SOLAR HEATING SYSTEMS WITH AQUIFER SEASONAL STORAGE AND HEAT PUMPS

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Abstract – In the Netherlands two central solar heating systems with seasonal heat storage have been realised in the past. Due to recent interest in the development of innovative energy infrastructures with seasonal storage of solar energy for new housing developments, a study has been conducted of different system concepts combining active solar energy, heat pumps and aquifer seasonal storage. The study was commissioned by NOVEM. The concepts vary in the temperatures used for heat storage and in the application of centralised or individual heating systems. Energy and cost calculations have been carried out with the goal to optimise the concept lay-out on cost effectiveness with respect to CO₂ reduction. A system lay-out with individual solar/heat pump systems attached to a collective aquifer seasonal storage system at low temperatures combines a large primary energy saving (56%) with a good cost-effectiveness when compared to a high temperature seasonal storage system. The key factors enabling this result are: low temperature heat storage and distribution which result in low system heat losses, a high collector efficiency and a high heat pump COP. The low temperature floor heating systems enable a direct solar contribution during part of the heating season. The low system heat losses combined with the high collector efficiency reduce the required collector area to 8 m²/dwelling within this concept. This results in the relatively good cost effectiveness of 540 euro per ton CO₂ reduction. Further technology developments required to implement this concept can be found in following fields: collector roof integration of large collective collector arrays, collector frost protection and overheating control, individual heat pumps that work with high source temperatures, and control strategies for the whole concept.

1. INTRODUCTION

In the Netherlands two central solar heating systems with seasonal heat storage have been realised in 1985. A large system in Groningen with a collector area of 2,400 m² and a soil heat exchanger and a smaller aquifer system at an office in Bunnik with 370 m² of collector area. The latter system has been removed in 1992 and the aquifer is now used as a cold storage.

Due to the interest of energy utilities to develop new innovative energy infrastructures with seasonal storage of solar energy for new housing developments, a study has been conducted of different system concepts combining active solar energy, heat pumps and seasonal aquifer storage [1]. The study was commissioned by NOVEM (Netherlands agency for energy and the environment). The concepts vary in the temperatures used for heat storage and in the application of centralised or individual heating systems. Energy and cost calculations have been carried out (based on general design parameters) with the goal to optimise the concept lay-out on cost effectiveness with respect to CO₂ reduction. Some additional simulations have been carried out to assess realistic parameter values for the given conditions. This paper covers the results of 4 out of 10 system lay-outs studied.

2. SEASONAL STORAGE WITH AQUIFERS

In The Netherlands aquifers are considered as the best option for the seasonal storage of solar heat on a large scale. Different from other European countries Dutch ground conditions (high ground water levels) are unfavourable for pit storage as is being practiced for example in Germany. Moreover natural aquifers are widely available in The Netherlands and cheaper than pit storage. Depending on the capacity prices vary between 650-800 euro per dwelling, compared to 2,200 euro for pit storage (Friedrichshafen; Germany) [2]. The capacity of an aquifer depends on the maximum flow (on average 80 m³/h) and the temperature difference that can be applied. The resulting aquifer power together with the maximum heating load of the houses in winter time determine how many houses can be connected to the storage. The efficiency of the aquifer depends on the temperatures of the hot and cold well. The efficiency is given in table 1.

<table>
<thead>
<tr>
<th>Temp. hot well °C</th>
<th>Temp cold well °C</th>
<th>Min. power [kWth]</th>
<th>Efficiency [%]</th>
</tr>
</thead>
<tbody>
<tr>
<td>20-15</td>
<td>5</td>
<td>930</td>
<td>90</td>
</tr>
<tr>
<td>35-25</td>
<td>12</td>
<td>1200</td>
<td>70</td>
</tr>
<tr>
<td>70-55</td>
<td>30</td>
<td>2300</td>
<td>50</td>
</tr>
</tbody>
</table>

High temperatures up to 70°C can be applied in aquifers, though some additional measures have to be taken to prevent problems with precipitation, degassing and bacterial growth.

3. SYSTEM CONCEPTS

3.1 Energy demand of the houses

The energy demand of the houses used for the study is based on a standard Dutch single family row house with 97 m² floor area, however with a better degree of insulation than required for the Dutch building code for
the year 2000. The energy demand of the house is 14 GJ/a for central heating en 7.3 GJ/a for domestic hot water.

