

## Geothermal Plant with absorption heat pump in Thisted. Integration with heat and power plant and use for heat storage and removal of CO<sub>2</sub>,

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### ABSTRACT

A geothermal plant in Thisted has produced and reinjected millions of cubic meters of a 15% saline geothermal water in a sandstone reservoir without corrosion or injection problems since 1984. The plant uses an absorption heat pump driven by heat from a combined heat and power incineration plant and the driving heat is fully recovered on the district heating network. Denmark has no volcanic activities and no hot springs, but many reservoirs with warm geothermal water which can be used for district heating. The geothermal resources exceed the energy needed for heating in Denmark for hundreds of years and a sound geothermal concept with low heat production costs has been developed. The ongoing establishment of large combined heat and power plants in Danish towns does however delay the further geothermal development. Heat production costs, plant concepts, absorption heat pump concept, operation experiences from Thisted and future applications such as use for heat storage and injection of CO<sub>2</sub> are discussed. A computer program calculating energy balances and costs for geothermal plants is also introduced.

### 1. INTRODUCTION

Denmark has no volcanic activities and no hot springs, but many reservoirs with warm geothermal water which can be used for district heating. The normal temperature increase with depths is 0.025-0.033°C per meter. The geothermal resources exceed the energy needed for heating in Denmark for hundreds of years but they are only exploitable in a limited number of towns. The possibility of producing electricity based on hot geothermal water from deep reservoirs has been investigated, but reservoirs with sufficiently low pumping costs have not been found in Denmark.

Geothermal energy may be used for many purposes such as e.g. food processing, green houses, fish farming and cooling plants, but the primary use of geothermal energy in Denmark is district heating.

It is possible to integrate geothermal plants and combined heat and power plants to units with more than 100% efficiency (output of heat plus power exceeding primary energy input). In the Thisted plant the major part of the driving heat for the absorption heat pump is supplied from an incineration plant producing power and heat. The use for storage of heat, the use for removal of CO<sub>2</sub>, and a computer program evaluating geothermal plants is also discussed in the following.

### 2. BACKGROUND

Dansk Olie og Naturgas A/S was granted a sole concession for the exploration and production of geothermal energy in Denmark in 1978 and has worked with geothermal energy since. One third of the concession area was given back to the state in 1993.

The geothermal potential in Denmark was investigated through seismics, investigation of oil- and gas wells and the drilling of

geothermal exploration wells. A computer program was also developed for the evaluation and optimization of plant concepts and for the calculation of the energy consumption and heat production costs for geothermal plants.

When the exploration started, the goal was to find approx. 100°C hot geothermal water and extract the heat by direct heat exchange. Three geothermal explorative wells were drilled to 3 km depth and 100°C warm water was found, but the permeability was too low.

It was thus decided to abandon the concept of direct heat exchange with water produced from deep wells and instead use more permeable reservoirs closer to the surface and heat pumps.

### 3. GEOTHERMAL PLANT IN THISTED

The geothermal plant in Thisted is based on heat transfer through heat pumps and a high permeable 46°C warm reservoir at 1250 m depth in the last drilled explorative well. A deeper 63°C reservoir was also tested, but not chosen due to a high fines content and risk of fines migration.

#### 3.1 Pilot plant

A geothermal pilot plant with a 1.26 MW electric heat pump was erected in Thisted in 1984 with production from and reinjection to the Gassum reservoir at 1250 m depth. The produced heat goes to a district heating network.

The pilot plant proved a concept for avoiding corrosion and damage of the injection well, but a reduction of electricity costs for the heat pump was needed and different alternatives were investigated. It was concluded, that the plant should be equipped with an absorption heat pump when the plant was expanded to a demonstration plant in 1988.

#### 3.2 Demonstration Plant

The demonstration plant in Thisted with the electric and the absorption heat pump started operating in 1988. In 1994 the electric heat pump was removed.

