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Current Status of the EGS Soultz Geothermal Project (France)

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ABSTRACT

Over two decades of research and development of the EGS Soultz reservoir carried out with French, German and Swiss governmental and European funding, a pilot geothermal power plant have been built by a French-German industrial consortium. The drilling of three boreholes to 5 km, the deepest penetration of crystalline rock in France, has yielded fundamental insights into the geology, nature of fracturing, fluid geochemistry, temperature and hydraulic properties of deep crystalline rock masses.

On surface, the binary power plant is based on an ORC system (Organic Rankine Cycle). The organic working fluid is isobutane and the pilot plant has a net capacity of 1,5MWe. The three deep deviated wells were drilled from the same platform and are cased from the surface to 4.5 km depth. After the drilling operations, all the wells were hydraulically stimulated as well as chemically stimulated. Several circulation tests were done and shown encouraging results. A fourth geothermal well corresponding to a former exploration well drilled to 3.6 km depth could be used as an additional re-injection well if needed. The geothermal fluid which is a natural brine (100g/L) is pumped from the 2 deep production wells equipped with down-hole pumps. After giving its energy to the isobutane, the cooled brine is fully re-injected. Surface equipments (turbine, air cooling system, heat exchanger) as well as two different types of down-hole pumps (Line Shaft Pump, Electro Submersible Pump) were installed respectively on surface and in the production wells.

Reservoir evolution is monitored from surface measurements in terms of hydraulics and temperature evolution. In the meantime, microseismicity is also monitored continuously during the circulation. On surface, corrosion-scaling studies are carried out based on on-site testing facilities by using various steels belonging to the geothermal components of the power plant. An innovative corrosion pilot was set up in the re-injection part of the geothermal loop (70°C, 20 bars).

The on-going Soultz project is now very close to the end of the pilot plant phase and has been able to produce electricity since June 2008. A new scientific and technical monitoring phase of the power plant is now running for 3 years for evaluating the performance of the reservoir but also for facing challenges and issues related to the different technologies used on surface and in the different wells.

1. INTRODUCTION

The Soultz experimental geothermal site is located in France and consists of three deviated, 5 km deep wells drilled from the same platform within fractured granite (Genter et al., 2009). A former exploration well drilled to 3.6 km depth can be used as an additional re-injection well. Geothermal water is pumped from the production wells (GPK2, GPK4) and re-injected at lower temperatures into the injection well GPK3 (Figure 1) and in the former well GPK1.

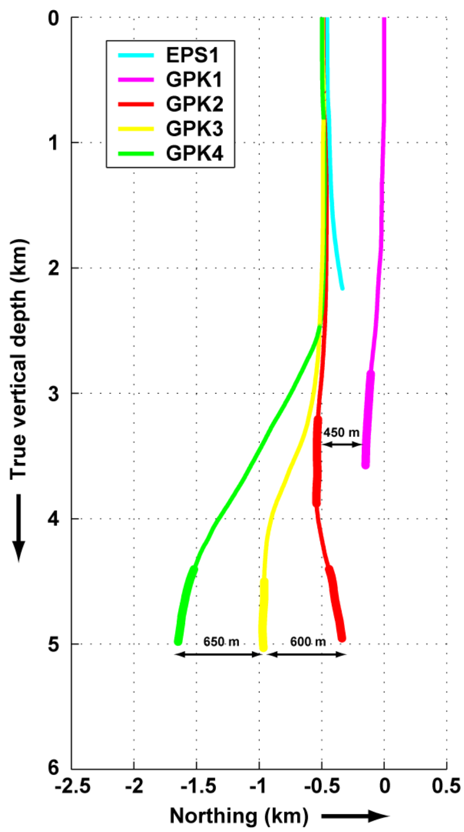

Figure 1: Schematic S-N cross section through the Soultz wells. GPK2 and GPK4 are equipped with down-hole pumps. GPK3 is the re-injection well. If needed, GPK1 can be used as a re-injection well. EPS1 is an observation well. Depths are expressed in True Vertical Depths (TVD).

Before 2000, the upper reservoir (3.6 km depth) was developed and successfully tested by hydraulic circulations. A lot of high quality datasets data have been collected, interpreted and numerically modeled by various teams in Europe (Baumgaertner et al., 1998; Baria et al., 1999; Gérard et al., 2006) in order to understand the hydro-thermo-mechanical and geochemical behavior of a deep crystalline basement dedicated to various hydraulic experiments (injection, production, hydraulic stimulation, chemical stimulation, inter-well circulation).

