground heat stores have been investigated in the study, *Figure 3.1*. The first store is based on a conventional technique, similar to the construction of ground heat stores in rock. The second type of ground heat store is a combination between a water filled pit and a ground heat store with a horizontal duct system. The first store has been constructed by drilling wells and the second by excavating, lining, duct system installation and gradual refilling of the previously excavated soil.

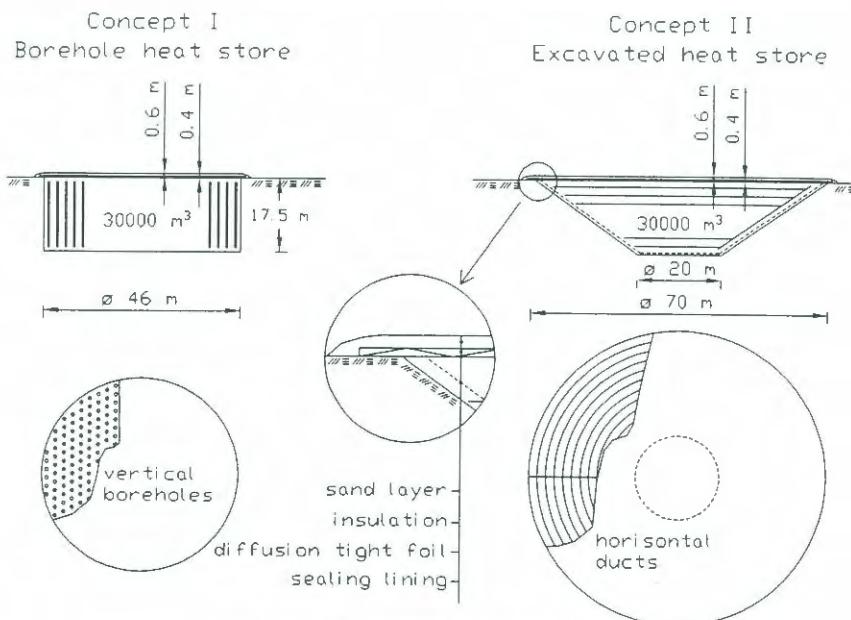


Figure 3.1. Heat store concepts I and II.

From the construction point of view, concept I is advantageous because of the well known drilling technique, compact store volume and flexible construction. The advantages of concept II are lower convective heat losses due to the sealing lining, flexible choice and mixture of refilling material, flexible choice of ground heat exchangers (tubes/ducts, radiators with ribs etc.) and the possibility to apply side insulation.

The heat store based on wells (concept I) has been constructed using conventional drilling equipment. The construction method comprises initial site surface preparation, drilling of wells supported by permanent casings, bottom tightening of casings, installation of concentric inner tubes in the wells, top tightening of casings, plumbing and manifold work, pressurised testing, top insulation and covering.

The configuration of the wells, with a diameter of 120 mm (five inches), forms a quadratic pattern with a spacing distance normally between 2-4 m. Wells deeper than 20 m are not considered in the study. Each well consists of a watertight casing and a concentric inner tube. The fluid is transported inside the concentric inner tube to the bottom of the casing. The volume between the concentric inner tube and the casing constitutes the channel for upward flow. The construction is in metal since the mechanical and temperature requirements are high (95 °C).

After installation, the wells are connected to each other to maintain a closed distribution system. A number of wells, dependent on the design demand of low pressure drop and turbulent flow, form one serial tube loop as part of a large number of parallel tube loops connected to the manifold system. The manifold system, including the top of the casings, is embedded in a layer of sand on which the industrially produced top insulation of 0.4 m thickness is placed. The insulation is covered by 0.6 m sand and protected from internal moisture by a diffusion tight foil placed underneath.

The excavated heat store (concept II) is constructed with traditional earthworks in friction soils using the principle of mass balance. The complete store volume is excavated and the soil is temporarily placed around the periphery of the store. Since the store is relatively deep and wide, due to the natural slope of the moraine, it is necessary to adapt the method of excavation and manual layout of ducts to the present conditions. The ground water level is temporarily lowered by ground water control while the store is under construction. The transport of excavated soil uses a temporary ramp providing lorry access to the deep bottom of the store. A sealing lining of geotextile and bentonite is designed to prevent the

bottom and the faces of the store from convective water transportation, in other words increased thermal heat losses. The sealing lining is embedded in a 0.6 m thick protecting layer of sand.

The first level of U-shaped plastic ducts (single U-pipes) is manually laid out on a horizontal levelling layer of sand at the bottom of the excavated volume. Each level of ground heat exchangers (GHE) is embedded under another 0.1 m thick layer of sand. There is full flexibility concerning the choice of maximum bending diameter of each GHE. Continuous duct sections of about 250 m, corresponding to five GHE without joints, can be installed. Due to the natural slope of the store, the number of duct loops on each level is different, decreasing with each deeper level of GHE. After approved pressurised testing, the two free parts of each loop are assembled in a few positions on each level for further vertical tubing and integration into the manifold system. The store volume is gradually refilled with the excavated soil to the next designed level of GHE (GHE spacing distance). The degree of water saturation, i.e. the heat capacity of the storage medium, is increased through the artificial supply of water.

For refilling, the necessary construction machinery includes an excavator, lorries, a bulldozer for the levelling procedure and a compactor (sand layers). The machinery makes full use of the gradual distributed refilling to enable operation foundation and at the same time protects the ducts. The manual procedure for duct layout is repeated for each GHE level up to the ground level. The industrially produced top insulation of 0.4 m thickness is protected underneath from moisture by a diffusion tight foil placed on a levelling layer of sand. The insulation is covered by 0.6 m sand.

The remaining excavated soil (20 %) can be used for restoration of the site and/or as a financial “by-product”. This possible resource has not been considered in the investment cost calculations.

## Chapter 4.

# Geotechnical Aspects

The design, construction and operation of a ground heat store must be based on geotechnical know-how. If the geotechnical aspects are considered in the early planning stage of a building scheme, it is possible to improve cost-effectiveness. The most relevant questions to observe are construction aspects, heat losses during operation and impact on the store and the surroundings due to expected settlements induced by load, temperature changes and ground water flow. Examples of consequences of poor geotechnical design are increased investments, interrupted fluid circulation in the ducts, impossible semi-utilisation of the ground area of the store and damage to the foundations of nearby buildings.

In the initial study, the geotechnical investigation should be focused on the evaluation of whether a proposed site is suitable for a heat store concept in general and specifically the type of store that can be built.

In the feasibility study, the geotechnical classification of the soil, its stratigraphy and the ground water situation are used to identify the available storage geometry, geotechnical and thermal properties of the soil and the ground water flow. A technical and to some extent an economic evaluation will form the basis for a suggested cost-effective design and construction of the store. Examples of aspects that may be considered are settlements and their extent around the store, homogeneity of the moraine with respect to the construction of the ground heat exchangers or the wells, ground water control to maintain excavation of soil, slope stability and calculation of soil quantities.

Furthermore, the suggested design and the geotechnical data will form the input basis for the thermal simulation study, the estimation of hydraulic heat losses and the calculation of investment costs.

# Chapter 5.

## Estimation of

# Specific Investment Costs

The heat cost for a conventional heating system is mainly dependent on the price of the fuel. The investment cost is a minor part of the total heat cost. The influence of the heat cost through a variation in the investment cost is therefore limited. However, for a solar heating system, the solar heat cost is mainly dependent on the investment cost. For this reason, the design of the solar heating system is not based on the requirements on total output capacity but instead on a solar heat cost optimised base load of the energy demand. An auxiliary heater is used to cover the peak load.

The investment cost calculation has been based on experience from ongoing projects, inquiries to constructors dealing with drilling and excavating, literature, product leaflets and personal collegial contacts. Most attention has been given to the investment cost calculations for the heat store concepts. The investment cost calculations for the heat stores also include costs not directly involved in the seasonal heat store costs, but more as investment costs for the supply system (see Table 5.1) and the operating cost that corresponds to 20 % of the total solar heat cost (see Chapter 5.3).

### **5.1. INVESTMENT COSTS FOR THE SOLAR COLLECTORS**

Roof integrated solar collectors are considered in the study. The investment costs for the solar collectors are based on a complete installation (Zinko & Dalenbäck et al., 1993). The specific investment cost is estimated to be 222 ECU/m<sup>2</sup> (2000 SEK/m<sup>2</sup>) for a 3000 m<sup>2</sup> option and 200 ECU/m<sup>2</sup> (1800 SEK/m<sup>2</sup>) for a 6000 m<sup>2</sup> option respectively. The specific investment costs for these options are used for a linear interpolation and extrapolation of the specific investment costs within a solar collector range of 2000-7000 m<sup>2</sup>.

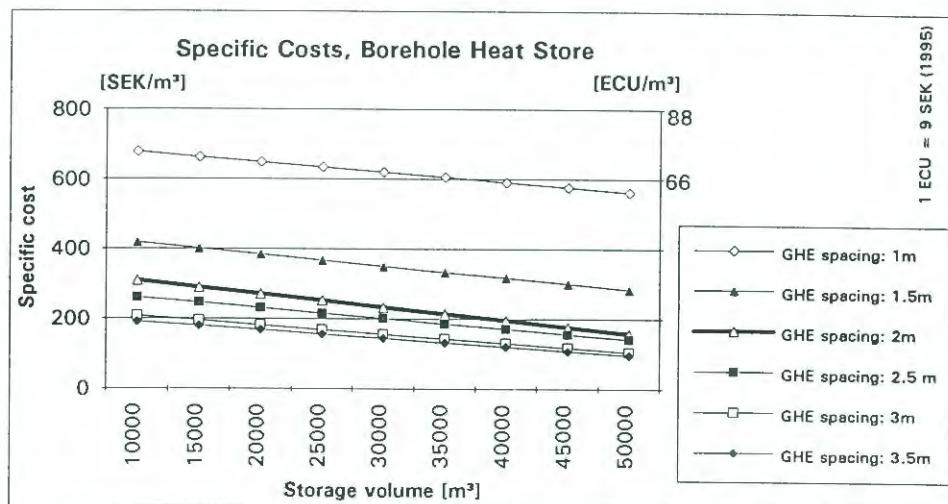
### **5.2. INVESTMENT COSTS FOR THE SEASONAL HEAT STORES**

The investment cost for the seasonal heat store as a function of the storage volume and the spacing distance of the ground heat exchangers is studied for the two store concepts. The specific investment costs [ECU/m<sup>3</sup>] are calculated for

two storage volumes ( $20000$  and  $30000\text{ m}^3$ ) and for four spacing distances ( $1.0$ ,  $1.5$ ,  $2.0$ ,  $2.5\text{ m}$ ). These results of the investment cost calculation are used for a linear interpolation and extrapolation of the specific investment costs within a storage volume range of  $15000$ - $50000\text{ m}^3$  and a spacing distance range of  $1$ - $3.5\text{ m}$ .

The specific investment costs for the heat store concepts are presented in *Figure 5.1* and *Figure 5.2*, see formulas at the beginning of Appendix C. *Figure 5.1* shows the specific investment costs for a borehole heat store concept versus storage volume and a variable GHE spacing. Since no calculations were conducted for the GHE spacing  $3$ - $3.5$ , these lines are extrapolated with the aid of *Figure 5.3*.

*Figure 5.2* shows the specific investment costs for an excavated heat store concept versus storage volume and a variable GHE spacing. Also the specific investment costs for an excavated heat store without mass balance are indicated (GHE spacing  $2\text{ m}$ ). This heat store is not placed entirely below ground level, but the volume of the excavated soil is used for the construction of an embankment, the upper supporting side of the heat store, placed on the ground surface around the periphery of the store. The store volume is filled with any available choice and mixture of cheap refilling material.



**Figure 5.1.** Specific investment costs for a borehole heat store versus storage volume.

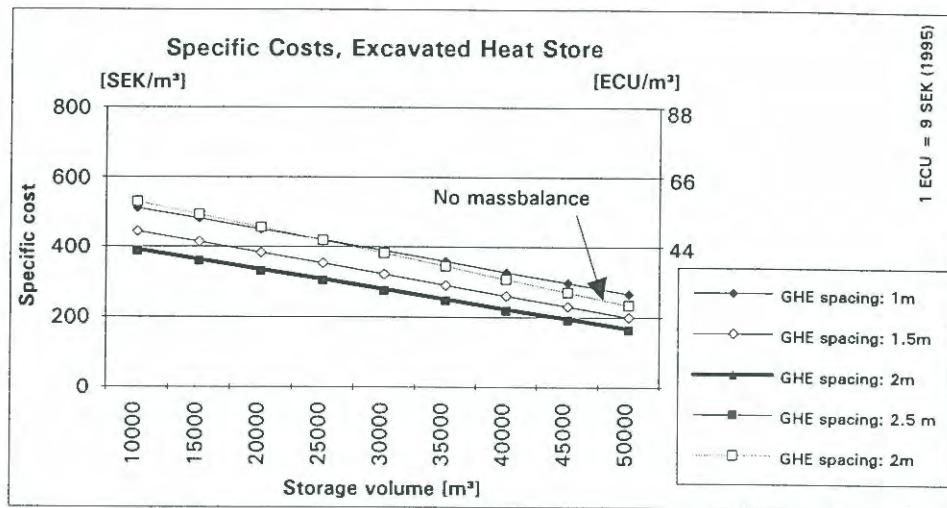


Figure 5.2. Specific investment costs for an excavated heat store versus storage volume.

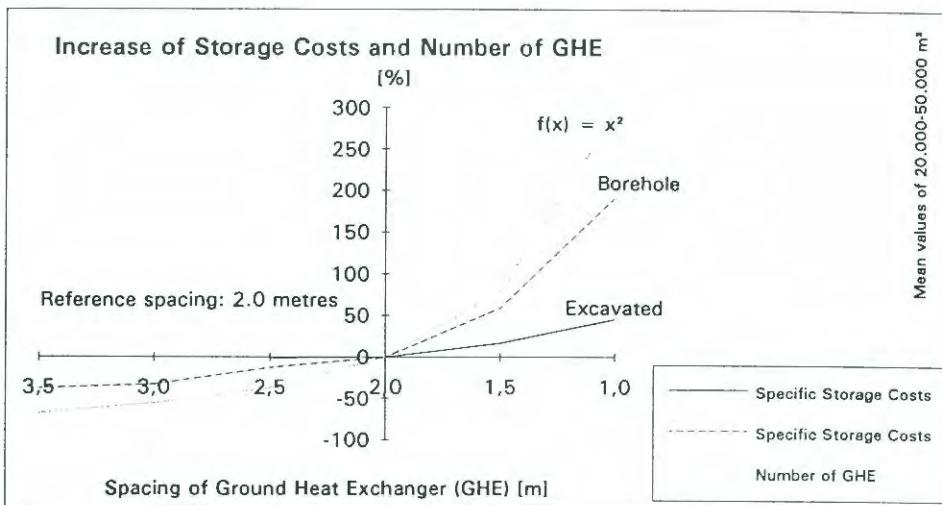


Figure 5.3. Increase in storage investment costs and number of GHE versus reduced GHE spacing.

The most competitive specific investment costs for the borehole heat store concept are lower compared with the excavated heat store concept. The lowest specific investment costs for the borehole concept are 11 ECU/m<sup>3</sup> (96 SEK/m<sup>3</sup>) and 21 ECU/m<sup>3</sup> (192 SEK/m<sup>3</sup>) for a store volume of 50000 m<sup>3</sup> and 15000 m<sup>3</sup>, respectively. These costs are representative for a GHE spacing of 3.5-3 m. The corresponding figures for the excavated heat store concept are 18 ECU/m<sup>3</sup> (163 SEK/m<sup>3</sup>) and 43 ECU/m<sup>3</sup> (387 SEK/m<sup>3</sup>). However, these costs are valid for a closer GHE spacing of 2.5-2 m. With a GHE spacing of 3.5 m, the further reduction in the specific investment costs is estimated to be small.