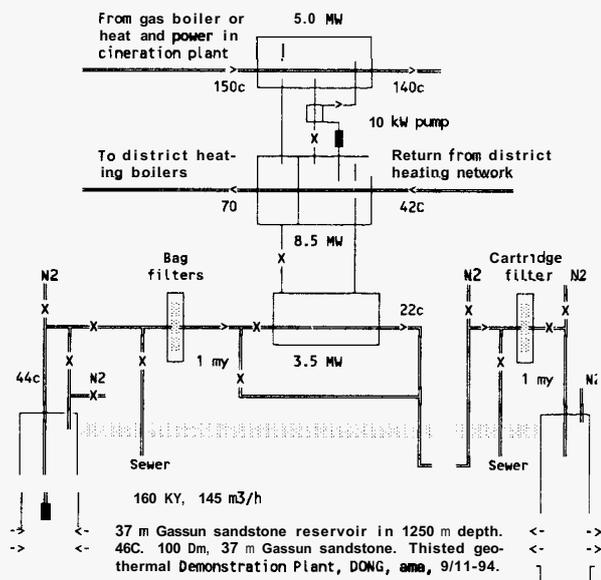
The plant now extracts up to 3.5 MW heat with the absorption heat pump alone from 145 m<sup>3</sup>/h of a 46°C, 15% saline geothermal water. The geothermal water is produced from and reinjected in the 100 Dm Gassum sandstone reservoir.

The plant is designed with:

- Carbon steel tubes (diffusion proof and even distribution of corrosion).
- Corrosion resistant materials at selected places (e.g. balls in ball valves).

- Filtering of geothermal water to one micron (1/1000 mm) in bag and cartridge filters.
- Recirculation valve on production well reducing start and sewer flow.
- Avoidance of underpressures from Bernoulli effects when operating.
- Nitrogen bottles securing overpressure during stops.
- Gravel packs in production and injection well.
- Computer controlled fail safe valves.
- Suitable equipment and wells.

A schematic of the demonstration plant is shown below.



The geothermal heat is transferred to the district heating network at Thisted by the LiBr absorption heat pump which is driven by 150-160°C hot water from boilers and a combined heat and power incineration plant.

2/3 of the heat used to operate the absorption heat pump is recovered on the district heating network together with the extracted geothermal heat. The driving heat for the absorption heat pump is borrowed and returned - and thus free if the driving heat normally goes direct to the district heating network.

Electric heat pumps use a compressor to suck low temperature vapours and extract heat from an evaporator and to compress the vapours and deliver the heat in a condenser at a higher temperature level. An absorption heat pump is driven by heat instead of electricity and the type used in Thisted uses a LiBr-water mixture to suck vapours from the evaporator instead of a compressor.

The temperature of the driving heat can be as low as 120°C, but 140-160°C driving heat should be used. The driving heat can be supplied from new or existing heat suppliers to the district heating network - e.g. from existing district heating boilers.

### 3.3 Operation of plant

Dansk Olie og Naturgas A/S owns the geothermal loop and has the responsibility for operating manuals and solving of problems for it while Thisted Varmeforsyning (the district heating company) owns the rest of the plant and takes care of the daily operation of the plant. The plant is operated with a computer based data collection and control system and:

- The plant starts and stops computer controlled.

- The system was carefully cleaned before first start up.
- The operating system keeps the pipe system pressurized.
- Overpressure is maintained from nitrogen bottles at stops.
- At restarts the system is cleaned up by pumping the geothermal water to the sewer until the water is clean (checked by filter coupons).

### 3.4 Gained experience

Together with a low CO<sub>2</sub> content and no H<sub>2</sub>S the above concept has led to corrosion rates below 0.1 mm/year and an injection of the 15% saline brine in the sandstone reservoir without the use of an injection pump since 1984. The submersible pump at 160 kW has operated without problems since it was installed in 1988.

The plant has demonstrated, that:

- Energy consumption and operating costs for heat pumps in a geothermal plant can nearly be eliminated by the use of an absorption heat pump.
- It is possible to reinject millions of cubic meters of a 15% saline geothermal water in a sandstone reservoir without the use of an injection pump (the injection well is prepared for clean up operations by nitrogen lift, but it has not yet been needed)
- Corrosion problems and injection problems can be avoided by the concept used in Thisted with nitrogen gas protection, iron tubing, filtering and clean up to a sewer system during start up.
- Down time can be reduced to less than one stop per year if the control system has been properly protected against transients from lightning, and if power failures are avoided.
- Filtering costs for the one micron filters can be reduced to less than one bag filter set per year and one cartridge filter set each second year when the wells are properly completed and the system is cleaned