Between 2005 and 2009, this pilot project's original aim was a general objective: the technical and economical design of large industrial units (> 25 MWe), based on multi-well Enhanced Geothermal Systems. However, at Soultz, no additional well was drilled, thus the electrical power target was a net capacity of 1.5 MWe based on binary technology using an Organic Rankine Cycle (ORC) unit (Fritsch et al., 2008).

Between 2005 and 2009, the most realistic objective was to design, build and test the main geothermal components of this EGS binary plant (Figure 2).

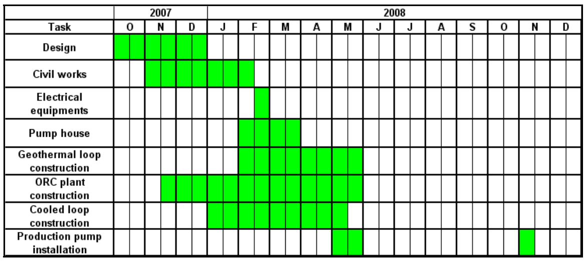

Figure 2: Time frame for the Soultz power plant construction.

2. MAIN SCIENTIFIC RESULTS FROM GEOTHERMAL EXPLORATION

2.1 Exploration by Drilling

Exploration and reconnaissance of the crystalline rocks were mainly based on drilling data (cuttings, cores, well logging, borehole image logs, vertical seismic profiling, geochemical fluid monitoring, temperature, hydraulics, stress field, induced seismicity) collected from the top basement (1.4 km), into the upper reservoir (3.6 km) and into the lower reservoir (5 km).

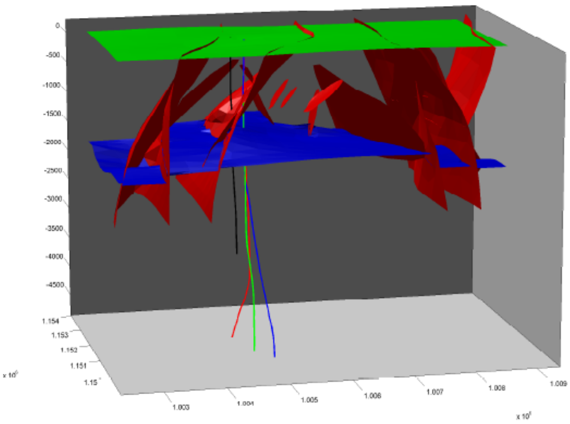

Figure 3: 3D model of the fault system (in red) derived from seismic interpretation (Renard and Courrioux, 1994). The top of the basement (blue surface) is at about 1.4 km depth (Valley, 2007). The deep geothermal borehole trajectories are also plotted (GPK2 in red, GPK3 in green, GPK4 in blue).

The Soultz area is located inside a Tertiary graben characterized by the occurrence of numerous normal faults developed in both the sedimentary cover and in the Paleozoic granitic basement (Figure 3). The subsurface of this area is well-known based on several thousand of wells drilled for oil exploitation from ages. Geothermal exploration by deep drilling shown that the wells penetrated hydrothermally altered and fractured zones (HAFZ) bearing natural brines having a salinity of 100g/L.

2.2 Well Systems

On surface, the 3 wells are drilled from the same geothermal platform. The horizontal distance between the wells is 6 m long only whereas at the bottom hole, the distance between each production well and the re-injection well is about 600 m length (Figure 1, Figure 3).

GPK1 is an old geothermal well that could be used for re-injection well if needed. All the wells are cased between surface and about 4.5 km depth offering an open-hole section of about 500 m length in each geothermal well (Figure 1).