The inclination of the lines, i.e. the dependence on storage volume, is steeper for the excavated heat store concept compared with the borehole heat store concept. The inclination is affected by the share of fixed investment costs compared with size dependent investment costs. This share is greater for the borehole heat store concept compared with the excavated heat store concept.

For a given storage volume and a GHE spacing of 2 m, an excavated heat store concept without mass balance is more expensive than the standard excavated heat store concept. Also, if the refilling is free of charge, the specific costs will be too high compared with the standard excavated heat store concept. The reason is more extensive land and insulation requirements, since the counter slope of the embankment exceeds the width of the store by 10 m.

Based on the specific investment cost calculations for the borehole heat store concept with a GHE spacing of 1-2.5 m, the specific investment cost is extrapolated for increased GHE spacing up to 3.5 m, see *Figure 5.3*. The increase in the specific investment costs for a borehole heat store concept versus reduced GHE spacing is strongly dependent on the increase in the number of GHE, described as  $f(x) = x^2$ .

The increase in the specific investment costs for an excavated heat store concept is moderate a decrease in GHE spacing (increased number of GHE). Compared with a reference GHE spacing of 2 m, the reduction in the specific investment costs for a borehole heat store concept is 33 % and 38 % for a GHE spacing of 3 m and 3.5 m, respectively.

Two examples of the distribution of investment costs are presented in *Figure 5.4* and *Figure 5.5*. Both the borehole heat store, *Figure 5.4*, and the excavated heat store, *Figure 5.5*, represent a store volume of 30,000 m<sup>3</sup> and a GHE spacing of 2 m.

### Borehole Heat Store, Distribution of Costs

Volume: 30,000 m<sup>3</sup>, GHE spacing: 2m

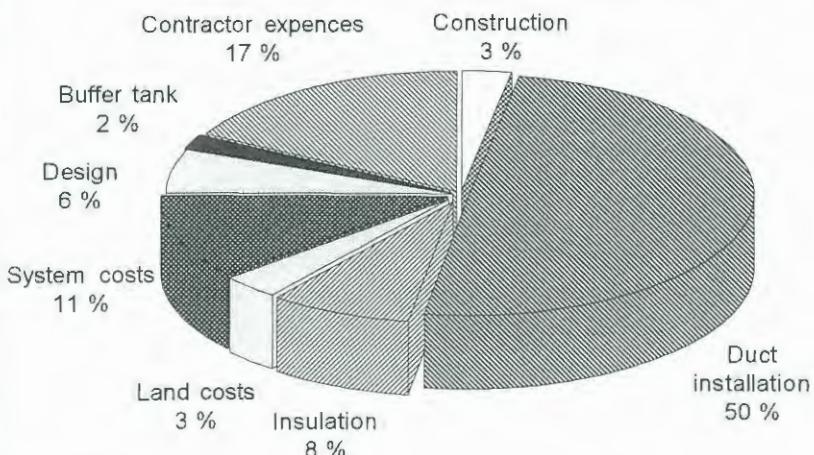


Figure 5.4. Distribution of investment costs for a borehole heat store concept.  
Total investment cost: 780,000 ECU (1 ECU = 9 SEK (1995)).

### Excavated Heat Store, Distribution of Costs

Volume: 30,000 m<sup>3</sup>, GHE spacing: 2m

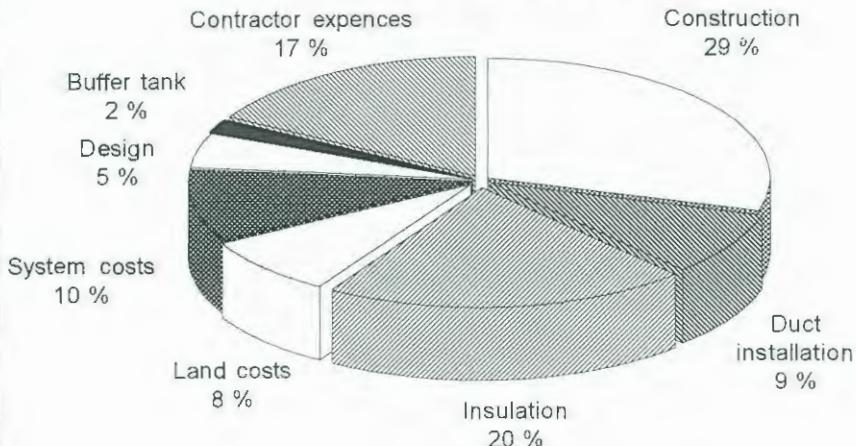


Figure 5.5. Distribution of investment costs for an excavated heat store concept.  
Total investment cost: 930,000 ECU (1 ECU = 9 SEK (1995)).

As indicated in *Figure 5.4* and *Figure 5.5*, there are two fundamental differences between the two concepts. The distribution of investment costs for construction and duct installation shows an entirely different character.

- The investment costs for construction are dominant in the excavated heat store concept. In the borehole heat store concept, the investment cost for “duct” installation is dominant. Seventy per cent of the investment costs for “duct” installation are related to drilling activities and concentric tube installation.
- The disadvantageous shape of the inverted circular cone geometry (concept II) compared with a cylindrical geometry greatly affects the ground area required. Therefore, the investment costs for land and insulation are higher for the excavated heat store concept. A semi-utilisation of the ground area, for example as a parking ground, is desirable for economic reasons.

### **5.2.1. Prerequisites for the calculation of investment costs for the seasonal heat stores**

#### *Geometry of the stores*

For the mass balance concept (concept II) the store depth is calculated from the estimated maximum natural slope angle of the moraine ( $35^\circ$ ) and with the emphasis on creating a compact geometry of the store with minimum excavation, i.e. an inverted circular cone geometry. To reduce and standardise the number of variations, an average store depth of 17.5 m is used in the investment cost calculations and in all simulations, including concept I. Some of the initial investment cost calculations were, however, based on a mixture of size dependent store depths within the range of 16-20 m. The geometry of the heat store concepts is shown in *Figure 6.1*.

All ambient areas are estimated for a circular geometry (concept I) and an inverted circular cone geometry of the store (concept II). An additional factor of 20 % is used to compensate for extra investment costs due to the fact that requirements on ground area and insulation are larger than the effective surface area of the store. Also for calculations of ambient areas of the heat stores, some of the initial results are based on inconsistency regarding the use of an average store depth.

*Number of ground heat exchangers (GHE) versus spacing distance of GHE*  
The density of the GHE is proportional to the ground surface area of the store.

This area is calculated from the volume and fixed depth (17.5 m) of the store. A uniform distribution of the GHE means that a certain horizontal area can be ascribed to each GHE. The ratio between the store surface area and the GHE area gives the number of GHE. To reduce and standardise the number of variations, the calculated number of GHE is rounded off to an equal quadratic pattern ( $8 \times 8 - 53 \times 53$ ). The number of GHE varies in the study within the range of 64-2809 units ( $15000\text{m}^3/3.5\text{m}-50000\text{m}^3/1\text{m}$ ).

### *Subdivision of the investment costs*

Subgroups are used to identify the distribution of the calculated investment costs for the heat stores. The groups consist of construction in earthworks, duct installation, insulation, ground area, solar supply system, design, buffer tank and miscellaneous / contractor expenses. The included range of investment costs for each group is indicated in *Table 5.1*. The costs for the solar supply system and design are not only strictly related to the investment costs for the heat store but also to the investment costs for the solar heating system in general. The summarised investment costs are divided by the current store volume to obtain the specific investment costs for the seasonal store expressed in ECU/m<sup>3</sup> and SEK/m<sup>3</sup>.

**Table 5.1. Included range of each defined cost distribution group.**  
See Appendix A for unit prices.

Cost distribution group	Range
Construction in earthworks	Establishing, ground water control, site surface preparation, excavation, refilling sand, refilling, bentonite, levelling layer, protecting layer.
Duct installation	Drilling, ground heat exchanger (GHE)/duct, duct blower, manifold, coupling, establishing, labour, hose reel, pressurising equipment, refilling sand, bending fixture, connecting wells.
Insulation	Insulation, diffusion tight foil, protecting layer, labour.
Cost of ground area	
Cost of solar supply system	Underground culvert, power equipment, control and plumbing equipment, connection, labour.
Design	Collector field, store with geotechnical investigation, system.
Buffer tank	
Miscellaneous/Contractor expenses	

### **5.3. ANNUITY RATE**

All economic calculations based on the depreciation of investments use an annuity rate equal to 0.08 (20-25 years, 5-6 % real rate of interest). A total annuity rate of 0.1 is used to compensate for operating and maintenance costs (0.02). This compensation is unfavourable for the borehole heat store concept due to less sacrificed efforts for fluid circuit circulation compared with the excavated heat store concept.

# Chapter 6.

## System Simulation Model, Input Set-Up

MINSUN is a system simulation program which models a solar heating system, see *Figure 6.1*, comprising heat production by solar collectors, seasonal heat storage, peak heat production by auxiliary heater and consumers' demand on heat load. The model also enables heat pump connection (Mazzarella, 1989). By specifying the heat load, physical parameters, system components such as GHE spacing and weather data and then varying the ratio between the storage volume and the solar collector area, the program calculates the heat balance of various system solutions. Examples of heat balances are shown in Appendix C.

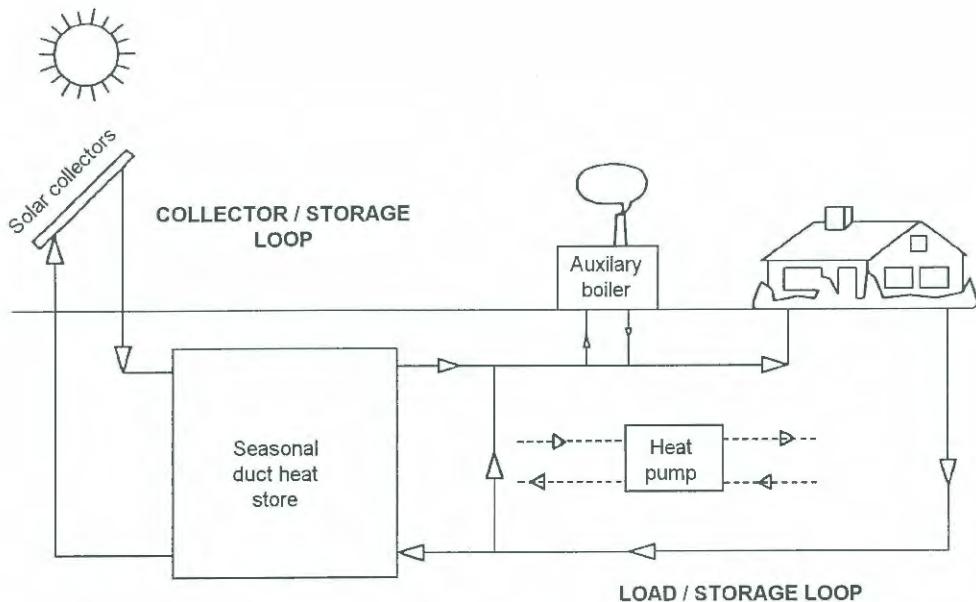


Figure 6.1. Solar heating system configuration (MINSUN user's guide)

The current parameter study includes flat plate solar collectors and two combinations of ground heat stores constructed in moraine. 200 apartment units using floor heating are considered in the study. Weather data for Stockholm in 1986 are used as a climate reference year for Sweden.

The natural thermal properties of the soil vary with depth because of changes in the degree of water saturation. The heat capacity and thermal conductivity of the natural moraine as storage medium (borehole heat store) as well as the surrounding ground material are assumed to be on average  $2240 \text{ J/m}^3 \cdot ^\circ\text{C}$  and  $2.0 \text{ W/m} \cdot ^\circ\text{C}$ , respectively. The corresponding thermal performance of the excavated heat store concept is assumed to be 25 % better compared with the natural moraine. The average heat capacity and thermal conductivity are in this case  $2800 \text{ J/m}^3 \cdot ^\circ\text{C}$  and  $2.5 \text{ W/m} \cdot ^\circ\text{C}$ , respectively. This improved high performance storage medium represents either a moraine fully saturated by additional supply of water, or a good quality waste product. Possible temperature dependence of the thermal properties is not considered in the study. The input set-up of the parameters is presented in Appendix B.

The ground store model of the MINSUN program is standardised to use a ground heat exchanger constructed as a borehole with concentric inner tube, cylindrical geometry of the store and the same design medium inside and outside the store. No hydraulic heat losses are considered.

The simulation model has been modified to compensate for the deviation in the standardised shape of the current heat store. The following circumstances which reduce thermal performance are considered.

- The borehole heat store concept is influenced by hydraulic heat losses (no sealing).
- The excavated heat store concept is designed with an unfavourable geometry (inverted circular cone). The concept uses an improved refilling or a waste product (different storage/ambient medium). Heat transfer is performed by single U-pipes (transformation of ground heat exchanger). The design of the sealing lining reduces the thermal influence due to the hydraulic heat losses compared to the borehole heat store concept.

The unfavourable geometry of the heat store and the hydraulic heat losses have been offset by reducing the collector array efficiency to 90 % (no storage effi-

ciency available in the simulation model). The construction medium outside the heat store in concept II, with reduced thermal performance compared with the storage medium, has been offset by replacing a 0.4 m thick artificial insulation ( $\lambda = 0.04 \text{ W}/(\text{m} \cdot ^\circ\text{C})$ ) with 20 m moraine ( $\lambda = 2 \text{ W}/(\text{m} \cdot ^\circ\text{C})$ ). The modifications are to be seen as an estimation that has not been fully evaluated. The thermal performance of the single U-pipe with a shank distance of 0.35 m and the bore-hole with lining (casing) has been equalised to a borehole diameter of 0.12 m (5 inches) with the aid of the GHE program (Hellström, 1989). The results of the calculations are shown in Appendix B. The calculation of the thermal performance of the single U-pipe compared with the borehole with lining is conservative since the U-pipe concept is flexible in the choice of increased shank distance and thermal conductivity ( $\lambda = 2.5 \text{ W}/(\text{m} \cdot ^\circ\text{C})$ ) of the ground, which may improve the thermal performance through reduced thermal resistance.

The heat balances of the thermal simulations and the specific size dependent investment costs (Chapter 5.1 and 5.2) have been used for calculating the collector investments and the store investments (including system costs). All the formulas used are shown at the beginning of Appendix C, "Summary of simulation results". Furthermore, the ratio of the investments to the heat produced (house load·solar fraction) by the solar heating system has been expressed as the specific investment cost in SEK/kWh (kr/kWh). The total specific investment cost has then been annualised, according to the economic parameters in Chapter 5.3, to obtain the solar heat cost in öre/kWh (0.01 · SEK/kWh). The content of Appendix C has been summarised, with international units (ECU), in Chapter 7.

The solar heat cost is not solely representative for the end heat cost of the consumer. Furthermore, regard must be paid both to the cost of the auxiliary heat and to the heat cost dependence on the fraction for each kind of heat source.

In the sensitivity analysis, undertaken with the MINSUN program, the response of the solar heat cost is observed by single variations of physical, system and economic parameters. Unless otherwise stated, all sensitivity analysis are made for parameter variations of  $\pm 20\%$  of the original value. Only the best result from the two heat store concepts, respectively, has been studied in the sensitivity analysis. In that respect, the sensitivity analysis is not complete. Other system solutions with acceptable performance, although with different characteristics compared with the optimum system solution, may behave in an unexpected way for a similar parameter variation.