## 4. HEAT PRODUCTION COSTS

Heat production costs for geothermal plants producing heat to a district heating networks are low if:

- The annual heat demand and the base load heat effect are high
- Supply temperatures and especially return temperatures are low
- Transmissivity (Dm) times reservoir temperature (°C) is high

### 4.1 Level for heat production costs

A new geothermal plant at a good location in Denmark may e.g. produce 0.3 mill. GJ/year heat through 25 years and have the following investment costs:

Production well	2.5 million US\$
Injection well	2.0 million US\$
Surface plant	7.5 million US\$
<b>Total</b>	<b>12.0 million US\$</b>

The investment costs may e.g. be paid through a 25 year loan with 6% real interest (or a 17 year loan with 3% real interest) and the total yearly costs can then become:

Payment on loan	0.9 mill. US\$/year
Power for pumps etc.	0.2 mill. US\$/year
Maintenance, adm. etc.	0.4 mill. US\$/year
<b>Total:</b>	<b>1.5 mill. US\$/year</b>

The cost per GJ becomes **US\$ 5 per GJ** while repaying the loan (equivalent fuel oil price for oil based heat: 140-150 US\$/ton oil) and **US\$ 2 per GJ** after the loan is repaid (equivalent fuel oil price for oil based heat: 40-50 US\$/ton oil)

The heat production costs for geothermal plants *can* thus become low, but a decision to cover the base load in larger Danish cities with heat from combined heating and power plants and the already made investments in a natural gas network makes it difficult to erect new geothermal plants in Denmark at present.

The heat production costs *can* easily become higher - e.g. in small towns with bad reservoirs. They *can*, however, also become lower yet - e.g. **US\$ 3-4** while repaying the plant loan and **US\$ 1-2 per GJ** after the loan is repaid. This can happen if hot springs *can* be used but also in countries with "normal" temperature gradients (25-35 °C/km) if the reservoir is very good and the plant supplies heat to a big district heating network with very low return temperatures. It can also happen if the plant is build using local labour and components in a country with lower cost levels than in Denmark.

The investment costs for the Geothermal plant in Thisted include costs for the Pilot Plant and a deep exploration well. The base load in Thisted is covered by a combined heat and power incineration plant and the remaining heat demand in Thisted is too small to allow production of enough heat to pay back all the investments.

**4.2 Estimation of concepts and costs**

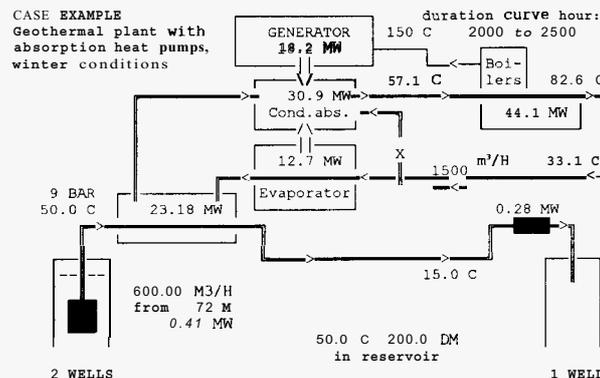
When it is discussed if and where to place geothermal plants it is important to be able to make fast evaluations of heat production costs based on available data. When it is decided to evaluate a specific plant location further and in a design phase it is also important to optimize selection of reservoir, location, flow of geothermal water, number of wells, size of plant, and adjustments to district heating network.

This *can* best be done through computer simulations of the whole plant including all operation conditions through a year. The model should calculate energy balances, size components, estimate costs and calculate heat production costs etc.

Dansk Olie og Naturgas has developed such a model which also includes simple reservoir simulations. It is used for evaluation of geothermal prospects and to help optimising a plant. A summary page **from** this program is included below as an example of very low heat production costs with costs converted to US\$.

The very low heat production costs below of **US\$ 2.9 per GJ** while repaying the loan and **US\$ 1.1 per GJ** after the loan is repaid are based on a low district heating return temperature, base load operation in a big town, a good reservoir (50°C, 100 m net sand with 2 Darcy permeability) and the present cost base for former Soviet Union.