The geothermal wells were drilled to 5 km depth and reached a bottom hole temperature of 200°C. They were subsequently hydraulically and chemically stimulated between 2000 and 2007 in order to enhance the low initial permeability of the 5 km reservoir (Evans et al., 2009; Nami et al., 2008; Schindler et al., 2008). The injectivity index, i.e. the injection flow rate per unit wellhead pressure under steady-state conditions, was significantly improved. For the three deep wells, each stimulated between 4.5 and 5.0 km TVD, the improvement for GPK2 and GPK4 was a factor of about 20, whereas that for GPK3 was only a factor of ~1.5 (Nami et al., 2008). A variety of acid stimulations were conducted on all deep wells after the hydraulic stimulations, with limited success (Nami et al., 2008). The improvement in 3-day injectivity/productivity index by the acid treatments was a factor of about 1.25 for GPK2, about 1.15 for GPK3, and about 2.5 for GPK4. It should be noted, however, that the large increase in productivity for GPK4 was largely due to the development of leaks in the casing whose origin are currently uncertain. If only the open hole is considered, the improvement achieved by the acid treatments was a factor of 1.5-1.75.

Microseismic activity was monitored during all stimulations. Typically, several thousand of microseismic events would be recorded during single stimulation with a down-hole seismic network and somewhat fewer with a surface seismic network (Cuenot et al., 2006 and 2008; Dorbath et al., 2009). Comparison of the seismic responses to stimulation of the three deep wells showed that they are dependent to some degree on the nature of the HAFZs encountered in each of the wells (Dorbath et al., 2009). In summer 2003, a microseismic event having a magnitude of 2.9 occurred during a shut-in period (after hydraulic stimulation of GPK3) was felt by the local population (Charléty et al., 2007).

2.3 The Deep Geothermal System during Circulation

2.3.1 Hydraulic Tests without Down-Hole Pumps

Several limited-duration circulations have been performed in the lower reservoir to date: without down-hole pumps in 2005, and with one down-hole pump and power generation in 2008. The first circulation test of the triplet of wells penetrating the lower reservoir (4.5−5.0 km) took place for 5 months between July and December 2005 (Gerard et al., 2006). Tracer tests conducted during the circulation showed that ~25% of the injected tracer was recovered from GPK2 but only 2% from GPK4 (Sanjuan et al., 2006). This asymmetrical response reflects the complex organization of fracture zones or faults describing different fluid circulation loops, the hydraulic connections between GPK3 and GPK2 being much more direct and faster than between GPK3 and GPK4 (Sanjuan et al., 2006). During this circulation, and all production tests conducted at 5 km depth, tracer tests and geochemical data invariably showed the presence of the native geothermal brine in the discharged fluids, even after large amounts of external fresh water had been injected into the wells (Sanjuan et al., 2006). This result points to the conclusion that the exchanger is connected to a deep natural reservoir. Some 600 microseismic events were recorded in the 6 months during and immediately following the circulation. Several exceeded magnitude 2.0, but none were felt.

2.3.2 Hydraulic Tests with Down-Hole Pumps

Between 2008 and 2009, several short duration hydraulic tests have been done with down-hole pumps and induced microseismicity and corrosion were monitored continuously. The detailed presentation of the submersible production pumps is done in the following paragraph. The thermal output ranged around 12 MW thermal for a cumulative flow-rate ranging around 28 l/s. At the surface, during circulation tests, the flow rate, the temperature and the pressure are systematically monitored at production and re-injection. All the data are systematically saved on an automate system which stores and saves the power plant datasets. Several hydraulic circulations tests were done by producing with GPK2 and re-injecting in GPK3 (duplet system): from the end of May to mid June 2008, from the end of June to mid August 2008 and from early March 2009 to June 2009. Between November and December 2008, the wells GPK2 and GPK4 were producing, with the help of down-hole technologies, and the cooled geothermal fluid was re-injected into GPK3. It was the first time that the triplet was operational for a significant period of time while the two producers were equipped with different production pumps. Because we were testing various components of the geothermal plant (filtering system, heat exchanger, cooling system), the ORC unit was partially operating, only a few kWh were produced by the power plant.

A hydraulic circulation was performed between all three wells with production from GPK2 via LSP and from GPK4 via ESP between November and December 2008 (Schindler, 2009). The LSP was mounted at 250 m depth. A measurement of pressure drawdown could not be performed for technical reasons. The ESP was installed at 500 m depth, the water level was a few times measured by nitrogen injection and more often determined from the temperature profiles of the fiber optic cable.