# Chapter 7.

## Results of the Simulation and Sensitivity Analysis

A total of 300 simulations have been undertaken in the parameter study, summarised in Appendix C. An identified lowest level of the solar heat cost versus the solar fraction is derived to be approximately 130 ECU/MWh (1.20 SEK/kWh) as shown graphically in *Figure 7.1*. The solar heat cost is relatively stable versus the solar fraction. Furthermore, the results show that there is no fundamental difference in the lowest solar heat cost between the two seasonal heat store concepts.

The simulation envelope for a given heat store concept and a solar collector area (SC area) is presented in *Figure 7.2* and *Figure 7.3*, respectively. In general, the optimum performance of each envelope curve increases with increased solar collector area up to 5000-6000 m<sup>2</sup>. The lowest solar heat cost for the borehole heat store concept, 130 ECU/MWh (1.20 SEK/kWh), appears at a solar fraction

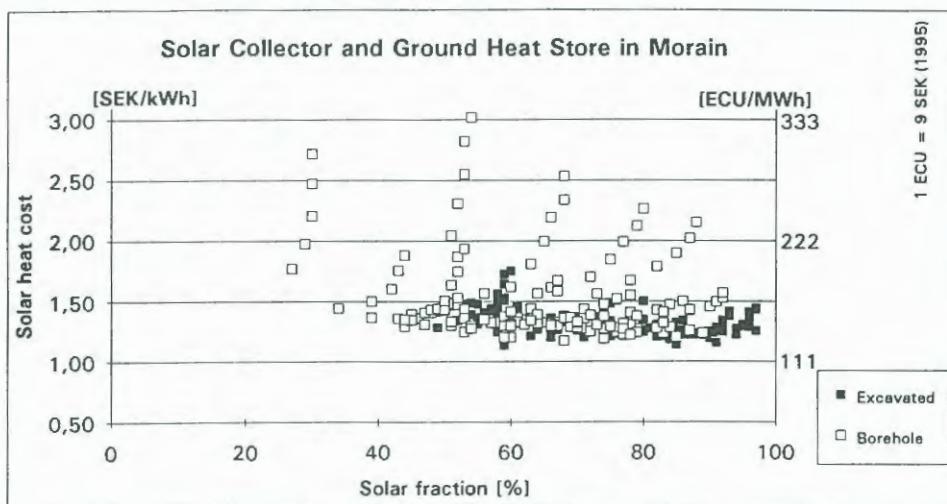


Figure 7.1. Solar heat cost versus solar fraction, summary of parameter study.

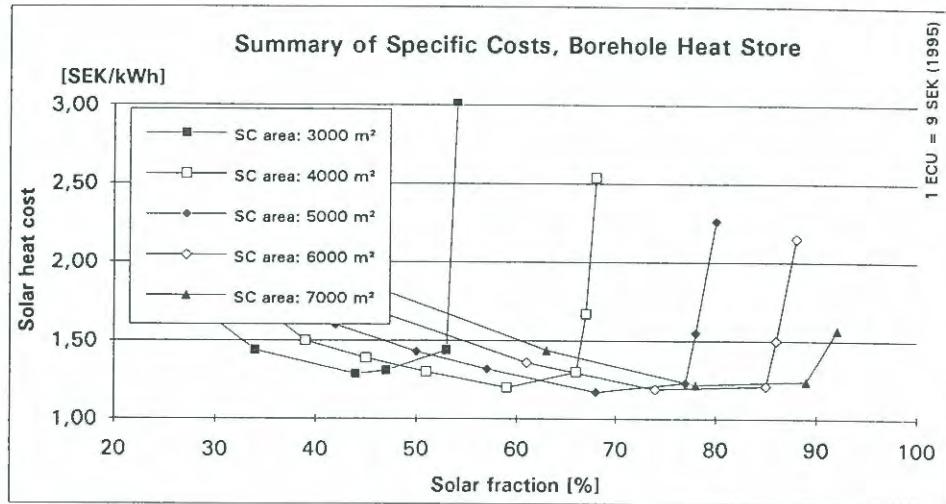


Figure 7.2. Solar heat cost versus solar fraction, borehole heat store.

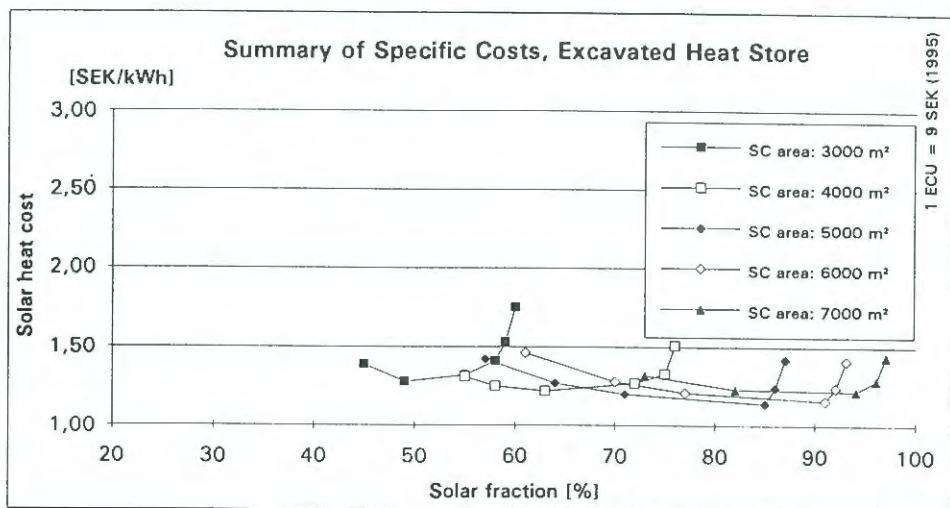
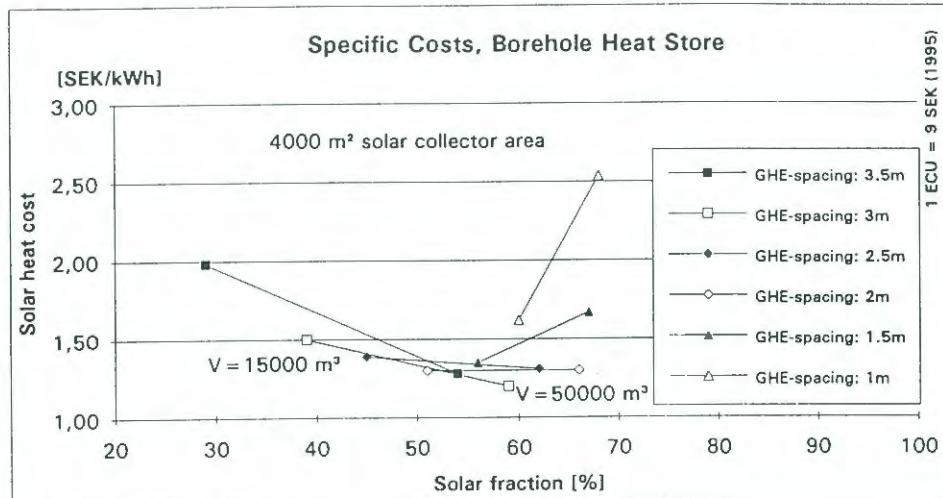


Figure 7.3. Solar heat cost versus solar fraction, excavated heat store.

of almost 70 %. The corresponding figure for the excavated heat store concept is 85 % at 127 ECU/MWh (1.15 SEK/kWh). The heat balances for these two solutions are given in Appendix C. On the right hand side, the steep increase in the solar heat cost for each envelope curve in Figure 7.2 is affected by the dominant investment costs related to drilling activities and concentric tube installation with reduced GHE spacing.

An example of the construction of an envelope curve is given in *Figure 7.4*. The curve is formed by the points with the lowest solar heat cost. The diagram shows the response of the solar heat cost versus solar fraction, for a given solar collector area, in this example 4000 m<sup>2</sup>, to variations in GHE spacing and store volume. Each GHE spacing curve is simplified as a straight line. The left/right hand end of each line is identified by the simulation results for the smallest/largest choice of store volume. The bases for all the envelope curves are gathered in Appendix C.

A variation in the store volume and the GHE spacing affects not only the specific investment for the store concept, the heat transfer capacity of the GHE and the relative heat loss of the store, but also the efficiency of the solar collector array through the variation in the return temperature of the collector loop. High collector performance, i.e. a low return temperature, is maintained by a large store volume and a large number of GHE.



**Figure 7.4.** Solar heat cost versus solar fraction for a given area of the solar collector and variations in GHE spacing and store volume.

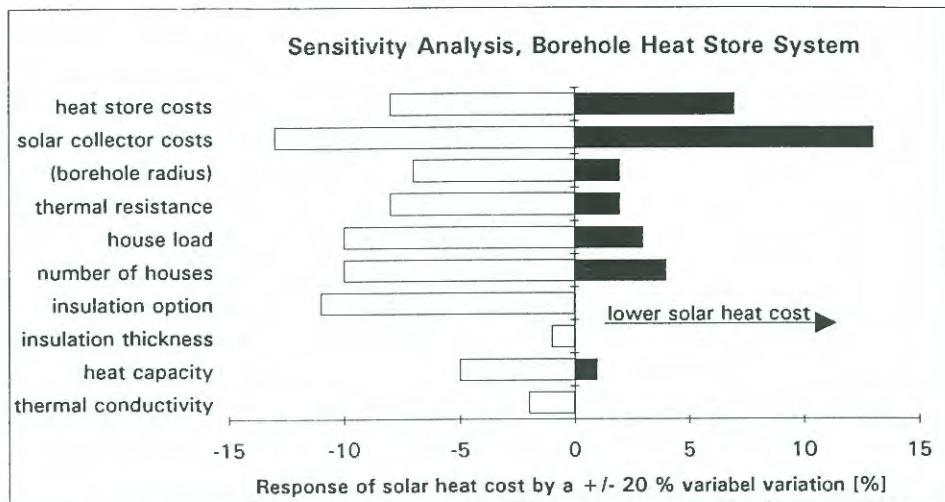
The results of the sensitivity analysis, comprising 10 single variations in ten different parameters, are shown in *Figure 7.5* and *Figure 7.6*. For both heat store concepts, the reduction in the solar heat cost (black bars) is most sensitive, 10–13 %, for a reduction in investment costs for the solar collector, followed by a reduction in the investment costs for the heat store (7–9 %). Other parameter variations reduce the solar heat cost by less than 5 %. A suitable combination of multiple parameter variation will, of course, reduce the solar heat cost even more. Another reflection is that the response to a parameter variation is more sensitive for an increase (white bars) in the solar heat cost compared with a corresponding decrease. For instance, a lower thermal conductivity is more sensitive in response compared with a higher value showing no response.

Variations of  $\pm 20\%$  in the investment costs may, for example, be the result of technical development (cost reduction potential), incorrect calculation of the investment, financial residual value of remaining excavated soil, initial heat losses, incorrect estimation of the annuity rate and financial support. The response of the solar heat cost is presented in *Figure 7.7* and *Figure 7.8*. In general, the response of the solar heat cost is about  $\pm 10\%$ .

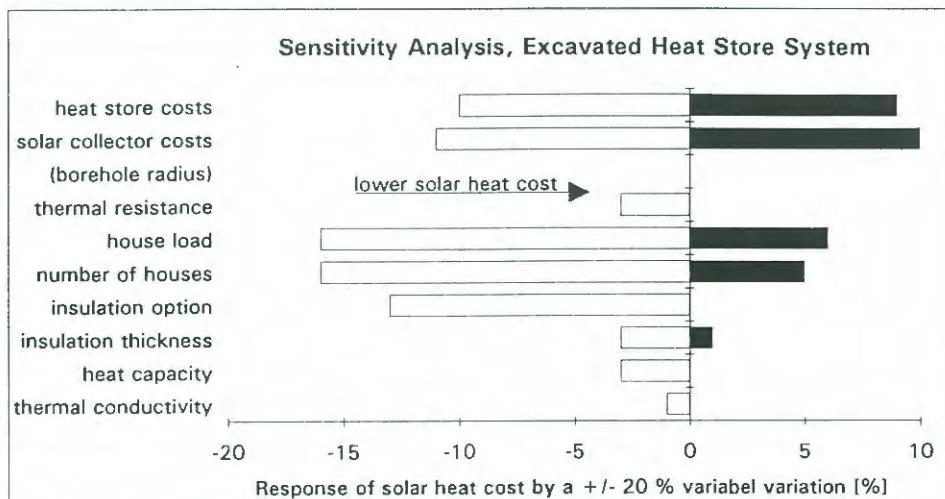
The response is largest for variations in solar collector investment costs. No fundamental variations are observed over the range of solar fraction. The borehole heat store system, *Figure 7.7*, is less sensitive to a variation in the heat store investment cost relative to a variation in the solar collector investment cost compared with the excavated heat store system, *Figure 7.8*.

A variation in borehole radius (*Figure 7.5*) affects both the thermal performance of the well and the specific investment cost of the borehole by the square of the radius of the borehole. The economic benefit of a borehole diameter reduction is small, approximately 2 %. The response is mainly affected by the improvement in the specific investment cost of the borehole compared with the reduction in thermal performance. However, the disadvantage of increased borehole radius must be observed.

The heat transfer efficiency of a ground heat exchanger is expressed in the thermal resistance. At no thermal resistance, the temperature of the fluid is equal to the ground temperature just outside the ground heat exchanger. If the thermal resistance is decreased, more heat will enter the store. Therefore, the store will become warmer and the heat losses will increase. However, the amount of heat that is extracted will also increase. The improvement in the solar heat cost is at most 2 %. However, a 20 % increase in thermal resistance results in 8 % higher



**Figure 7.5** Sensitivity analysis of a borehole heat store system. Response of the solar heat cost to a +/- 20 % parameter variation.



**Figure 7.6** Sensitivity analysis of an excavated heat store system. Response of the solar heat cost to a +/- 20 % parameter variation.

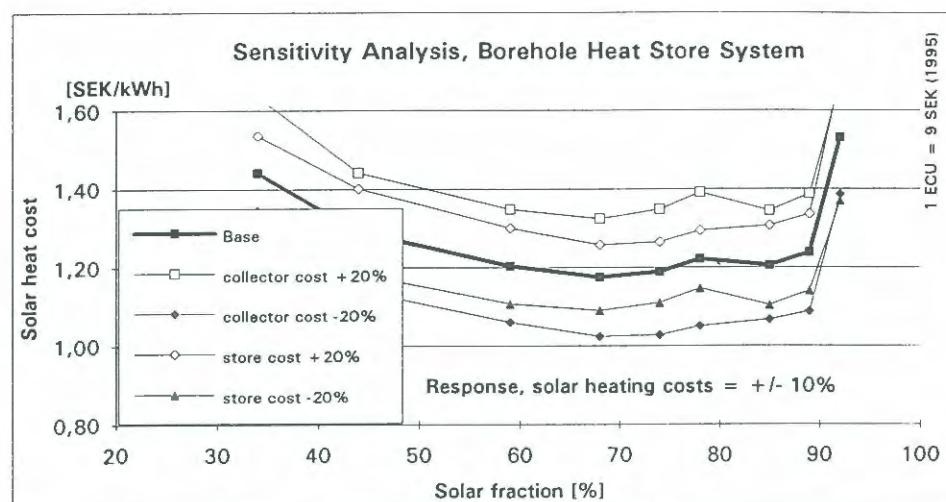


Figure 7.7 Sensitivity analysis of a borehole heat store system. Response of the solar heat cost to a  $\pm 20\%$  variation in investment costs.