AMA, 10/05-1994, 12:58:52, CASE EXAMPLE



Investment costs in US\$ milli.on:	
Production well, test, misc.	0.92
Injection well, test	0.91
Other geothermal wells	0.72
Production plant	9.57
Injection plant, pipeline	1.13
Adm., design, miscell.	2.28
Building loan costs	1.49
<b>Total,</b>	<b>17.02</b>

At 5 % p.a. real interest during 20 years and 721.2 TJ produced per year:

	US\$ per year	US\$/GJ
Interest and repayment on loan	1.36	1.89
Maintenance, administration	0.44	0.61
Power for heat pumps	0.02	0.03
Power for other pumps etc.	0.32	0.44
<b>Total while repaying loan</b>	<b>2.14</b>	<b>2.97</b>
<b>Total after repay of loan</b>	<b>0.78</b>	<b>1.08</b>

**5 COMBINED CONCEPTS**

Geothermal plants can be considered:

- Combined with heat and power generation to units with more than 100% efficiency (output of heat plus power exceeding primary energy input).
- Combined with heat storage and recovery - e.g. in order to store excess heat production associated with power production in the Summer time and recover it in the Winter time.
- Used to dispose unwanted components in the flue gases - e.g. NOx, SO<sub>2</sub> and CO<sub>2</sub>.

In the Thisted plant the major part of the driving heat for the absorption heat pump is supplied from an incineration plant producing power and heat.

The heat effect and power balance for a simple gas turbine combined with a geothermal plant transferring all heat to a district heating network through absorption heat pumps (AHP) can e.g. be as follows.

AHP driving heat	20 MW	
Extracted geothermal heat	14 MW	
<b>Heat to network</b>	<b>34 MW</b>	<b>34 MW</b>
Power used by pumps etc.	1 MW	
Steam used by AHP:	20 MW	
<b>Energy used by geoth. plant</b>	<b>21 MW</b>	<b>-21 MW</b>
Power from gas turbine	10 MW	
Steam from gas turbine	20 MW	
Water based heat from gast.	15 MW	
<b>Energy produced by gast.</b>	<b>45 MW</b>	<b>45 MW</b>
Energy loss, gas turbine	3 MW	
<b>Burned gas</b>	<b>48 MW</b>	<b>-48 MW</b>
<b>Gained energy</b>		<b>10 MW</b>

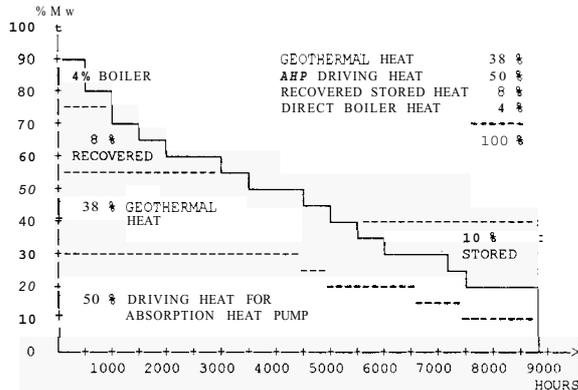
The total efficiency becomes then 121% (9 MW power and 49 MW heat from 48 MW primary energy). The total efficiency *can* however become much higher if geothermal heat can be transferred by direct

heat exchange.

### 5.2 Combination with heat storage

A geothermal plant can be used for heat storage e.g. a plant with two production wells. One of the production wells are then always used for production of geothermal water. The other well is sometimes used for reinjection of stored heat and sometimes for production of geothermal or/and stored heat.

An example of the energy balance for a geothermal plant with heat storage is shown on the duration curve below.



The stored heat is recovered by a direct heat exchanger supplemented by heat transferred through the absorption heat pump .

Nearly all stored heat is recovered. The stored hot water is fully recovered because it is stored in a zone from where more than the stored water is produced. The heat loss from the stored water is also low because of the elevated temperature level in a geothermal reservoir.

### 5.3 CO<sub>2</sub> removal

Different processes for removal of CO<sub>2</sub> from flue gasses exists. The following is based on removal of CO<sub>2</sub> produced in a gas turbine. Liquefied CO<sub>2</sub> is assumed produced from the flue gasses using an amine based process. Hydrocarbon Processing April 1994, page 75 gives the following costs for such a process:

Investment cost: US\$ 11 million for a 200 ton CO<sub>2</sub> per day plant removing 90% of the CO<sub>2</sub> in a flue gas from a gas turbine or gas based boiler.