The circulation between GPK3 and GPK4 was five weeks long, and all three wells were simultaneously operative for a period of about two weeks. The production from GPK4 started on November 17th lasted until December 20th, 2008. The production rate decreased fast at the beginning from an initial value of 60 m³/h to the final 44 m³/h which was kept constant (Figure 4). The production temperature increased from 151 to 155°C, which is slower than the increase observed at GPK2 due to the lower production rates. For a constant injection flow (22nd to 30th November) of about 40 to 42 m³/h, the injection pressure at GPK3 is also constant about 28 bars. The tendency to increase with time appears therefore only at higher flow rates, as soon as GPK2 contributes to the circulation, and reaches up to 86 bar. The hydraulic data of the well GPK2 show a clear temperature improvement with time to 163°C (Figure 4). Since the water level was not observed, statements concerning GPK2 productivity cannot be made. A rough estimate of the productivity of GPK4 from the water level data yields a productivity significantly smaller than the anticipated 0.5 l/s/bar.

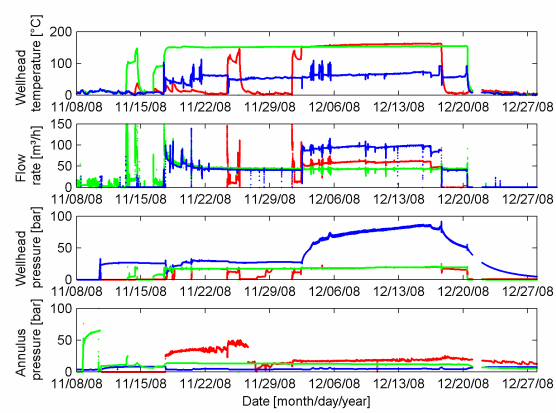

Figure 4: Overview of hydraulic data from November to December 2008 with GPK2 in red, GPK3 in blue and GPK4 in green. The upper graph shows production and injection temperatures, the second plot illustrates production (GPK2, GPK4) and injection (GPK3) flow rates, the third graph is the production (pump) and injection pressure. The fourth illustration shows the pressure in the annuli between the casings and the formation in the same color code as above.

In March 2009, a tracer test was conducted by BRGM between GPK3 and GPK2 (Gentier et al., 2009). An inert gas was injected into GPK3 and monitored on site, at production in GPK2 well. Preliminary results in terms of peak detection are consistent with previous tracer tests done in the past with organic fluids (Sanjuan et al., 2006).

2.3.3 Seismic Activity during Hydraulic Circulation

During the different circulation tests conducted in 2008 and 2009, microseismicity was fully monitored using seismic stations installed at surface level (Cuenot, 2009 a, b). The monitoring of the microseismic activity shows that the earthquakes took place within the same areas as those in the 2005 circulation test. The main difference between the two experiments is the level of magnitude, which was much lower in 2008 and 2009 (Figure 5). One of the main seismic events, with a magnitude of 1.7 observed in December 2008, is related to an accidental sharp stop of the LSP pump within GPK2 (Figure 5).

2.3.4 Corrosion and Scaling Studies during Circulation

At Soultz, corrosion and the creation of deposits were investigated based on an on-site testing system using three different steels in order to determine the reaction of those materials to the geothermal brine with a high salinity. An innovative corrosion pilot was set up on the geothermal loop at the surface and tested for the first time between September 2008 and February 2009 (Figure 6). After their extraction from 3 different chambers, coupon samples were analyzed using various chemical techniques. The main results consisted of a significant reaction to the geothermal brine on all studied steels. Newly created deposits, mainly sulphates, formed on the surface of samples (Baticci, 2009). Corrosion occurred beneath the deposits and corresponded to pits. A series of physico-chemical parameters, such as pH, Eh, conductivity and temperature, was measured in the meantime at re-injection conditions (Gentier et al., 2009).

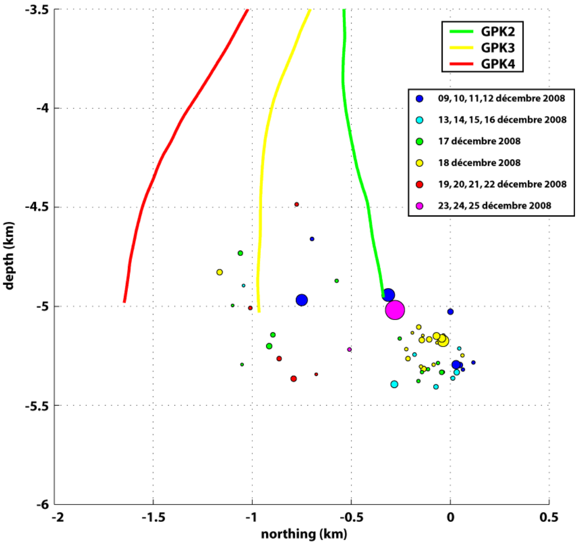

Figure 5: N-S vertical cross section showing the microseismicity recorded between November and December 2008 at Soultz (Cuenot, 2009a).