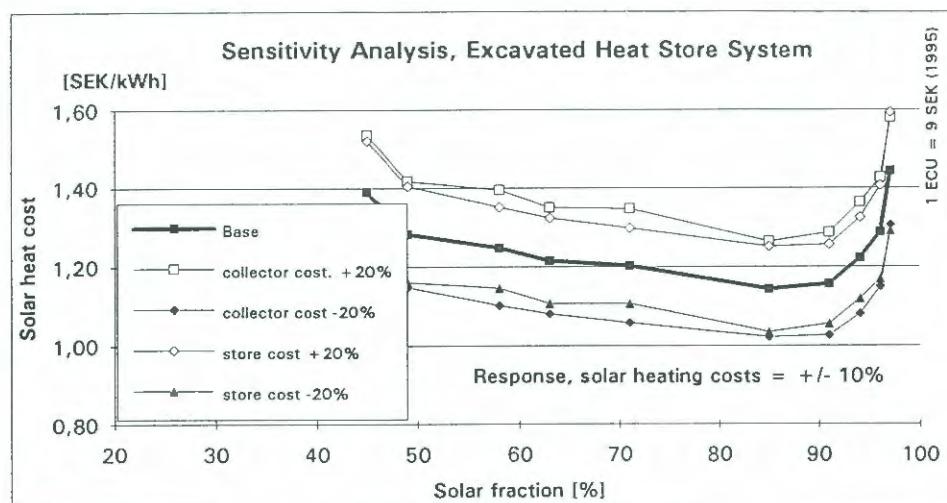


Figure 7.8 Sensitivity analysis of an excavated heat store system. Response of the solar heat cost to a  $\pm 20\%$  variation in investment costs.

solar heat cost.

An increased house load demand from reduced thermal insulation of the houses or an increase in the number of houses connected to the solar heating system reduces the solar heat cost by about 5 % at the expense of a reduced solar fraction of 10 %. The negative response of the solar heat cost to an opposite change is about 10 % for the borehole heat store concept and 15 % for the excavated heat store system, respectively.

The response of the insulation option is negative, with an increase in the solar heat cost of at least 10 % as well as a decrease in the solar fraction. In this environmentally positive option, the 0.4 m industrial insulation is replaced by 3.5 m (20 % of the store height) natural refilling with a thermal conductivity of 2 W/(m · °C). A 20 % reduced thickness of the insulation to 0.32 m or an equivalent increase in the assumed thermal conductivity of the insulation reduces the solar heat cost by about 1 %.

The thermal conductivity and the heat capacity of the storage medium are uncertain to appoint. Furthermore, heat store concept II is based on the principle of artificial improvement of the storage medium either by supplying water or by replacing the natural storage medium with other available types of bulk, such as waste products. The response of the solar heat cost to a change in the thermal properties is limited to a maximum increase in performance with 1 %. However, with a 20 % reduction in the heat capacity, the negative response of the solar heat cost is 5 %.

# Chapter 8.

## Discussion

The parameter study is focused on the level of the solar heat cost versus the thermal performance expressed as a solar fraction for a defined house load. Each system simulation is unique in respect to the thermal performance. Therefore, the study is not directly suitable for a comparison of the solar heat cost since the usefulness of each system varies.

For a heating system based on solar, the total end price of heat is formed as an average value of the solar heat cost and the cost of the auxiliary heat over a 20-25 year life expectancy. A conventional heating system for 200 dwellings will supply heat at an estimated cost of 75 ECU/MWh (average value, today's end price = 60 ECU/MWh, end price escalation of 2 % a year over 20 years). Compared with such a system, the seasonal solar heat cost based on storage in moraine is too high, 130 ECU/MWh (1.20 SEK/kWh). Twenty per cent of this solar heat cost corresponds to activities related to operation and maintenance of the plant. If attention is given to the cost of auxiliary heat, the total end price may be increased.

The designed seasonal solar heat cost based on storage in soft clay and in water filled pits (moraine) is about 90 ECU/MWh (0.80 SEK/kWh). However, ground heat stores compared with pit stores have in practice so far shown an advantage in current costs compared with design calculations. The solar cost and its competitiveness in Sweden are on the whole significant in the international situation of seasonal solar applications.

The obtained solar heat cost calculations are not valid for substituted friction soils or other geologies. The simulation model is on the one hand flexible in the choice of storage medium assuming similar thermal performance (the same heat balance is generated). The moraine is therefore replaceable by any other storage medium, such as sand. On the other hand, each investment calculation is individual in respect to the choice of ground heat store concept and the current geology. A ground heat store in sand may therefore possibly admit a more competitive

solar heat cost since the expected investment costs are lower compared to the studied concepts. However, the hydraulic heat losses for this concept are expected to increase since the permeability increases.

The matter of hydraulic heat losses in a ground heat store is observed from different aspects in the literature. The ground heat store in Groningen in the Netherlands has been investigated theoretically and practically. The store consists of water-saturated sand with a number of clay layers between. The permeability for the sand is  $5 \cdot 10^{-12} \text{ m}^2$ . The results of the validation showed that the presence of impermeable horizontal layers suppresses free convection. Compared with a heat store influenced only by heat conduction, the study indicated that the total heat losses in permeable soils are 20 % higher for a permeability of  $5 \cdot 10^{-12} \text{ m}^2$  and 40 % higher for a permeability of  $10^{-11} \text{ m}^2$ , respectively (Meurs & Hoogendoorn, 1983). However, the monitoring heat losses in the seasonal heat store in Groningen were 60 % higher than expected (Wijsman & Havinga, 1988). The tilting time of the temperature front, from a vertical to a horizontal shape, in a permeable soil may be used as guidance in estimating the influence of free convection on the hydraulic heat losses (Claesson et al., 1985).

The current moraine in this study has a permeability of  $10^{-13} \text{ m}^2$ . This low permeability suppresses free convection. Furthermore, the tilting time is significantly longer than the period time of the storage cycle. The influence of hydraulic heat losses on the overall thermal performance of the store is therefore expected to be moderate. However, the compensation rate (90 % collector field efficiency) should be treated in more detail in future studies.

The optimum of the simulation results is based on  $5000 \text{ m}^2$  solar collectors and a heat store of  $50,000 \text{ m}^3$ . Typical characteristics are shown in *Table 8.1*. It is possible to reduce the size of the collector field and/or the heat store volume with a limited reduction in performance, see Appendix C. This may be necessary when available space and/or the depth of soil are restricted or the solar fraction is to be diminished. The excavated heat store concept compared with the borehole heat store concept is more flexible in that respect (wider range of storage volume / collector area in *Table 8.1*).

The maximum temperature requirement of the moraine heat store concept is  $78^\circ\text{C}$  in *Table 8.1*. However, simulation results, with performance close to the best selections, reach a maximum temperature just below  $100^\circ\text{C}$  (sign 247, Appendix C).

**Table 8.1. Characteristics of optimised solar heating systems with seasonal storage in moraine.**

Parameter	Borehole heat store	Excavated heat store
Heat capacity [J/(m <sup>3</sup> ·°C)]	2240	2800
Thermal conductivity [W/(m·°C)]	2	2.5
Solar heat cost [ECU/MWh]	130 - 133	127 - 133
Collector cost / storage cost [-]	1.5 - 2	1 - 1.5
Storage cost [ECU]	575000	700000 - 925000
Collector cost [ECU]	858000 - 1200000	1025000 - 1200000
Solar fraction [%]	60 - 75	70 - 90
Collector area / annual load [m <sup>2</sup> /MWh]	2 - 3.5	2.5 - 3.5
Collector output [kWh/m <sup>2</sup> ·a]	300 - 350	300 - 375
Storage volume / collector area [m]	8 - 13	3 - 10
Storage efficiency [%]	80	85 - 90
GHE spacing [m]	3	1.5 - 2
Maximum storage temperature [°C]	44 - 52	51 - 78

Further research and development in the area of seasonal storage in moraine should be concentrated to the borehole heat store concept. The economic performance of the two heat store concepts is relatively similar. Since no relevant experience is available from large excavated heat stores, the potential of the technique must be estimated with care. The borehole drilling technique has, however, proved to be successful in other applications than heat storage in moraine. Furthermore, simulation tools and practical experience of the high temperature behaviour and influence of hydraulic heat losses are lacking. Regarding the investment cost calculations, experience is limited not only from the application itself, but also from the absolute investment cost level and the simplified, linear, size dependent, specific investment cost variation. In respect to earthworks, moraine is in general a complex soil. If an alternative geology is considered, for example sand, the investment costs are expected to be reduced.

Applications optimised with regard to broad environmental benefits of the study, such as the use of waste products as storage medium and the replacement of industrially produced insulation by natural bulk insulation, are less competitive than other heat store concepts in moraine.

In accordance with the sensitivity study, the cost reduction target should be focused on investment cost reductions since the response is greatest in that respect. Investment cost reductions are maintained by competitive installation of ground heat exchangers and by cost effective manufacturing of solar collectors. The latter improvement is particularly favourable to the borehole heat store system,

where the ratio of solar collector costs compared with the heat store costs is clearer. Changes in thermal parameters affecting the industrial insulation and the natural ground properties of the moraine seem to have minor impact on the solar heat cost. For a system configuration with increased relative storage heat losses (for example sign 109, Appendix C), the impact of the solar heat cost is probably greater by variation of thermal properties.

# Chapter 9.

## Conclusions and Recommendations

**B**ased on the results from the calculations and simulations, the following conclusions and recommendations can be given:

- The cost of solar heat is not competitive today.

The commercial introduction of a solar heating plant with seasonal heat storage in moraine requires a reduction in the solar heat cost clearly below the present expected level of supplied conventional heat. However, some consumers are willing to pay more for "clean" heat. The reduction in solar heat cost should primarily be based on the reduction in the investment cost as well as on the improved performance of the technique. It is necessary to achieve a 40 % reduction of the investment cost. A shortage of primary energy and consideration for the environment may increase the cost of conventional heat at the expense of reduced competitiveness compared with seasonal solar heating. These scenarios are greatly affected by international political and commercial decisions.

The performance for ground heat storage in moraine (in combination with solar collectors) should be evaluated to both conventional and other solar heating concept alternatives. Design studies of pit heat stores in moraine indicate a solar heat cost of 90 ECU/MWh (0.80 SEK/kWh). However, the evaluation must be kept open since both the heat store concepts still have to prove convergence between designed and verified solar heat costs.

- R&D should be concentrated to investment cost reduction.

The reduction in the solar heat cost is almost equal through an investment reduction for the store and collector system, respectively. Concerning the investment reduction for the store, the greatest influence is expected from an

improved cost-effectiveness of the borehole drilling technique. The investment in the collector may be reduced by the transfer from manual to industrial manufacturing. This process assumes an increased demand for collectors. Furthermore, market oriented procurement may improve the prices asked by contractors.

- The concept of the borehole heat store is preferable to the excavated heat store.

The borehole heat store concept as well as the drilling technique are well-known for other types of geology and applications. Furthermore, experience of large excavated heat stores is limited. Since the thermal and economic performance of both concepts is equal, R&D efforts should be concentrated to the borehole heat store concept.

- The thermal influence on the moraine induced by hydraulic heat losses must be determined.

Beside the investment cost, the thermal heat losses are the most important aspect exerting an influence on the solar heat cost. The heat losses are affected by both thermally conductive and hydraulic properties of the moraine. Design tools for the calculation of conductive heat losses are available. Hydraulic heat losses are discussed in applications related to aquifer heat storage, primarily for low and medium temperature systems. The influence of hydraulic heat losses is expected to increase with increased temperature. The temperature increase affects the natural convection of the ground water due to the difference between the density of the ground water within and outside the storage region. However, if ground heat storage in moraine is evaluated to be competitive, there is a general lack of R&D experience concerning hydraulic heat losses, especially in high temperature applications (95 °C).

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## Appendix A

## Unit Prices

Moment	Quantity	Unit price	Unit
Establishing, drilling / excavating	1	20,000 / 50,000	SEK/object
Drainage	1	500,000	SEK/object
Site surface preparation concept I / II	1	100,000 / 25,000	SEK/object
Excavation, incl. handling and ramp		30	SEK/m <sup>3</sup>
Refilling sand, distributed		60	SEK/m <sup>3</sup>
Refilling, incl. handling		15	SEK/m <sup>3</sup>
Bentonite, distributed		100	SEK/m <sup>2</sup>
Levelling layer	0.2 m	75	SEK/m <sup>3</sup>
Protecting layer	0.2 m	75	SEK/m <sup>3</sup>
Drilling incl. casing (20 m / 5 inches)	>200 wells	350	SEK/m
Duct		20	SEK/m
Duct blunker		100	SEK/well
Manifold	% of duct costs	20	SEK
Coupling	3 units/loop	60	SEK/unit
Labour		350	SEK/hour
Hose reel	1	10,000	SEK/object
Pressurise equipment		10,000 + 500	SEK/object + /loop
Bending fixture		100	SEK/ vertical GHE
Connecting Well	1	100,000	SEK/object
Insulation, distributed (polystyrene, expanded)	0.4 m	500 + 200	SEK/m <sup>3</sup> + (labour and overlay)
Diffusion tight foil		50	SEK/m <sup>2</sup>
Cost of land		150	SEK/m <sup>2</sup>
Cost of solar supply system	1	800,000	SEK/object
Design	1	400,000	SEK/object
Buffer tank		5	SEK/m <sup>3</sup> seasonal storage volume
Miscellaneous/Contractor expenses	20		% of expenses

Exchange rate: 1 ECU = 9 SEK (1995)

## Appendix B

### Input Set-Up

Out Prints of the Minsun and  
Ground Heat Exchanger Programs



RUN	OPTIONS	COLLECTORS	STORAGE	LOADS	AUXILIARY	TAP	WATER	COSTS
-----	---------	------------	---------	-------	-----------	-----	-------	-------

<ESC> to exit

**YESC> to exit**

RUN OPTIONS      COLLECTORS      STORAGE      LOADS      AUXILIARY      TAP WATER      COSTS

<ESC> to exit

RUN OPTIONS COLLECTORS STORAGE LOADS AUXILIARY TAP WATER COSTS

<ESC> to exit

<ESC> TO EXIT

GROUND HEAT STORAGE - Heat transfer capacity of Ground Heat Exchangers (GHE)

MM

INPUT PARAMETER VALUES		3
Storage volume	25000	3
Thermal conductivity of the ground	2	3
GHE type	Borehole	3
GHE pattern	Quadratic	3
GHE active length	20	3
GHE spacing	2	3
Thermal resistance fluid/ground	0.0247	3
Borehole radius	0.06	3
	3	
	3	
	3	
	3	
	3	
DDD4		
Thermal resistance	0.199 K/(W/m)	3
Cross-sectional area	4.000 m <sup>2</sup>	3
Heat transfer length	1.262 m	3
Vol. heat transfer capacity	1.255 W/(m <sup>3</sup> K)	3
Total heat transfer capacity	31.385 kW/K	3
Number of GHE	312	3
MM		
F1 Help	F2 F4 F5	ESC to quit

Thermal resistance between fluid and ground

MM

Pipe:	Inner radius	0.029	3
Pipe:	Outer radius	0.0315	3
Pipe:	Thermal conductivity	0.200	3
Liner:	Inner radius	0.06	3
Liner:	Outer radius	0.06	3
Liner:	Thermal conductivity	0.400	3
Filling:	Thermal conductivity	0.600	3
Contact resistance filling/ground	0.0200	3	
Volumetric flow rate	0.0008	3	
Reference temperature	50	3	
DDD4			
Inner fluid/pipe	0.0035 K/(W/m)	3	
Pipe material	0.0658 K/(W/m)	3	
Pipe/Outer fluid	0.0185 K/(W/m)	3	
Outer fluid/Liner	0.0047 K/(W/m)	3	
Lining material	0.0000 K/(W/m)	3	
Filling material	0.0000 K/(W/m)	3	
Contact filling/ground	0.0200 K/(W/m)	3	
Total outer fluid/ground	0.0247 K/(W/m)	3	
Reynolds number: Inner pipe	31867	3	
Reynolds number: Annulus	10100	3	
MM			