3.2 Conventional reference system
The houses are connected to a gas grid and equipped with a gas fired high efficiency condensing boiler for space heating (efficiency 94% gas upper value) as well as for domestic hot water production (efficiency 70% gas upper value). The space heating systems function at conventional water temperatures of 90/70°C (supply/return). The primary energy consumption of the reference house is 26.4 GJ/a, which is 75 kWh/m²/a. The CO₂-emission is 1,34 ton/a. Due to a higher degree of insulation the energy consumption is 30% below the Dutch building code requirements for the year 2000. The reference costs for this system include the gas grid infrastructure. All additional costs for the different concepts (seasonal storage, heat distribution infrastructure, additional costs for low temperature heat delivery systems in the dwellings) are related to these reference costs.

3.3 Central solar heating plant with seasonal storage
The system lay-out of a central solar heating plant with seasonal storage (CS-SS) is given in figure 1. This lay-out is a common lay-out for central solar heating systems with seasonal storage and similar to the Groningen system. The houses are equipped with a low temperature heating system with radiators at 70-55/30°C (supply/return). The aquifer is loaded in summer to 70°C so heat can be delivered directly to the heat delivery system in the houses. In this case the aquifer heat is bypassing the individual condensing gas-fired boilers that function as auxiliary heaters. The hot well temperature decreases from 70 to 55°C during winter. Due to the high aquifer capacity 560 dwellings can be connected to the aquifer. The relatively high aquifer heat losses need to be compensated by the solar system. This leads to a large collector area required. The collector area amounts to 34 m² per dwelling with a solar yield of 1.5 GJ/m²/a. This is the maximum available roof area per dwelling. This limits the solar fraction to around 50 %.

3.4 Individual solar heating, individual heat pump and central seasonal storage
In this system lay-out the houses are equipped with individual solar/heat pump systems connected to a central seasonal storage (IS-HP-SS). The aquifer is now loaded to a maximum temperature of 35°C. The heat distribution network functions at 30/10°C (supply/return). The houses have a low temperature floor heating systems (30-40/20°C). The auxiliary heating is done by an electric heat pump, so there is no gas grid. Part of the heating season the aquifer can deliver heat directly to the heat delivery system in the houses by bypassing the heat pumps. A central ambient air heat exchanger is incorporated as cost-effective central heat source in the low temperature range. These heat exchangers can be noisy but can optionally be replaced by uncovered solar collectors (i.e. road collectors). Due to the lower aquifer temperature less houses can be attached to the storage (370 houses), thus increasing the aquifer costs per house. However the reduced system temperatures lead to significant lower system heat losses and to a higher collector efficiency. Therefore less collector area is needed: 8 m²/dwelling, with a solar yield of 2.5 GJ/m²/a resulting in reduced collector costs per dwelling. The low system temperatures also enable direct summer cooling.

3.5 Individual heat pump and seasonal storage
A concept that is currently being developed for the new housing development Broekpolder has no solar contribution, individual heat pumps and a central aquifer seasonal storage (HP-SS) [3]. The aquifer is used as source for the heat pumps. Aquifer regeneration is done by surface water as source, possibly in combination with an air heat exchanger. The aquifer is kept at low temperature, at a maximum of 20°C. The heat distribution network functions at 17.5/3°C (supply/return). The low temperatures enable a low cost distribution network without insulation. The houses use low temperature floor heating systems (30-40/20°C, supply/return). This means that no direct heat delivery from the aquifer is possible,
the heat pumps are always used to deliver heat at the required temperature. Within this concept 290 houses can be connected to the aquifer. The low system temperatures result in low system heat losses and enable summer cooling.

![Figure 3: Concept with individual heat pumps and seasonal storage at low temperature (no solar collectors).](image)

### 3. RESULTS

The performance and cost effectiveness for the presented system lay-outs is summarised in Table 2. The presented Seasonal Performance Factor (SPF) is the overall average system SPF for space heating as well as domestic hot water heating, including all auxiliary electricity needed for pumps in the heat distribution network and air heat exchangers.

