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Storage of mechanical energy and extraction of heat via artificial fractures in low permeable rock

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ABSTRACT

Due to the transformation of current energy systems and for stabilising electrical grids, storage solutions for energy are becoming more and more important. Hydrogen or synthetic fuels may be stored in the deep underground and converted to electricity when required. But the deep underground might also be important for the storage of mechanical energy.

In the geothermal project Genesys massive waterfrac tests and post-frac injection and flowback experiments were performed in Triassic sedimentary rock in the Northern German Basin. The results and observations of these tests are revisited for investigating the question if large artificial fractures can be used for mechanical energy storage in the underground. Cyclic injection and flowback tests revealed that approximately half of the electric energy necessary for injection could have been recovered during flowback. Obviously, a large portion of the pump energy was stored in the underground as mechanical energy due to ballooning of a fracture and due to elastic compression of water and rock surrounding the fracture. Mechanical energy in the magnitude of 100 MW_{me} was temporary stored as a side effect of the performed hydraulic tests[1].

The efficiency of energy storage can be improved significantly by implementing a horizontal well design with multiple fractures. This is shown based on model calculations. If water is injected in parallel artificial fractures the static pressure level between the fractures increases, water losses decrease and the flowback is improved. Furthermore, overpressure reservoirs and low permeable rock are favourable. Thereby the injected water remains in the vicinity of the fractures and the complete artesian flowback is ensured. Overpressure formations seem to be widespread in the deep underground of sedimentary basins as in the North German Basin.

Mechanical energy storage in the deep underground could be combined with geothermal heat extraction. At the test site Horstberg thermal water at a temperature of about 100°C was produced in cyclic tests. Numeric modelling results suggest that a thermal power of approximately 1 MW_{el} can be extracted by cyclic production in the long term via the large fracture in Horstberg.

For the realisation of the storage concept several challenges have to be met. Besides the creation of good underground conditions, the handling of the produced saline water and its reinjection without scaling is a serious issues. On the other hand the storage of surplus power as mechanical energy in the underground and its retransformation to power can be more efficient than a conversion into hydrogen or synthetic fuels and less expensive than battery storage. The reuse of abandoned deep wells in the Northern German Basin could be an appropriate starting point for demonstrating this concept.

1. INTRODUCTION

All over the world renewable energies are utilized increasingly for power production. As power from wind turbines or solar panels fluctuates, options for energy storage become more important. For the short term storage of electricity batteries are usually considered as favourite option. Currently, in Germany the installed storage capacity of stationary batteries amounts to about 4 GWh_{el} (Figgener et al. 2022). Until 2030 a more than twentyfold increase up to 100 GWh_{el} is expected (Wille-Haussmann et al. 2022). For the long term storage Ptx options like hydrogen or methane production, its storage and reconversion may play a significant role to balance the power supply (Brandes et al. 2021). Besides those options there are increasing research and development activities to use the underground for mechanical energy storage. The company Hydrostor (Hydrostor 2022) develops an advanced compressed air energy storage concept (A-CAES). Compressed air is stored in artificial caverns in the underground and later expanded through a turbine to generate electricity. Unlike to already existing CAES-facilities as in Huntorf, Germany (Donadei and Schneider 2022), the excess heat arising from compressing the air is extracted and stored in pools or stockpiles at the surface. The stored heat is then used for reheating the decompressed air while producing, and thus, increasing the overall efficiency. the company Quidnet pursues another concept for storing mechanical energy (Quidnet 2022). Water is stored in an artificial fracture in the underground. The fracture and the surrounded rock are compressed due to water injection and decompressed during flowback. Here the hydraulic energy of the pumps is stored as elastic mechanical energy in the rock surrounding the fracture.

In this paper experiments at the geothermal research well Horstberg are presented and discussed. These experiments were performed in order to investigate the potential of heat extraction from low permeable rock after fracturing. As a side effect they offer insights into the option of mechanical energy storage via large artificial fractures in overpressure reservoirs (Fig. 1). Based on the experiments in Horstberg this concept is further evaluated and aspects like energy efficiency, the improvement by multiple fracturing, the handling of the produced water and the comparison to battery storage are discussed.

[1] Throughout this paper the indices el, me and th are used for electric energy, mechanical energy and thermal energy, respectively.

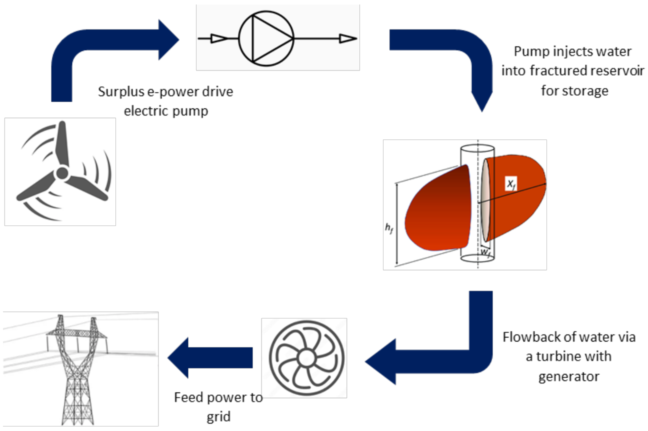

Figure 1: Illustration of the concept for storing excess power from wind turbines as mechanical energy in the artificially fractured underground and its reconversion to electricity.