Steam consumption: 2.3 ton per ton of CO<sub>2</sub>  
 Cooling water: 114 m<sup>3</sup> per ton of CO<sub>2</sub>  
 Power: 240 kWh per ton of CO<sub>2</sub>  
 Chemicals: 3 US\$ per ton of CO<sub>2</sub>

The source does not inform about heat effects and temperature levels, but it includes a process diagram.

Based on this and knowledge of other processes it is judged possible to produce the process steam on the combined heat and power gas turbine and possible to recover the steam energy as heat on a district heating network. Then the process steam does not carry any costs.

Power from the gas turbine can e.g. have a sales price of US\$ 0.05 per kWh. The costs of the power for the CO<sub>2</sub> plant becomes then US\$ 12 per ton of CO<sub>2</sub>.

Other operation costs plus interest and repayment on a 25 year loan for the plant may become US\$ 1.3 million per year - or US\$ 18 per

ton of CO<sub>2</sub> in base load operation mode.

The total costs for liquefied CO<sub>2</sub> becomes then: US\$ 30-40 per ton of CO<sub>2</sub>, depending on the load and number of operation hours per year.

A simple gas turbine producing power and heat to a district heating network may e.g. produce 10 MW power, 20 MW steam and 15 MW heated water when it burns 85 ton gas per day (48 MW). It will then produce 222 ton of CO<sub>2</sub> per day of which the above process can remove approx. 200 ton per day.

The process steam demand of 2.3 ton steam per ton of CO<sub>2</sub> (460 ton steam per day) for the CO<sub>2</sub> plant may be produced from 13 MW of the steam, which leaves 7 MW steam to drive the absorption heat pump of the geothermal plant.

An absorption heat pump driven by 7 MW heat can extract 5 MW of heat from the geothermal water - e.g. by cooling 200 m<sup>3</sup>/h of geothermal water from from 40-50°C to 15-25°C (heat with higher temperature levels than the return temperature of the district heating water is transferred through direct heat exchange)

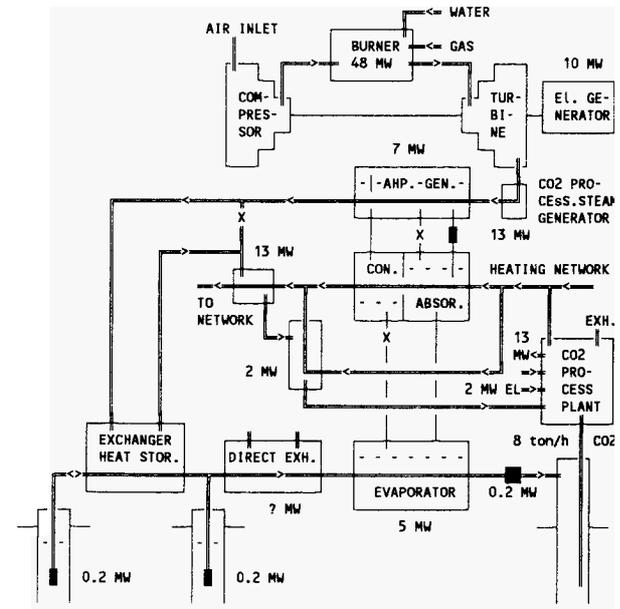
CO<sub>2</sub> at 25°C requires approx. 70 bar to remain liquid and the 200 ton of CO<sub>2</sub> per day (8 ton/hour) gives a CO<sub>2</sub> flow of 11-12 m<sup>3</sup>/h.

A CO<sub>2</sub> flow of 12 m<sup>3</sup>/h can be injected through a 750 m long 2" tubing in the injection well of the geothermal plant.

The reservoir pressure does normally exceed the critical CO<sub>2</sub> pressure of 72.8 bar and the critical temperature of 304.2 K. The CO<sub>2</sub> will then remain in dense phase. The critical density is 470 kg/m<sup>3</sup> and the density at e.g. 120 bar and 45°C approx. 610 kg/m<sup>3</sup>.

### 5.4 Combined concepts, perspectives,

An example of a combined plant with a gas turbine, heat storage and CO<sub>2</sub> injection is shown below. Please note that not all connections and exchangers are shown.