Figure 6: Photograph of the corrosion pilot installed at re-injection conditions in the Soultz geothermal loop.

3. GEOTHERMAL SITE PRESENTATION

3.1 Geothermal Plant

On surface, a binary power plant was designed and built based on an ORC technology (Organic Rankine Cycle). Surface equipments (turbine, heat exchanger, filtering system) as well as two different types of down-hole pumps were installed respectively on surface and in the production wells (Figure 7, Figure 8). Two down-hole pumps have been installed, and several hydraulic circulation tests were done with 2 wells (GPK2, GPK3) in summer 2008 and March 2009, and with 3 wells (GPK2, GPK3, GPK4) in November-December 2008. The first kWh was produced mid-June 2008. However, from 2008 to 2009, several significant technological improvements have been done above the surface (filtering system, lubrication system, heat exchanger), and the power plant is close to being fully operational despite some challenges yet to be solved.

Figure 7: The Soultz geothermal power plant: in the back, the ORC power unit; in the middle, the 3 geothermal wells; in the front, the cooled geothermal loop.

3.2 Production Pump Technology

<u>3.2.1 Pump Presentation</u>

Production pumps represent strategic equipment for developing EGS technology. LSP and ESP technologies, Line Shaft Pump and Electro Submersible Pump respectively, were designed and selected. The LSP pump was installed at a 350 m depth in April 2008 in GPK2, and the ESP was deployed at a 500 m depth in GPK4 in November 2008. The LSP was tested alone during summer 2008, and both pumps were tested simultaneously from November to December 2008 (Figure 8).

<u>3.2.2 Down-Hole Pumps Selected for the Soultz Wells</u>

In order to produce higher flow rates than those obtained during the artesian test done in 2005, we needed production pumping of high temperature geothermal fluids. Thus, it was decided to test simultaneously the LSP in GPK2 and ESP in GPK4 (Figure 8).

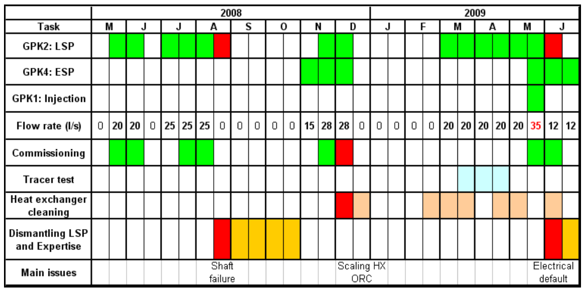

Figure 8: Chronogram of the down-hole pump installation and geothermal circulation at Soultz (in green). The main issues are colored in red.

The LSP was installed at a 345 m depth in GPK2 by mid-April. In that well, drawdown estimated calculations were done with different hypotheses about formation production index and casing friction losses. These calculations showed that according to limiting parameters, which are the minimal pressure required at pump intake and the maximal (flow-rate, Total Dynamic Head) pump characteristics established at maximal speed, expected operating flow-rate could be between 25 and 35 L/s (Faucher and Goerke, 2009).

During summer 2008, between 07th July and 17th August, after six weeks of geothermal production (25 l/s, 155°C), we observed some scaling problem within the lubrication part of the shaft. The fresh water used for lubricating the shaft was too mineralized and some carbonate deposits (calcite, aragonite) precipitated. Then, a poor lubrication occurred and the first axis of the shaft broke. Between mid August and November 2008, both the shaft and the pump were fully dismantled, analyzed and a demineralization water system was set up. The LSP pump has been re-installed at a 250 m depth in GPK2 (Figure 8).