2. STORAGE OF MECHANICAL ENERGY BY INJECTING WATER IN OVERPRESSURE RESERVOIRS

If water is injected in a permeable aquifer with hydrostatic pressure the pore pressure increases locally and after stopping and opening the well a certain amount of water will flow back without pumping. In overpressure reservoirs, where the pore pressure is significantly higher than the hydrostatic one, the full amount of injected water can be regained at an elevated wellhead pressure without pumping. Then, not only the total amount of water can be regained, but a significant part of the hydraulic energy used for injection may be regained too.

Figure 2 shows a generic example for water and energy storage in a highly conductive and overpressure aquifer. While injecting at a rate of 50 l/s, the pressure increases by about 50 bar. Similarly, the pressure drops by about 50 bar during flow back. In this example 62 % of the pump energy or 40 % of the electric energy can be regained if an efficiency of 80 % is assumed for the conversion of electricity to mechanical (pump) energy and vice versa. The colored areas below the pressure curve illustrate the amounts of mechanical energy. The electrical power for pumping is about 1,6 MW_{el} and therefore in the typical range for an onshore wind turbine, which produces power but cannot feed into the grid, temporarily.

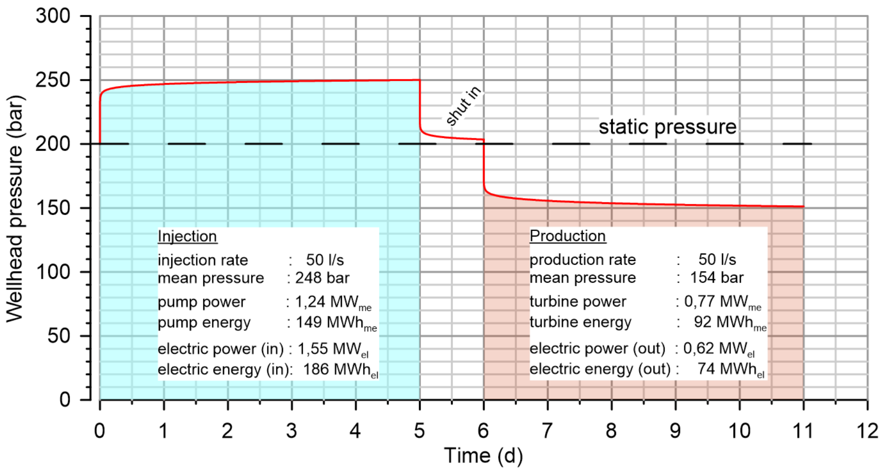

Figure 2: Pressure curve for the injection of water in an overpressure aquifer for five days at a rate of 50 l/s and succeeding flowback within five days at the same rate. Parameters: formation transmissivity: 10 Dm[2], porosity: 0,20; total compressibility: $1*10^{-9}$ Pa^{-1}; well radius: 0,011 m; wellbore storage: $3*10^{-8}$ m^3/Pa; dynamic fluid viscosity: $5*10^{-4}$ Pa*s, fluid density: 1,1 kg/l. The calculation was made with the software module "Saphir" as part of "Kappa workstation 5.40" (co. Kappaenegineering).

An essential precondition for this energy storage concept is, as for any kind of fluid storage in the underground, a high transmissivity of the target formation. But in general the permeability decreases with depth and aquifers with a transmissivity of some tens of Darcymeter are rare in the deep underground (Ehrenberg and Nadeau 2005). Nevertheless low permeable formations can also be used for storage. In this case large artificial fractures have to be created. These fractures can serve as pathways for the fluid flow and for the storage of water at elevated pressure.

[2] Dm: Darcymeter (1 Dm ≈ 10^{-12} m^3)

Another important, or even necessary precondition is a static overpressure in the reservoir. The higher the overpressure the more energy can be stored for the same volume of water. Reservoirs with overpressure are common in deep sedimentary basins (Osborne and Swarbrick 1997). This phenomenon is well known from the North Sea (Lindberg et al. 1980), from the Gulf of Mexico (Sathar and Jones 2016), from the Bavarian Foreland Molasse Basin (Drews et al. 2018), from the North German Basin (Nollet et al. 2005) and for many other regions in the world (Zhao et al. 2018). Different mechanisms for overpressure have been discussed. Disequilibrium compaction during the burial process in combination with a good sealing seems to be one of the most relevant factors (Osborne and Swarbrick 1997; Zhao et al. 2018).

3. TEST SITE HORSTBERG

The research well Horstberg Z1 is located some 80 km northeast of Hannover in Germany (Fig. 3). The stratigraphy of the abandoned gas well comprises sedimentary rock from the Quaternary at the top to the Permian Rotliegend at the bottom (Fig. 4). Before the start of geothermal investigations the gas bearing layers in the deepest part of the well were cemented and plugged. The accessible part of the well reaches down to 4120 m. The well is fully cased and almost vertical. More details about the well and the test site are provided elsewhere (Jung et al. 2005; Tischner et al. 2020).