The demand for electricity in Denmark and a decision to cover most of the heat demand on district heating networks in larger Danish cities with heat from combined heating and power plants has together with the already made investments in a natural gas network made it difficult to erect new geothermal plants in Denmark.

New concepts respecting the demand for combined heat and power plants was therefore developed. The absorption heat pump in the geothermal plant in Thisted is as earlier mentioned already driven by heat from the incinerating based heat and power plant in Thisted.

The demand for heat on district heating networks is expected to increase if the development of small heat and power generation plants continues and the power generation efficiency continues to rise. This is together with the above mentioned other possible combined uses expected to improve the prospects for future geothermal plants.

In Denmark geothermal energy can also be used for food processing, green houses, fish farming and cooling plants, but the primary use of geothermal energy in Denmark will remain district heating. In countries with geothermal water of low salinity it can also be used for supply of warm and cold water (before and after heat extraction) and in countries with hot reservoirs also for electricity production and industrial processes.

## 6.0 ENVIRONMENTAL ASPECTS

Geothermal water found in Denmark is basically concentrated sea water. It is thus not allowed to flood farm land or go into the ground water, but small spills are not more harmful than sea water entering rivers, sea water blown across land by the wind or salt used on the roads to prevent ice in winter time.

The geothermal plant in Thisted is constructed with a closed loop and the salty water is not leaked to the ground. Geothermal water which is used to clean up the pipe system before reinjection starts is lead to the sea through the sewer system. The absorption heat pump does not use CFC-gasses, but a LiBr-water solution - and it does not leak harmful gasses to the atmosphere.

Geothermal plants reduces pollution of the environment by the amount of pollution normally produced from the heat sources, that it substitutes. If it is combined with heat storage it may also relieve nature of the load from the production of cooling water, load from cooling towers and heating of rivers.

Geothermal plants can be used for removal of CO<sub>2</sub>, NO<sub>x</sub> and SO<sub>2</sub> from flue gasses. Fluids with low pH does already exist in the ground and it is hard to see how the acid should do any harm at e.g. 1500 m depth if it is checked that the acid can coexist with the reservoir matrix and that there is no exchange between reservoir water and drinking water zones. In Denmark the salinity of the

geothermal water is high (e.g.10-20%). This means that there normally is no exchange between geothermal reservoirs and drinking water zones.

## 7.0 ORGANISATION

Dansk Olie og Naturgas A/S was granted a sole concession for the exploration and production of geothermal energy in Denmark in 1978 of which one third of the area was given back to the state in 1993.

The geothermal Pilot Plant was erected and initially also operated by Dansk Olie og Naturgas A/S. The expansion to the present demonstration plant with the absorption heat pump was performed in joint venture with Thisted Varmeforsyning (The district heating company of Thisted owned by the heat consumers).

Thisted Varmeforsyning expanded and operates the heat pump plant with the absorption heat pump assisted by Houe & Olsen, who also designed the integration with the combined heat and power incineration plant. Dansk Olie og Naturgas A/S expanded the geothermal water loop and operates it in cooperation with Thisted Varmeforsyning.

Apart from personnel with specific knowledge about geothermal plants, Dansk Olie og Naturgas A/S employs geologists, geophysicists, reservoir engineers, drilling engineers, facility engineers and economists with expertise within exploration, evaluation, establishment, analysis and operation of geothermal plants.

Dansk Olie og Naturgas A/S cooperates with specialists within Aarhus University regarding reservoir temperature levels, Geological Survey of Denmark and Petroleum Geology Investigators regarding reservoir parameters and has a close cooperation with Houe & Olsen regarding absorption heat pumps and district heating network related problems and geothermal plant erections in general.

A decision to cover the base heat load in larger Danish towns with heat from combined heat and power plants has delayed the further geothermal development in Denmark. Since the erection of the plant in Thisted Dansk Olie og Naturgas A/S has been involved in geothermal investigations outside Denmark. In the Kaliningrad Region, in Germany and Poland (as consultant to Houe & Olsen), in Latvia and Lithuania (as partner to Petroleum Geology Investigators) and now as project manager for the Danish technical assistance to the erection of a planned 600 m<sup>3</sup>/h geothermal plant in Klaipeda, Lithuania.