F3 Export value

F10 to return

GROUND HEAT STORAGE - Heat transfer capacity of Ground Heat Exchangers (GHE)  
 MMM  
 INPUT PARAMETER VALUES  
 Storage volume 25000 3  
 Thermal conductivity of the ground 2 3  
 GHE type Borehole 3  
 GHE pattern Quadratic 3  
 GHE active length 20 3  
 GHE spacing 2 3  
 Thermal resistance fluid/ground 0.0248 3  
 Borehole radius 0.06 3  
 3  
 3  
 3  
 3  
 3  
 3  
 DDD4  
 Thermal resistance 0.199 K/(W/m) 3  
 Cross-sectional area 4.000 m<sup>2</sup> 3  
 Heat transfer length 1.263 m 3  
 Vol. heat transfer capacity 1.255 W/(m<sup>3</sup>K) 3  
 Total heat transfer capacity 31.364 kW/K 3  
 Number of GHE 312 3  
 MMM  
 F1 Help F2 F4 F5 ESC to quit

Thermal resistance between fluid and ground  
 MMM  
 Pipe: Inner radius 0.029 3  
 Pipe: Outer radius 0.0315 3  
 Pipe: Thermal conductivity 45 3  
 Liner: Inner radius 0.055 3  
 Liner: Outer radius 0.06 3  
 Liner: Thermal conductivity 45 3  
 Filling: Thermal conductivity 0.600 3  
 Contact resistance filling/ground 0.0200 3  
 Volumetric flow rate 0.0007 3  
 Reference temperature 50 3  
 DDD4  
 Inner fluid/pipe 0.0039 K/(W/m) 3  
 Pipe material 0.0003 K/(W/m) 3  
 Pipe/Outer fluid 0.0161 K/(W/m) 3  
 Outer fluid/Liner 0.0045 K/(W/m) 3  
 Lining material 0.0003 K/(W/m) 3  
 Filling material 0.0000 K/(W/m) 3  
 Contact filling/ground 0.0200 K/(W/m) 3  
 Total outer fluid/ground 0.0248 K/(W/m) 3  
 Reynolds number: Inner pipe 27884 3  
 Reynolds number: Annulus 9348 3  
 MMM  
 F3 Export value F10 to return

GROUND HEAT STORAGE - Heat transfer capacity of Ground Heat Exchangers (GHE)  
MM

INPUT PARAMETER VALUES		3
Storage volume	25000	3
Thermal conductivity of the ground	2	3
GHE type	Single U_	3
GHE pattern	Quadratic	3
GHE active length	25.0	3
GHE spacing	2.000	3
Thermal resistance fluid/ground	0.0821	3
U-pipe radius	0.016	3
U-pipe shank spacing	0.35	3
		3
		3
		3
		3

DD4

Thermal resistance	0.200 K/(W/m)	3
Cross-sectional area	4.000 m <sup>2</sup>	3
Heat transfer length	1.265 m	3
Vol. heat transfer capacity	1.250 W/(m3K)	3
Total heat transfer capacity	31.258 kW/K	3
Number of GHE	250	3

MM

F1 Help F2 F4 F5 ESC to quit

Thermal resistance between fluid and ground

Pipe: Outer radius	0.016	3
Pipe: Inner radius	0.014	3
Pipe: Thermal conductivity	0.400	3
Contact resistance pipe/ground	0.0200	3
Volumetric flow rate	0.00012	3
Reference temperature	50	3
		3
		3
		3

DD4

3  
3  
3  
3

Thermal resistances

Fluid/pipe	0.0090 K/(W/m)	3
Pipe material	0.0531 K/(W/m)	3
Contact pipe/ground	0.0200 K/(W/m)	3
Total	0.0821 K/(W/m)	3
Reynolds number	9902	3

MM

F3 Export value F10 to return

## Appendix C

# Summary of Simulation Results

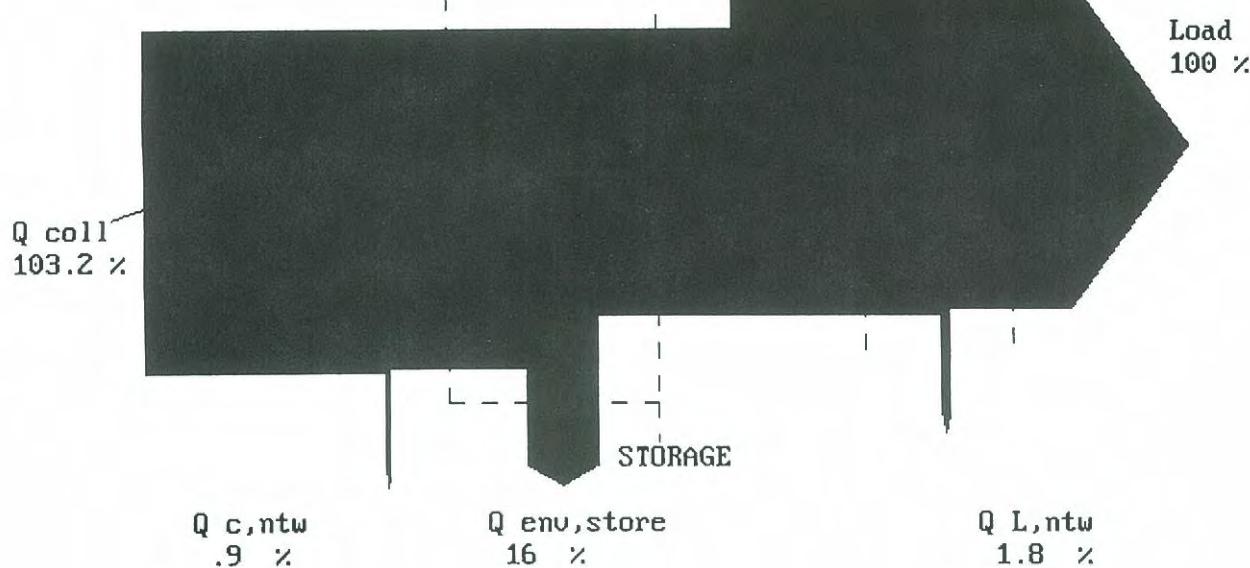
194

A N N U A L      M A R C H    A P R I L    M A Y    J U N E    J U L Y    J U L Y    A U G    S E P T    O C T    N O V    D E C

- Solar Fraction = . 84.6 %
- Renewable Energy contribution to Load= 86.2 %

Q aux  
15.6 %

T<sub>s,max</sub>= 51.3  
T<sub>s,min</sub>= 29  
[°C]



Load (Annual End User Energy Requirement) = 1817.87 MWh

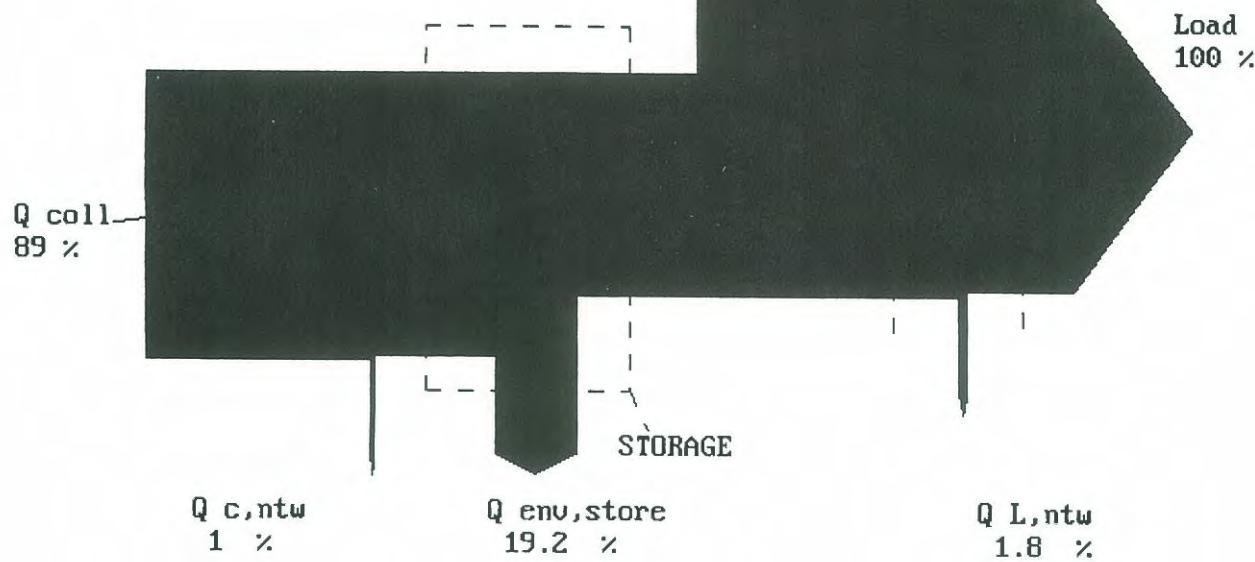
( press any key to continue )

- Solar Fraction = 67.5 %
- Renewable Energy contribution to Load= 68.7 %

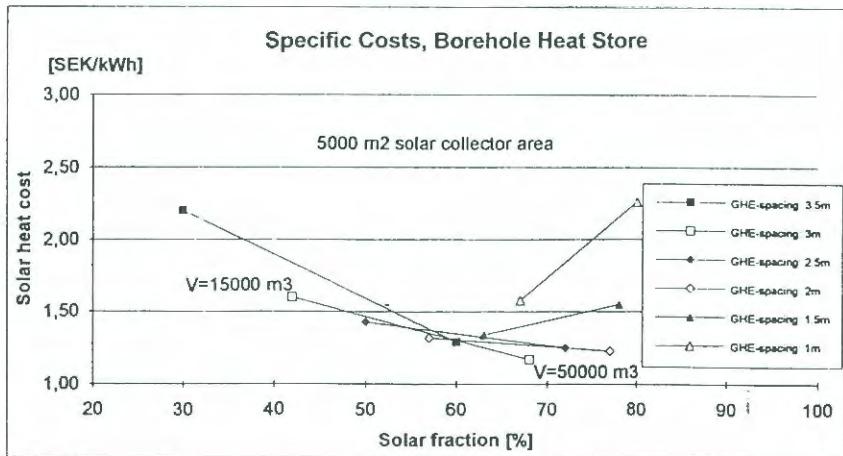
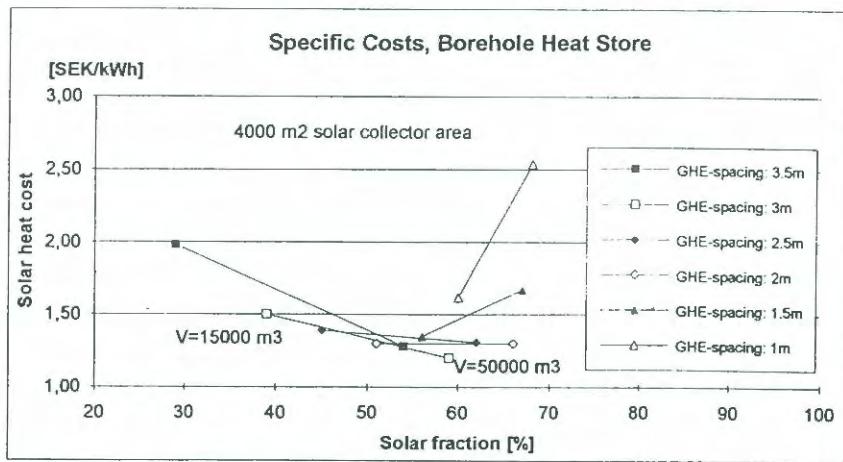
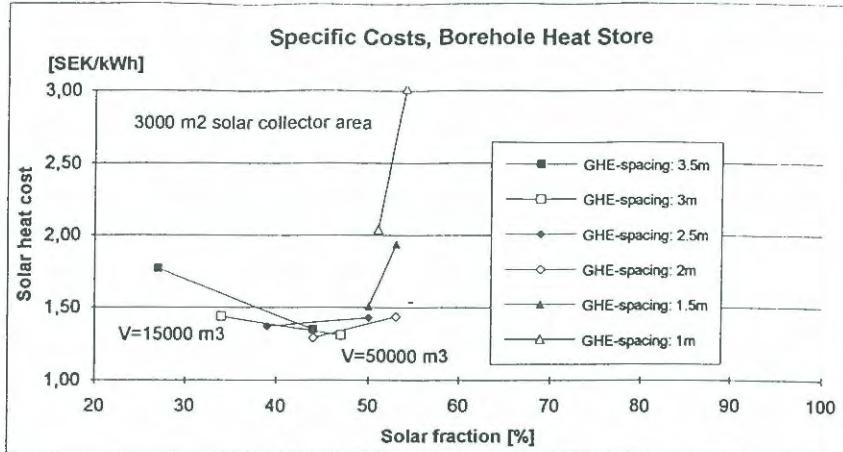
Q aux  
33.1 %

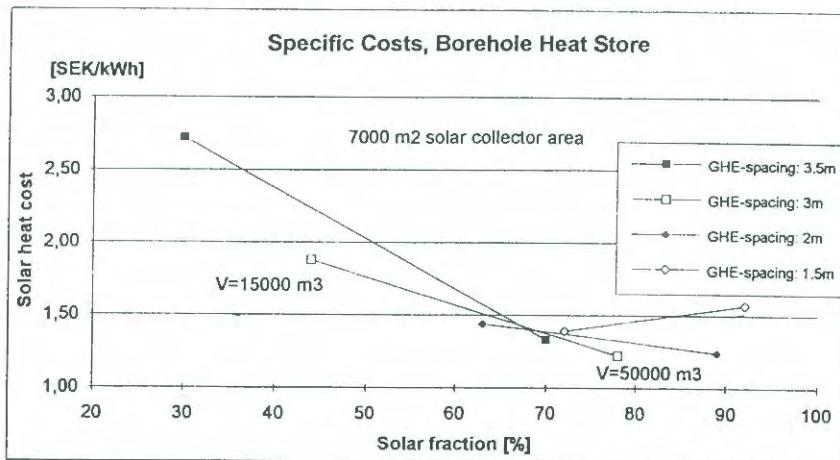
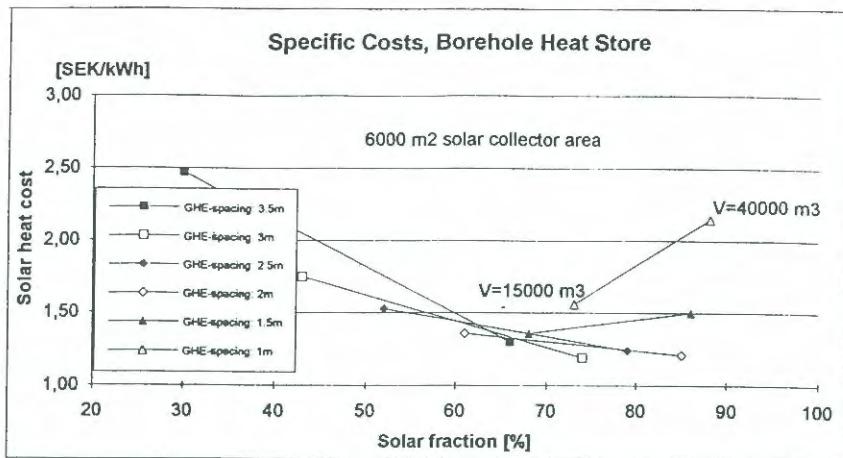
263