**Table 2: Performance and cost effectiveness per dwelling for different aquifer seasonal storage concepts relative to conventional reference concept.**

<table>
<thead>
<tr>
<th>System concept</th>
<th>CS-SS</th>
<th>IS-HP-SS</th>
<th>HP-SS</th>
</tr>
</thead>
<tbody>
<tr>
<td>Central solar</td>
<td>ind. solar</td>
<td>ind. heatp.</td>
<td>ind. heatp.</td>
</tr>
<tr>
<td>Collector area [m²/dwelling]</td>
<td>34</td>
<td>8</td>
<td>0</td>
</tr>
<tr>
<td>Solar yield [GJ/m²/a]</td>
<td>1.5</td>
<td>2.5</td>
<td>--</td>
</tr>
<tr>
<td>Overall system SPF [-]</td>
<td>13.2</td>
<td>11.7</td>
<td>18.5</td>
</tr>
<tr>
<td>Spec. primary energy consumption [GJ/a]</td>
<td>38</td>
<td>34</td>
<td>53</td>
</tr>
<tr>
<td>Primary energy reduct. [%]</td>
<td>50%</td>
<td>56%</td>
<td>30%</td>
</tr>
<tr>
<td>Additional investment [euro/dwelling]</td>
<td>11,600</td>
<td>6,200</td>
<td>3,600</td>
</tr>
<tr>
<td>Additional yearly costs [euro/dwelling]</td>
<td>720</td>
<td>370</td>
<td>220</td>
</tr>
<tr>
<td>Cost effectiveness [euro/todmes CO₂ reduction]</td>
<td>1,200</td>
<td>540</td>
<td>730</td>
</tr>
</tbody>
</table>

In Figure 4 a comparison of the cost-benefit ratio is shown between the solar seasonal storage concepts described and regular solar hot water systems with diurnal storage for dwellings (SDHW-DS) and for communal buildings like homes for the elderly (CS-DS). The investment costs for the systems with diurnal storage are determined for large scale application in projects. The cost-benefit ratio is expressed as the initial investment costs in euro divided by the annual primary energy savings in kWh. It can be concluded that the solar seasonal storage concepts are not yet cost-competitive with the regular solar systems with diurnal storage. However the primary energy saving of the seasonal storage concepts is almost a threefold compared to regular SDHW-systems.

### 4. REQUIRED TECHNOLOGY DEVELOPMENT

In order to realise the concepts described in practice some further technology development is required in the following areas:

- **Collector roof integration**
  In order to integrate large scale collective collector fields in housing developments effective collector roof integration methods need to be developed. At this moment the development efforts are limited, however manufactures have shown interest in the topic.

- **Collector frost protection**
  The drain down principle that is prevailing in The Netherlands is complicated for large surfaces on dwellings. Manufactures however see solutions for this problem. Another option is to make use of the temperature storage concept (CS-SS). The individual heat pump concept without solar contribution (HP-SS) shows a better cost-effectiveness than the high temperature concept (CS-SS), however the primary energy reduction is limited to 30%.
principles used in other countries with completely filled system.

- **Individual heat pumps**
  In the heat pumps currently available the temperature at the evaporator side is mostly restricted to approx. 25°C and for domestic hot water production a maximum temperature of 55°C is reached which is below the government regulation that require 60°C.

- **Low temperature heating systems**
  A low supply temperature to the heat delivery system is very important for the heat pump efficiency (COP). Low temperature floor- and wall heating with a maximum supply temperature of 40°C are slow systems that currently do not fulfil general heating speed requirements.

- **Control strategies**
  Adequate control strategies to adjust and match all required flows and temperatures have to be developed. A first step would be the development of detailed simulation models for the system lay-outs discussed.

5. CONCLUSIONS

The recent interest in The Netherlands in low temperature seasonal storage of solar energy is confirmed by this study. A system lay-out with individual solar/heat pump systems attached to a collective aquifer seasonal storage system combines a large primary energy saving potential (56%) with a good cost-effectivity when compared to a high temperature seasonal storage system, due to:

- low temperature heat storage and distribution which result in low heat losses, a high collector efficiency and a high heat pump COP,
- a direct solar contribution during part of the heating season
- a relatively small collector area (8 m²/dwelling).

Some further technology developments are required to implement this concept. For instance on: collector roof integration of large collective collector arrays, collector frost protection and overheating control, individual heat pumps that work with high source temperatures, and control strategies for the whole concept.

REFERENCES