With the ESP, both the pump and its motor were placed within the GPK4 well at a 500 m depth. The maximum expected flow rate from GPK4 equipped with the ESP is 25 l/s, but the pump is designed to generate a maximum flow rate of 40 l/s. Due to the expected maximum temperature (185°C) and salty composition of the brine, a specific design and noble metallurgy have been used. The electrical motor is beneath the pump and connected to it by a seal section which compensates for oil expansion and metallic dilation. The motor is cooled by the pumped geothermal brine and internal oil temperature can reach 260°C. A fiber optic cable was installed with the EPS pump and allows for monitoring of the motor temperature as well as gives down-hole information about the geothermal draw-down in the well.

At the same time as the re-installation of the LSP in GPK2 at a 250m depth, the first production tests from GPK4 with the ESP, with an expected target of 25 l/s, started in mid November 2008. After some days of production, GPK4 production decreased to 12.5 l/s at 152°C, and the geothermal water was re-injected into GPK3 at 50°C. LSP started again and GPK2 flow-rate was stabilized at 17.5 l/s with a temperature of around 158°C. Both flows coming from GPK2 and GPK4 were re-injected under full automatism in GPK3 at 30 l/s. The ORC pre-commissioning started under these geothermal conditions at around 155°C. It was the first time that the triplet was operational for a significant amount of time while the two producers were equipped with production pumps.

Table 1: Line Shaft Pump (LSP) performance at two different depths in GPK2 well.

Date	07 August 08	09 April 09
Pump depth	350 m	250 m
Flow rate	24.8 l/s	20 l/s
Production temperature	165°C	162°C
Back pressure	54 bars	44 bars
Intake pressure	36.6 bars	33.72 bars
Total dynamic head	17.4 bars	10.28 bars
Hydraulic drawdown	80 m	10 m
Hydraulic power P1	43.1 kW	20.56 kW
Electrical power P2	64 kW	37.87 kW
Global recovery (P1/P2)	67%	54%

A calculation of the pump recovery has been done for two different depths of the LSP (Table 1). At 350 m, with a flow rate of 24.8 l/s, a pump power consumption of 43 kW is needed. In that case, the LSP pump recovery is around 70%. At a 250 m depth, with a flow rate of 20l/s, a pump power consumption of 38 kW is needed. Under these conditions, the LSP global pump recovery is around 55% (Faucher and Ravier, 2009).

With the installation of the ESP pump at a 500 m depth, the hydraulic performance compared to the electrical power consumption gives a global recovery of 34% (Table 2). This value confirms the relatively poor productivity of the GPK4 well. Thus, the ESP pump does not work within its better efficiency range due to the bad hydraulic conditions of the GPK4 well.

Table 2: Electro-Submersible Pump (ESP) performance in GPK4 well at 500 m.

Date	Flow rate	Frequency	Total dynamic head	Electric al power
Dec. 2008	46,2 m^3/h	50,5 Hz	250 m	144 kW
June 2009	40,7 m^3/h	45 Hz	177 m	118 kW

4. FEED-IN TARIFF IN FRANCE

The selling of electricity at Soultz is strongly related to the French feed-in tariff. The current price for selling electricity from geothermal energy in France is 12.5 ct€ per kWh on the net power. The topic n°22 of the Grenelle de l’Environnement done by the French government is specifically dedicated to a significant revision of the feed-in tariff in order to be as close as possible to the German one, which is 24 ct€ per kWh on the gross selling power. Thus, the GEIE “Exploitation Minière de la Chaleur” has not signed the power selling contract yet and is waiting for the new tariff which is thought to be ready by the end of 2009. In the meantime, a lot of improvements and tests are conducted on the geothermal site in order to improve the whole efficiency of the geothermal installation. A new R&D phase has been starting from Mid 2009 with the help of industry and French-German public funding in order to monitor scientific and technically the geothermal site. The main areas covered by this new project deal with reservoir studies (temperature, fluid geochemistry), environmental purposes (microseismicity, noise, radioactivity) and technical challenges (pumps, corrosion, heat exchanger).

5. CONCLUSION

At Soultz, drilling of several deep wells in crystalline rocks has yielded fundamental insights into the geology, nature of fracturing, fluid geochemistry, temperature and hydraulic properties of deep crystalline basement. A geothermal ORC plant has been built with a net capacity of 1,5MWe and but is still in its testing and commissioning phase. A negotiation with the French government is under discussion because the feed-in tariff in France is about 12c€ per kWh. The target for the future should be to reach the level of Germany which is 24c€ per kWh for power plants having a net power below 10MWe. This target could be reached by the end 2009 in France.

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