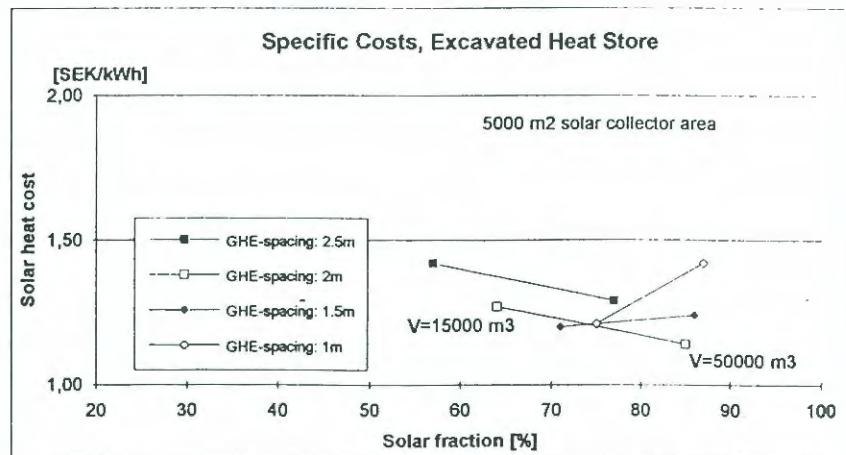
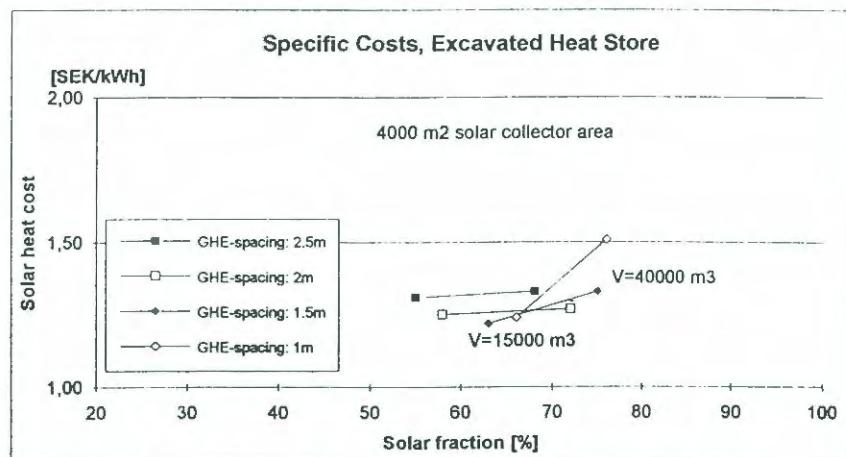
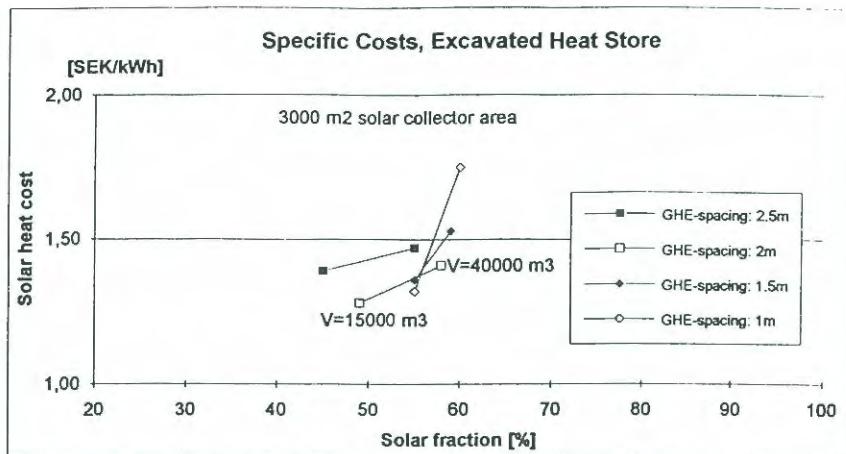
T<sub>s,max</sub>= 48.3  
T<sub>s,min</sub>= 28.4  
[°C]

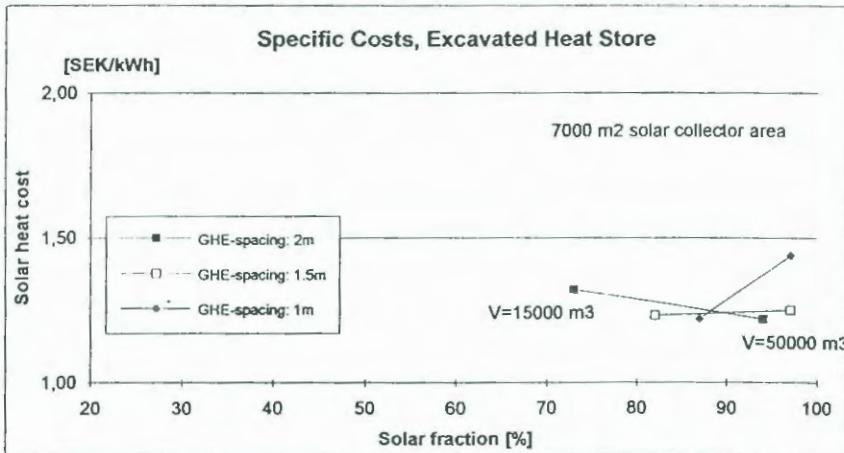
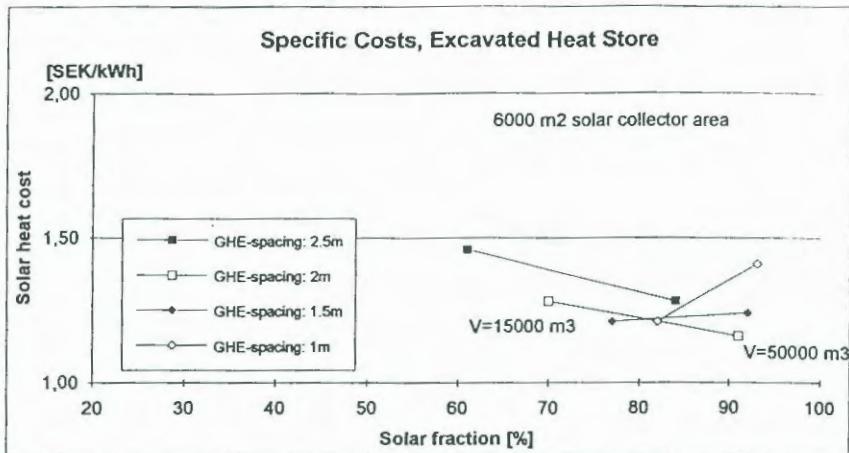


( press any key to continue )









PARAMETER STUDY - SOLAR COLLECTOR AND GROUND HEAT STORE IN MORAIN			
<b>Data</b>		<b>Calculation, based on economical life time figures</b>	
200 dwellings		Specific annuity solar costs = specific investment costs * 0,1 * 100%	
House load = 1820 MWh/år			
Floor heating			
Separate tap water system			
Store I = Ground heat store (boreholes) in natural morain			
Store II = Mass balance heat store in saturated morain			
	Store I	Store II	Ground
Conductivity [W/m°C]	2,0	2,5	2,0
Capacity [J/m³°C]	2240	2800	2240
Store height [m]	17,5	17,5	
Top insulation [m]	0,4	0,4	
Side insulation	ground	ground	
"Compensation" of hydraulic storage heat losses (I)			
"Compensation" of unfavourable store geometry (II), additional heat losses			
Compensation rate = collector array efficiency 90 %			
<b>Variables of parameter study</b>			
Collector area	3000-7000 m²		
Storage volume	15000-50000 m³		
Spacing of ground heat exchanger (GHE)	1,0/1,5/2,0/2,5/3,0/3,5 m		
<b>Calculations, based on yearly figures</b>			
A = Collector output			
B = Storage losses (inclusive collector network losses)			
C = Collector and storage supply			
D = Auxiliary boiler supply			
E = Distribution network losses			
F = Solar fraction = C / (C + D)			
House load = C + D - E			
Specific investment costs = total investment / (house load * solar fraction)			

Sign	Input	Simulation heat balance										Solar cost calculations					
		Collector	Store	GHE	Store	A		B		C	D	E	F	Collector	Store I/I	Annuity II	Annuity I
						[m <sup>2</sup> ]	[m <sup>3</sup> ]	[m]	[°C]								
1	3000	15000	2	56/24	1033	98(116)	917	936	33	49	6,73	6,11	1,28				
2	3000	20000	2	52/25	1102	115(131)	971	884	33	52	6,34	7,08	1,34				
3	3000	25000	2	49/25	1154	129(145)	1009	845	33	54	6,11	7,81	1,39				
4	3000	30000	2	47/25	1194	142(156)	1038	816	33	56	5,89	8,21	1,41				
5	3000	35000	2	45/26	1220	153(167)	1053	800	33	57	5,78	8,47	1,43				
6	3000	40000	2	43/26	1247	162(176)	1071	780	33	58	5,68	8,45	1,41				
7	4000	15000	2	64/25	1213	118(136)	1077	776	33	58	7,33	5,16	1,25				
8	4000	20000	2	60/26	1313	76(95)	1218	634	33	66	6,44	5,58	1,20				
9	4000	25000	2	56/26	1398	156(175)	1223	629	33	66	6,44	6,39	1,28				
10	4000	30000	2	53/26	1465	173(189)	1276	576	33	69	6,16	6,67	1,28				
11	4000	35000	2	51/26	1503	185(202)	1301	549	33	70	6,07	6,90	1,30				
12	4000	40000	2	49/27	1549	200(216)	1333	518	33	72	5,90	6,81	1,27				
13	5000	15000	2	71/26	1353	135(155)	1198	656	33	64	8,01	4,67	1,27				
14	5000	20000	2	66/27	1485	160(180)	1305	547	33	70	7,33	5,26	1,26				
15	5000	25000	2	62/27	1592	184(202)	1390	462	33	75	6,84	5,62	1,25				
16	5000	30000	2	59/27	1689	275(293)	1396	456	33	75	6,84	6,13	1,30				
17	5000	35000	2	56/28	1736	225(244)	1492	360	33	80	6,41	6,03	1,24				
18	5000	40000	2	54/28	1796	245(262)	1534	318	33	83	6,18	5,90	1,21				
193	5000	45000	2	52/29	1833	265(282)	1551	302	33	84	6,11	5,74	1,18				
194	5000	50000	2	51/29	1876	291(307)	1569	284	33	85	6,03	5,40	1,14				
19	6000	15000	2	77/27	1460	149(169)	1291	564	33	70	8,48	4,27	1,28				
20	6000	20000	2	72/28	1622	182(202)	1420	433	33	76	7,81	4,84	1,27				
21	6000	25000	2	68/28	1751	213(233)	1518	335	33	82	7,24	5,14	1,24				
22	6000	30000	2	65/29	1854	245(264)	1590	262	33	86	6,90	5,35	1,22				
23	6000	35000	2	61/27	1953	460(478)	1475	378	33	80	7,42	6,03	1,35				
24	6000	40000	2	61/32	1969	287(305)	1664	189	33	90	6,59	5,45	1,20				
195	6000	45000	2	59/33	2005	315(333)	1672	178	33	90	6,59	5,36	1,20				
196	6000	50000	2	58/34	2049	345(364)	1685	165	33	91	6,52	5,04	1,16				
197	7000	15000	2	81/27	1538	160(180)	1357	496	33	73	9,13	4,10	1,32				
198	7000	20000	2	77/28	1729	202(222)	1507	347	33	81	8,23	4,54	1,28				
199	7000	25000	2	73/30	1874	244(264)	1610	242	33	87	7,66	4,85	1,25				
200	7000	30000	2	71/32	1971	264(284)	1687	165	33	91	7,33	5,05	1,24				
201	7000	35000	2	68/34	2029	298(318)	1711	142	33	92	7,25	5,25	1,25				
202	7000	40000	2	67/36	2094	340(358)	1736	118	33	94	7,09	5,21	1,23				
203	7000	45000	2	65/37	2138	375(393)	1745	109	33	94	7,09	5,13	1,22				
204	7000	50000	2	60/28	2383	787(805)	1578	275	33	85	7,84	5,40	1,32				
25	3000	15000	2	55/24	1007	176(195)	812	1040	33	44	7,49	5,43	1,29				
26	3000	20000	2	52/24	1076	200(216)	860	993	33	46	7,17	6,47	1,36				
27	3000	25000	2	49/24	1129	218(235)	894	956	33	48	6,87	7,21	1,41				
28	3000	30000	2	47/25	1173	235(251)	922	931	33	50	6,59	7,68	1,43				
29	3000	35000	2	46/25	1198	247(262)	936	916	33	50	6,59	8,23	1,48				
30	3000	40000	2	44/25	1229	260(275)	954	902	33	51	6,46	8,40	1,49				
205	3000	45000	2	43/25	1245	267(282)	963	889	33	52	6,34	8,37	1,47				
206	3000	50000	2	42/25	1269	278(293)	976	874	33	53	6,22	8,14	1,44				
31	4000	15000	2	63/24	1177	207(227)	950	902	33	51	8,33	4,69	1,30				
32	4000	20000	2	60/26	1273	140(158)	1115	738	33	60	7,08	4,96	1,20				
33	4000	25000	2	56/25	1360	258(276)	1084	769	33	58	7,33	5,97	1,33				
34	4000	30000	2	54/26	1427	280(296)	1131	722	33	61	6,97	6,30	1,33				
35	4000	35000	2	52/26	1469	293(309)	1160	694	33	62	6,85	6,64	1,35				
36	4000	40000	2	50/26	1518	311(327)	1191	662	33	64	6,64	6,70	1,33				
207	4000	45000	2	48/26	1545	324(340)	1205	645	33	65	6,54	6,69	1,32				
208	4000	50000	2	47/26	1583	338(353)	1230	622	33	66	6,44	6,54	1,30				
37	5000	15000	2	69/25	1304	233(253)	1051	804	33	57	9,00	4,19	1,32				
38	5000	20000	2	66/26	1436	269(289)	1147	705	33	62	8,27	4,80	1,31				
39	5000	25000	2	63/26	1543	298(316)	1227	627	33	66	7,77	5,24	1,30				
40	5000	30000	2	60/27	1633	289(307)	1326	527	33	72	7,12	5,33	1,25				

41	5000	35000	2	57/27	1691	344(362)	1329	522	33	72	7,12	5,72		1,28
42	5000	40000	2	55/27	1758	364(380)	1378	474	33	74	6,93	5,79		1,27
209	5000	45000	2	53/27	1800	380(396)	1404	449	33	76	6,75	5,73		1,25
210	5000	50000	2	52/27	1853	400(416)	1437	416	33	77	6,66	5,60		1,23
43	6000	15000	2	74/26	1401	256(276)	1125	727	33	61	9,73	3,92		1,36
44	6000	20000	2	71/26	1560	298(318)	1242	611	33	67	8,86	4,44		1,33
45	6000	25000	2	68/27	1691	336(356)	1335	516	33	72	8,24	4,81		1,30
46	6000	30000	2	65/27	1805	369(387)	1418	436	33	76	7,81	5,05		1,29
47	6000	35000	2	62/28	1873	393(411)	1462	393	33	79	7,51	5,21		1,27
48	6000	40000	2	60/27	1969	505(524)	1445	405	33	78	7,61	5,49		1,31
211	6000	45000	2	58/28	2007	444(464)	1543	307	33	83	7,15	5,24		1,24
212	6000	50000	2	57/29	2073	476(494)	1579	273	33	85	6,98	5,07		1,21
213	7000	15000	2	78/26	1467	271(293)	1174	678	33	63	10,58	3,79		1,44
214	7000	20000	2	75/27	1662	325(345)	1317	538	33	71	9,39	4,19		1,36
215	7000	25000	2	72/28	1813	369(389)	1424	429	33	77	8,66	4,50		1,32
216	7000	30000	2	79/28	1942	411(431)	1511	342	33	82	8,13	4,68		1,28
217	7000	35000	2	67/29	2022	442(462)	1560	293	33	84	7,94	4,90		1,28
218	7000	40000	2	65/29	2120	485(504)	1616	238	33	87	7,66	4,93		1,26
219	7000	45000	2	64/31	2162	494(513)	1649	204	33	89	7,49	4,89		1,24
220	7000	50000	2	61/28	2303	754(773)	1530	322	33	83	8,03	5,20		1,32
49	3000	15000	2,5	52/25	947	93(111)	836	1016	33	45	7,33	6,58	1,39	
50	3000	20000	2,5	50/26	1036	111(129)	907	944	33	49	6,73	7,42	1,42	
51	3000	25000	2,5	47/26	1080	124(140)	940	913	33	51	6,46	8,16	1,46	
52	3000	30000	2,5	46/26	1136	136(153)	983	869	33	53	6,22	8,55	1,48	
53	3000	35000	2,5	44/26	1167	147(164)	1003	847	33	54	6,11	8,80	1,49	
54	3000	40000	2,5	42/26	1194	156(171)	1023	829	33	55	5,99	8,75	1,47	
55	4000	15000	2,5	59/28	1091	45(65)	1026	827	33	55	7,73	5,38	1,31	
56	4000	20000	2,5	56/27	1222	129(149)	1073	778	33	58	7,33	6,27	1,36	
57	4000	25000	2,5	53/27	1289	145(164)	1125	727	33	61	6,97	6,82	1,38	
58	4000	30000	2,5	51/27	1376	164(182)	1194	658	33	64	6,64	7,08	1,37	
59	4000	35000	2,5	49/27	1422	178(196)	1226	625	33	66	6,44	7,20	1,36	
60	4000	40000	2,5	48/27	1463	193(209)	1254	598	33	68	6,25	7,08	1,33	
61	5000	15000	2,5	64/27	1202	118(138)	1064	791	33	57	9,00	5,19	1,42	
62	5000	20000	2,5	62/28	1362	147(167)	1195	658	33	64	8,01	5,68	1,37	
63	5000	25000	2,5	58/28	1449	167(187)	1262	591	33	68	7,54	6,12	1,37	
64	5000	30000	2,5	56/28	1563	191(209)	1354	498	33	73	7,02	6,21	1,32	
65	5000	35000	2,5	54/28	1629	213(231)	1398	454	33	75	6,84	6,33	1,32	
66	5000	40000	2,5	52/29	1682	231(249)	1433	420	33	77	6,66	6,25	1,29	
67	6000	15000	2,5	68/28	1276	127(149)	1127	725	33	61	9,73	4,85	1,46	
68	6000	20000	2,5	66/28	1474	164(184)	1290	562	33	70	8,48	5,20	1,37	
69	6000	25000	2,5	62/29	1574	189(209)	1365	487	33	74	8,02	5,62	1,36	
70	6000	30000	2,5	60/28	1731	331(351)	1380	471	33	74	8,02	6,13	1,41	
71	6000	35000	2,5	59/30	1789	251(271)	1518	333	33	82	7,24	5,79	1,30	
72	6000	40000	2,5	57/31	1853	278(296)	1557	296	33	84	7,06	5,73	1,28	
73	3000	15000	2,5	51/25	909	160(180)	729	1124	33	39	8,45	5,20		1,37
74	3000	20000	2,5	50/25	1004	185(204)	800	1054	33	43	7,67	5,90		1,36
75	3000	25000	2,5	47/25	1049	202(220)	829	1024	33	45	7,33	6,59		1,39
76	3000	30000	2,5	46/25	1109	220(236)	873	982	33	47	7,01	7,05		1,41
77	3000	35000	2,5	44/25	1142	233(249)	893	962	33	48	6,87	7,45		1,43
78	3000	40000	2,5	43/26	1167	245(262)	905	945	33	49	6,73	7,67		1,44
221	3000	45000	2,5	42/26	1193	255(271)	922	931	33	50	6,59	7,71		1,43
222	3000	50000	2,5	41/26	1213	264(278)	935	918	33	50	6,59	7,75		1,43
79	4000	15000	2,5	57/25	1044	182(202)	842	1011	33	45	9,44	4,51		1,39
80	4000	20000	2,5	55/26	1173	215(235)	938	913	33	51	8,33	4,98		1,33
81	4000	25000	2,5	53/26	1240	235(255)	985	865	33	53	8,02	5,60		1,36
82	4000	30000	2,5	52/26	1331	258(276)	1055	798	33	57	7,45	5,81		1,33
83	4000	35000	2,5	50/26	1380	275(293)	1087	765	33	59	7,20	6,06		1,33
84	4000	40000	2,5	48/26	1422	291(309)	1113	740	33	60	7,08	6,26		1,33
223	4000	45000	2,5	47/27	1458	305(322)	1136	716	33	61	6,97	6,32		1,33
224	4000	50000	2,5	46/27	1491	316(333)	1158	694	33	62	6,85	6,25		1,31
85	5000	15000	2,5	62/26	1138	198(220)	918	934	33	50	10,26	4,05		1,43
86	5000	20000	2,5	61/28	1294	176(196)	1098	754	33	59	8,69	4,30		1,30

87	5000	25000	2,5	57/27	1385	264(282)	1103	751	33	59	8,69	5,03		1,37
88	5000	30000	2,5	56/27	1505	295(315)	1190	662	33	64	8,01	5,18		1,32
89	5000	35000	2,5	54/27	1571	315(333)	1238	616	33	67	7,65	5,34		1,30
90	5000	40000	2,5	53/27	1629	335(353)	1276	578	33	69	7,43	5,45		1,29
225	5000	45000	2,5	51/28	1680	355(373)	1307	544	33	70	7,33	5,51		1,28
226	5000	50000	2,5	50/28	1725	369(387)	1338	514	33	72	7,12	5,38		1,25
91	6000	15000	2,5	64/26	1200	211(233)	967	885	33	52	11,41	3,90		1,53
92	6000	20000	2,5	65/27	1398	262(284)	1114	736	33	60	9,89	4,23		1,41
93	6000	25000	2,5	62/28	1502	291(311)	1191	662	33	64	9,27	4,64		1,39
94	6000	30000	2,5	61/28	1643	329(349)	1294	558	33	70	8,48	4,73		1,32
95	6000	35000	2,5	59/28	1722	355(375)	1347	504	33	73	8,13	4,90		1,30
96	6000	40000	2,5	57/28	1794	380(400)	1394	456	33	75	7,91	5,01		1,29
255	6000	45000	2,5	55/29	1858	404(422)	1436	416	33	77	7,71	5,01		1,27
256	6000	50000	2,5	54/29	1916	429(447)	1469	384	33	79	7,51	4,90		1,24
97	3000	15000	1,5	59/25	1098		1089	763	33	59	5,59	5,78	1,14	
98	3000	20000	1,5	54/24	1164	120(136)	1028	825	33	55	5,99	7,65	1,36	
99	3000	25000	1,5	50/25	1202	135(149)	1053	800	33	57	5,78	8,49	1,43	
100	3000	30000	1,5	48/25	1236	145(160)	1076	776	33	58	5,68	9,15	1,48	
101	3000	35000	1,5	46/25	1260	156(171)	1089	762	33	59	5,59	9,50	1,51	
102	3000	40000	1,5	44/25	1280	165(180)	1100	751	33	59	5,59	9,72	1,53	
103	4000	15000	1,5	69/24	1314	129(147)	1167	684	33	63	6,74	5,41	1,22	
104	4000	20000	1,5	63/25	1413	149(165)	1248	605	33	67	6,34	6,28	1,26	
105	4000	25000	1,5	58/26	1474	164(180)	1294	560	33	70	6,07	6,92	1,30	
106	4000	30000	1,5	55/26	1534	180(196)	1338	514	33	72	5,90	7,37	1,33	
107	4000	35000	1,5	52/26	1574	193(207)	1367	485	33	74	5,74	7,58	1,33	
108	4000	40000	1,5	50/26	1607	207(222)	1385	467	33	75	5,67	7,65	1,33	
109	5000	15000	1,5	78/25	1482	151(169)	1313	540	33	71	7,22	4,80	1,20	
110	5000	20000	1,5	71/26	1613	176(195)	1418	435	33	76	6,75	5,54	1,23	
111	5000	25000	1,5	66/26	1702	198(216)	1486	367	33	80	6,41	6,05	1,25	
112	5000	30000	1,5	62/27	1778	218(235)	1543	309	33	83	6,18	6,39	1,26	
113	5000	35000	1,5	59/27	1833	240(256)	1577	276	33	85	6,03	6,60	1,26	
114	5000	40000	1,5	56/28	1876	264(280)	1596	256	33	86	5,96	6,67	1,26	
227	5000	45000	1,5	54/29	1905	287(304)	1601	249	33	86	5,96	6,63	1,26	
228	5000	50000	1,5	53/29	1931	313(329)	1602	249	33	86	5,96	6,39	1,24	
115	6000	15000	1,5	85/26	1618	173(193)	1425	427	33	77	7,71	4,43	1,21	
116	6000	20000	1,5	78/27	1774	205(224)	1550	302	33	84	7,06	5,01	1,21	
117	6000	25000	1,5	72/28	1876	235(253)	1623	229	33	88	6,74	5,50	1,22	
118	6000	30000	1,5	69/30	1949	253(271)	1678	175	33	90	6,59	5,90	1,25	
119	6000	35000	1,5	66/32	1998	285(304)	1694	156	33	92	6,45	6,09	1,25	
120	6000	40000	1,5	64/33	2038	315(333)	1705	147	33	92	6,45	6,24	1,27	
229	6000	45000	1,5	62/34	2074	345(362)	1712	140	33	92	6,45	6,19	1,26	
230	6000	50000	1,5	60/35	2105	375(391)	1714	138	33	92	6,45	5,97	1,24	
231	7000	15000	1,5	91/27	1722	191(211)	1511	340	33	82	8,13	4,16	1,23	
232	7000	20000	1,5	84/28	1900	233(253)	1647	204	33	89	7,49	4,73	1,22	
233	7000	25000	1,5	79/32	1989	256(275)	1714	140	33	92	7,25	5,26	1,25	
234	7000	30000	1,5	76/35	2062	298(316)	1746	107	33	94	7,09	5,65	1,27	
235	7000	35000	1,5	73/37	2118	338(356)	1762	91	33	95	7,02	5,90	1,29	
236	7000	40000	1,5	71/39	2151	355(373)	1778	73	33	96	6,94	5,98	1,29	
237	7000	45000	1,5	69/40	2193	387(405)	1788	65	33	96	6,94	5,94	1,29	
238	7000	50000	1,5	68/41	2229	418(436)	1793	60	33	97	6,87	5,66	1,25	
121	3000	15000	1,5	59/24	1085	78(95)	990	864	33	53	6,22	6,25		1,25
122	3000	20000	1,5	54/24	1149	215(231)	918	934	33	50	6,59	8,46		1,51
123	3000	25000	1,5	51/24	1187	231(245)	942	913	33	51	6,46	9,91		1,64
124	3000	30000	1,5	49/24	1224	247(262)	962	891	33	52	6,34	11,13		1,75
125	3000	35000	1,5	47/24	1247	260(275)	972	878	33	52	6,34	12,35		1,87
126	3000	40000	1,5	45/25	1267	271(285)	982	869	33	53	6,22	13,15		1,94
127	4000	15000	1,5	68/24	1294	233(251)	1043	809	33	56	7,59	5,92		1,35
128	4000	20000	1,5	63/24	1387	260(276)	1111	742	33	60	7,08	7,05		1,41
129	4000	25000	1,5	59/26	1447	171(187)	1260	593	33	68	6,25	7,43		1,37
130	4000	30000	1,5	56/25	1509	298(315)	1194	658	33	64	6,64	9,04		1,57
131	4000	35000	1,5	53/25	1553	313(329)	1224	629	33	66	6,44	9,73		1,62
132	4000	40000	1,5	51/26	1587	327(342)	1245	607	33	67	6,34	10,40		1,67

133	5000	15000	1,5	76/24	1453	269(289)	1164	687	33	63	8,14	5,26		1,34
134	5000	20000	1,5	71/25	1580	304(322)	1258	594	33	68	7,54	6,22		1,38
135	5000	25000	1,5	66/25	1665	329(347)	1318	533	33	71	7,22	7,12		1,43
136	5000	30000	1,5	63/26	1749	353(369)	1380	474	33	74	6,93	7,82		1,47
137	5000	35000	1,5	60/26	1805	378(395)	1410	442	33	76	6,75	8,45		1,52
138	5000	40000	1,5	57/26	1856	391(407)	1449	404	33	78	6,57	8,93		1,55
139	6000	15000	1,5	83/25	1582	302(322)	1260	593	33	68	8,73	4,87		1,36
140	6000	20000	1,5	78/26	1734	345(364)	1370	482	33	74	8,02	5,72		1,37
141	6000	25000	1,5	73/26	1842	378(396)	1446	407	33	78	7,61	6,48		1,41
142	6000	30000	1,5	69/27	1945	409(427)	1518	333	33	82	7,24	7,06		1,43
143	6000	35000	1,5	66/27	2018	436(454)	1564	287	33	84	7,06	7,65		1,47
144	6000	40000	1,5	63/28	2078	462(478)	1600	253	33	86	6,90	8,10		1,50
239	7000	15000	1,5	89/25	1683	331(351)	1332	520	33	72	9,26	4,60		1,39
240	7000	20000	1,5	84/26	1865	384(404)	1461	391	33	79	8,44	5,36		1,38
241	7000	25000	1,5	79/27	1987	424(444)	1543	309	33	83	8,03	6,09		1,41
242	7000	30000	1,5	75/28	2105	465(484)	1621	231	33	87	7,66	6,65		1,43
243	7000	35000	1,5	72/29	2185	505(524)	1661	191	33	90	7,41	7,14		1,45
244	7000	40000	1,5	70/31	2229	518(536)	1693	160	33	91	7,33	7,66		1,50
245	7000	45000	1,5	68/32	2276	554(573)	1703	147	33	92	7,25	8,06		1,53
246	7000	50000	1,5	66/33	2318	587(605)	1713	140	33	92	7,25	8,45		1,57
145	3000	15000	1	61/24	1144	109(125)	1019	833	33	55	5,99	7,20	1,32	
146	3000	20000	1	55/24	1194	124(138)	1056	796	33	57	5,78	8,68	1,45	
147	3000	25000	1	51/24	1229	136(151)	1078	774	33	58	5,68	9,94	1,56	
148	3000	30000	1	48/25	1254	149(164)	1090	762	33	59	5,59	10,87	1,65	
149	3000	35000	1	46/25	1273	158(173)	1100	751	33	59	5,59	11,69	1,73	
150	3000	40000	1	44/25	1289	167(182)	1107	744	33	60	5,49	12,01	1,75	
151	4000	15000	1	72/24	1385	136(153)	1232	620	33	66	6,44	6,00	1,24	
152	4000	20000	1	65/25	1465	155(171)	1294	556	33	70	6,07	7,06	1,31	
153	4000	25000	1	60/25	1523	147(162)	1361	493	33	73	5,82	7,89	1,37	
154	4000	30000	1	56/26	1567	184(198)	1369	484	33	74	5,74	8,66	1,44	
155	4000	35000	1	53/26	1603	196(211)	1392	462	33	75	5,67	9,19	1,49	
156	4000	40000	1	50/26	1629	211(225)	1404	447	33	76	5,59	9,49	1,51	
157	5000	15000	1	82/25	1573	164(182)	1391	460	33	75	6,84	5,28	1,21	
158	5000	20000	1	74/26	1689	187(204)	1485	369	33	80	6,41	6,18	1,26	
159	5000	25000	1	68/26	1773	209(225)	1548	305	33	83	6,18	6,94	1,31	
160	5000	30000	1	63/27	1831	229(245)	1586	265	33	86	5,96	7,46	1,34	
161	5000	35000	1	60/26	1898	400(416)	1480	373	33	80	6,41	8,62	1,50	
162	5000	40000	1	57/28	1907	273(289)	1618	233	33	87	5,89	8,29	1,42	
163	6000	15000	1	91/26	1727	191(209)	1518	333	33	82	7,24	4,83	1,21	
164	6000	20000	1	82/26	1865	220(238)	1627	224	33	88	6,74	5,62	1,24	
165	6000	25000	1	76/28	1956	258(276)	1680	171	33	91	6,52	6,33	1,29	
166	6000	30000	1	72/31	1998	273(289)	1709	145	33	92	6,45	6,97	1,34	
167	6000	35000	1	68/33	2036	302(318)	1718	135	33	93	6,38	7,41	1,38	
168	6000	40000	1	66/34	2074	333(349)	1725	129	33	93	6,38	7,75	1,41	
247	7000	15000	1	99/27	1849	213(231)	1618	235	33	87	7,66	4,55	1,22	
248	7000	20000	1	90/29	1994	260(278)	1716	138	33	92	7,25	5,38	1,26	
249	7000	25000	1	85/34	2056	284(302)	1754	98	33	95	7,02	6,07	1,31	
250	7000	30000	1	80/37	2114	325(344)	1770	80	33	96	6,94	6,68	1,36	
251	7000	35000	1	77/40	2149	342(360)	1789	64	33	96	6,94	7,18	1,41	
252	7000	40000	1	74/41	2187	371(389)	1798	55	33	97	6,87	7,43	1,43	
253	7000	45000	1	72/42	2225	405(424)	1801	51	33	97	6,87	7,58	1,45	
254	7000	50000	1	69/42	2258	436(454)	1804	49	33	97	6,87	7,56	1,44	
169	3000	15000	1	81/24	1140	85(102)	1038	814	33	56	5,89	9,77		1,57
170	3000	20000	1	56/24	1191	224(238)	953	900	33	51	6,46	13,98		2,04
171	3000	25000	1	52/24	1224	240(255)	969	884	33	52	6,34	16,76		2,31
172	3000	30000	1	49/24	1247	255(269)	978	874	33	53	6,22	19,28		2,55
173	3000	35000	1	47/24	1265	265(280)	985	867	33	53	6,22	21,97		2,82
174	3000	40000	1	45/24	1282	276(291)	991	860	33	54	6,11	24,05		3,02
175	4000	15000	1	72/24	1378	251(267)	1111	742	33	60	7,08	9,11		1,62
176	4000	20000	1	66/24	1456	275(291)	1165	687	33	63	6,74	11,32		1,81
177	4000	25000	1	61/24	1513	295(311)	1202	651	33	65	6,54	13,41		1,99
178	4000	30000	1	57/25	1554	309(324)	1230	622	33	66	6,44	15,48		2,19

	179	4000	35000	1	54/25	1589	322(336)	1253	600	33	68	6,25	17,12		2,34
	180	4000	40000	1	52/25	1618	336(351)	1267	585	33	68	6,25	19,10		2,54
	181	5000	15000	1	82/24	1565	296(315)	1250	602	33	67	7,65	8,16		1,58
	182	5000	20000	1	75/24	1674	329(345)	1329	525	33	72	7,12	9,91		1,70
	183	5000	25000	1	69/25	1756	353(369)	1387	467	33	75	6,84	11,62		1,85
	184	5000	30000	1	65/26	1816	373(389)	1427	334	33	77	6,66	13,27		1,99
	185	5000	35000	1	61/26	1863	389(405)	1458	393	33	79	6,49	14,74		2,12
	186	5000	40000	1	58/26	1905	405(422)	1483	369	33	80	6,41	16,24		2,26
	187	6000	15000	1	90/24	1718	340(358)	1360	494	33	73	8,13	7,49		1,56
	188	6000	20000	1	83/25	1851	380(398)	1453	400	33	78	7,61	9,14		1,68
	189	6000	25000	1	77/26	1954	411(429)	1525	327	33	82	7,24	10,63		1,79
	190	6000	30000	1	72/26	2036	440(456)	1580	275	33	85	6,98	12,02		1,90
	191	6000	35000	1	68/27	2098	464(480)	1618	235	33	87	6,82	13,38		2,02
	192	6000	40000	1	65/28	2145	491(507)	1638	213	33	88	6,74	14,76		2,15
	255	3000	15000	3	47/25	807	147(167)	640	1213	33	34	9,70	4,73		1,44
	256	3000	35000	3	43/26	1069	218(236)	833	1020	33	45	7,33	6,11		1,34
	257	3000	50000	3	40/26	1165	276(293)	872	980	33	47	7,01	6,08		1,31
	258	4000	15000	3	51/26	909	160(182)	727	1125	33	39	10,90	4,12		1,50
	259	4000	35000	3	47/27	1273	255(273)	1000	854	33	54	7,87	5,09		1,30
	260	4000	50000	3	44/27	1413	302(320)	1093	758	33	59	7,20	4,84		1,20
	261	5000	15000	3	53/26	965	169(191)	774	1078	33	42	12,21	3,83		1,60
	262	5000	35000	3	51/28	1427	287(307)	1120	733	33	60	8,55	4,58		1,31
	263	5000	50000	3	48/28	1618	349(367)	1251	602	33	68	7,54	4,20		1,17
	264	6000	15000	3	54/26	996	173(195)	801	1051	33	43	13,80	3,74		1,75
	265	6000	35000	3	54/29	1551	316(336)	1215	638	33	66	8,99	4,17		1,32
	266	6000	50000	3	52/29	1783	395(415)	1368	484	33	74	8,02	3,86		1,19
	267	7000	15000	3	54/27	1014	175(196)	818	1036	33	44	15,15	3,65		1,88
	268	7000	35000	3	57/29	1649	344(365)	1284	567	33	69	9,66	3,99		1,36
	269	7000	50000	3	55/30	1916	440(460)	1456	396	33	78	8,55	3,66		1,22
	311	3000	15000	3,5	42/26	660	135(158)	504	1349	33	27	12,21	5,49		1,77
	312	3000	50000	3,5	39/26	1089	262(280)	809	1044	33	44	7,49	5,99		1,35
	313	4000	15000	3,5	43/26	700	138(160)	540	1313	33	29	14,65	5,12		1,98
	314	4000	50000	3,5	43/28	1294	280(298)	996	856	33	54	7,87	4,88		1,28
	315	5000	15000	3,5	43/27	718	140(162)	556	1298	33	30	17,09	4,95		2,20
	316	5000	50000	3,5	45/29	1460	318(338)	1122	731	33	60	8,55	4,40		1,29
	317	6000	15000	3,5	43/27	723	142(164)	559	1293	33	30	19,78	4,95		2,47
	318	6000	50000	3,5	49/30	1594	355(375)	1219	633	33	66	8,99	4,00		1,30
	319	7000	15000	3,5	43/27	725	142(164)	561	1291	33	30	22,22	4,95		2,72
	320	7000	50000	3,5	51/31	1670	387(409)	1261	562	33	70	9,52	3,77		1,33

SENSITIVITY ANALYSIS - SOLAR COLLECTOR AND MORAIN HEAT STORE SYSTEM																						
Sign	Input			Simulation heat balance						Solar cost calculations												
	Collector Area [m <sup>2</sup> ]	Store Volume [m <sup>3</sup> ]	GHE Length [m]	Store Temp [°C]	A		B		C		D		E		F		Collector Cost [kr/kWh]	Store I/II Cost [öre/kWWh]	Annuity I	Annuity II	Response	Remark
					-	-	-	-	-	-	-	-	-	-	-	-	[%]	[%]	[%]	[%]		
194	5000	50000	2	51/29	1876	291(307)	1569	284	33	85	6,03	5,40	1,14								base, excavated heat store	
270	5000	50000	2	51/29	1880	298(315)	1565	289	33	84	6,11	5,46	1,16	-1							thermal conductivity	
271	5000	50000	2	52/29	1869	280(296)	1573	280	33	85	6,03	5,40	1,14	0							thermal conductivity	
272	5000	50000	2	51/29	1893	307(324)	1569	284	33	85	6,03	5,40	1,14	0							thermal conductivity	
273	5000	50000	2	52/29	1883	289(305)	1578	275	33	85	6,03	5,40	1,14	0							thermal conductivity	
274	5000	50000	2	51/29	1889	300(316)	1573	278	33	85	6,03	5,40	1,14	0							thermal conductivity	
275	5000	50000	2	51/29	1853	287(304)	1549	302	33	84	6,11	5,46	1,16	-1							thermal conductivity	
276	5000	50000	2	51/29	1847	269(285)	1562	291	33	84	6,11	5,46	1,16	-1							thermal conductivity	
277	5000	50000	2	51/29	1851	278(295)	1556	296	33	84	6,11	5,46	1,16	-1							thermal conductivity	
280	5000	50000	2	51/29	1874	293(309)	1565	287	33	84	6,11	5,46	1,16	-1							thermal capacity	
281	5000	50000	2	51/29	1875	287(304)	1571	282	33	85	6,03	5,40	1,14	0							thermal capacity	
282	5000	50000	2	49/30	1896	309(325)	1571	282	33	85	6,03	5,40	1,14	0							thermal capacity	
283	5000	50000	2	50/30	1893	302(318)	1575	278	33	85	6,03	5,40	1,14	0							thermal capacity	
284	5000	50000	2	50/30	1894	305(322)	1572	280	33	85	6,03	5,40	1,14	0							thermal capacity	
285	5000	50000	2	54/28	1840	289(305)	1535	318	33	83	6,18	5,53	1,17	-3							thermal capacity	
286	5000	50000	2	55/28	1838	280(296)	1542	311	33	83	6,18	5,53	1,17	-3							thermal capacity	
287	5000	50000	2	54/28	1840	285(302)	1538	315	33	83	6,18	5,53	1,17	-3							thermal capacity	
290	5000	50000	2	48/26	1943	564(580)	1363	489	33	74	6,93	5,94	1,29	-13							insulation option	
297	5000	50000	2	49/27	1927	244(260)	1667	550	33	75	5,70	5,10	1,08	5							increased number of houses, 240 houses	
298	5000	50000	2	56/35	1743	355(372)	1371	118	33	92	6,98	6,24	1,32	-16							decreased number of houses, 160 houses	
301	5000	50000	2	50/27	1931	243(259)	1674	537	35	76	5,65	5,05	1,07	6							increased house load, 2174 MWh	
302	5000	50000	2	56/36	1733	356(373)	1360	138	34	91	7,01	6,27	1,33	-16							decreased house load, 1464 MWh	
305	5000	50000	2	51/29	1840	282(298)	1542	311	33	83	6,18	5,53	1,17	-3							increased thermal resistance	
306	5000	50000	2	52/29	1896	296(313)	1583	269	33	85	6,03	5,40	1,14	0							decreased thermal resistance	
311	5000	50000	2	52/29	1869	275(291)	1578	275	33	85	6,03	5,72	1,18	-3							increased insulation thickness	
312	5000	50000	2	51/29	1883	311(327)	1556	296	33	84	6,11	5,23	1,13	1							decreased insulation thickness	
194	5000	50000	2	51/29	1876	291(307)	1569	284	33	85	7,24	5,40	1,26	-11							increased solar collector costs	
194	5000	50000	2	51/30	1876	291(307)	1569	284	33	85	4,83	5,40	1,02	10							decreased solar collector costs	
194	5000	50000	2	51/31	1876	291(307)	1569	284	33	85	6,03	6,48	1,25	-10							increased excavated heat store costs	
194	5000	50000	2	51/32	1876	291(307)	1569	284	33	85	6,03	4,32	1,04	9							decreased excavated heat store costs	



CHARACTERISTICS - SOLAR COLLECTOR AND MORAIN HEAT STORE SYSTEM																							
Input		Simulation heat balance								Solar cost calculations													
Sign	Collector	Store	GHE	Store	A			B			Collector	Store III	Collector	Annuity I	Annuity II	Collector cost/store cost	Collector output [kWh/m²*a]	Storage efficiency	area/house load [m²/MWh]	temperature			
		[m³]	[m]	[°C]	[MWh/a]			-	C	D	E	F	[kr/kWh]	[öre/kWh]	[-]	[-]	[%]	[m]	[°C]	[öre/kWh]	volume/area		
49	3000	15000	2,5	52/25	947	93(111)	836	1016	33	45	7,33	6,58	1,39				5,0	1,6	52	1,54	1,24	1,52	1,26
1	3000	15000	2	56/24	1033	98(116)	917	936	33	49	6,73	6,11	1,28				5,0	1,6	56	1,42	1,15	1,41	1,16
7	4000	15000	2	64/25	1213	118(136)	1077	776	33	58	7,33	5,16	1,25				3,8	2,2	64	1,39	1,10	1,35	1,15
103	4000	15000	1,5	69/24	1314	129(147)	1167	684	33	63	6,74	5,41	1,22				3,8	2,2	69	1,35	1,08	1,32	1,11
109	5000	15000	1,5	78/25	1482	151(169)	1313	540	33	71	7,22	4,80	1,20	1,5	296	90	3,0	2,7	78	1,35	1,06	1,30	1,11
194	5000	50000	2	51/29	1876	291(307)	1569	284	33	85	6,03	5,40	1,14	1,1	375	84	10,0	2,7	51	1,26	1,02	1,25	1,04
196	6000	50000	2	58/34	2049	345(364)	1685	165	33	91	6,52	5,04	1,16	1,3	342	83	8,3	3,3	58	1,29	1,03	1,26	1,06
203	7000	45000	2	65/37	2138	375(393)	1745	109	33	94	7,09	5,13	1,22				6,4	3,8	65	1,36	1,08	1,32	1,12
237	7000	45000	1,5	69/40	2193	387(405)	1788	65	33	96	6,94	5,94	1,29				6,4	3,8	69	1,43	1,15	1,41	1,17
254	7000	50000	1	69/42	2258	436(454)	1804	49	33	97	6,87	7,56	1,44				7,1	3,8	69	1,58	1,31	1,59	1,29
255	3000	15000	3	47/25	807	147(167)	640	1213	33	34	9,70	4,73	1,44				5,0	1,6	47	1,64	1,25	1,54	1,35
25	3000	15000	2	55/24	1007	176(195)	812	1040	33	44	7,49	5,43	1,29				5,0	1,6	55	1,44	1,14	1,40	1,18
260	4000	50000	3	44/27	1413	302(320)	1093	758	33	59	7,20	4,84	1,20	1,5	353	78	12,5	2,2	44	1,35	1,06	1,30	1,11
263	5000	50000	3	48/28	1618	349(367)	1251	602	33	68	7,54	4,20	1,17	1,8	324	78	10,0	2,7	48	1,33	1,02	1,26	1,09
266	6000	50000	3	52/29	1783	395(415)	1368	484	33	74	8,02	3,86	1,19	2,1	297	78	8,3	3,3	52	1,35	1,03	1,27	1,11
269	7000	50000	3	55/30	1916	440(460)	1456	396	33	78	8,55	3,66	1,22				7,1	3,8	55	1,39	1,05	1,29	1,15
212	6000	50000	2	57/29	2073	476(494)	1579	273	33	85	6,98	5,07	1,21				8,3	3,3	57	1,35	1,07	1,31	1,10
219	7000	45000	2	64/31	2162	494(513)	1649	204	33	89	7,49	4,89	1,24				6,4	3,8	64	1,39	1,09	1,34	1,14
245	7000	45000	1,5	68/32	2276	554(573)	1703	147	33	92	7,25	8,06	1,53				6,4	3,8	68	1,68	1,39	1,69	1,37

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