Figure 3: Location of the well Horstberg in northern Germany.

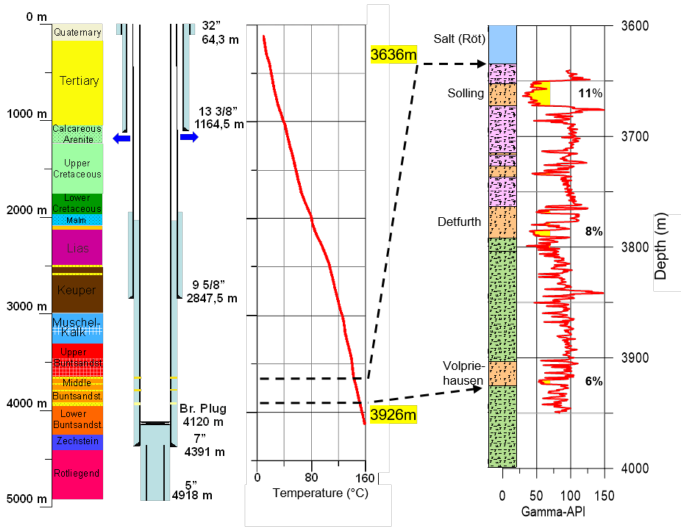

Figure 4: Stratigraphy, completion, temperature, lithology and gamma ray in the Middle Buntsandstein formation of the wellbore Horstberg. In the gamma ray log the sandstones are marked yellow and labeled with its porosities (cut-off: 70 API). The blue arrows indicate the reinjection zone via the annulus.

The target formation for hydraulic experiments and geothermal investigations is the Middle Buntsandstein formation between 3636 and 3926 m depth where the temperature reaches appr. 145°C. Here three sandstone layers in the sub formations Volpriehausen, Detfurth and Solling were investigated and tested. The thickness of these layers ranges from 5 m to 20 m. They were accessed by perforating the casing sections successively. Table 1 summarizes hydraulic parameters derived from tests in these intervals.

Table 1: Hydraulic properties of the sandstone layers in the Middle Buntsandstein based on hydraulic tests. The thickness is derived from the gamma-ray log (see Fig. 4) and the porosity from a sonic log. Dm: Darcymeter; mD: Millidarcy.

Middle Buntsandstein sub formation	Sandstone thickness (m)	Perforation interval (m)	Porosity	Transmissivity[3] (Dm)	Permeability (mD)
Solling	20	3.655 – 3.673	11	~0,3	~15
Detfurth	6	3.787 – 3.791	8	0,01-0,02	2-3
Volpriehausen	5	3.920 – 3.926	6	<0,001	<0,1

The productivity of the Volpriehausen sandstone is negligible because of its low permeability and an inefficient frac operation. No measureable venting flow rate was achieved from the Volpriehausen before and after a medium scale waterfrac test (Tischner et al. 2020). The Solling sandstone was perforated, but after the discussed tests here. Therefore, within the framework of this study only the perforation of the Detfurth sandstone was hydraulically active.

The Buntsandstein at Horstberg is an overpressure reservoir. Under equilibrium conditions and with the borehole filled with natural formation water (density: 1,25 kg/l) the wellhead pressure was about 140 bar. Therefore, by just opening the well the Detfurth was producing at a flowrate of appr. 1 l/s. The flowrate from the Detfurth increased drastically after a massive waterfrac test, even when the pressure dropped significantly below the static reservoir pressure (Tischner et al. 2020).

[3] Transmissivity means the product of permeability and thickness.

It is important to note that the produced formation water from the Buntsandstein could be reinjected and disposed in the calcareous arenite of the same well. The reinjection horizon at about 1.100 m depth is a sub formation of the Upper Cretaceous. Injection into this layer was possible via the annulus. This was a comfortable and cost efficient option to dispose of the formation water.

4. HYDRAULIC TESTS IN THE DETFURTH SANDSTONE

After determining productivity and pore pressure by a production test, a massive waterfrac operation was carried out in the Detfurth sandstone at about 3790 m depth. During the frac operation about 20.000 m³ of fresh water without additives were injected in three steps, interrupted by shut-in periods and a short production phase (Fig. 5). The mechanical pump energy needed for the frac operation was about 180 MWh_{me}. Details of the stimulation operation and about the fracture performance are given elsewhere (Jung et al. 2005; Orzol et al. 2005). Different approaches lead to a fracture area between 200.000 and 500.000 m² that was created during stimulation (Fig. 6). A significant part of the vertical fracture remained highly conductive even at a pressure significantly below the static pore pressure (Tischner et al. 2020). A very good hydraulic connection between the well and the fracture was observed. In particular, no closing of the fracture in the vicinity of the well occurred, which is often suspected for waterfracs in oil and gas wells.

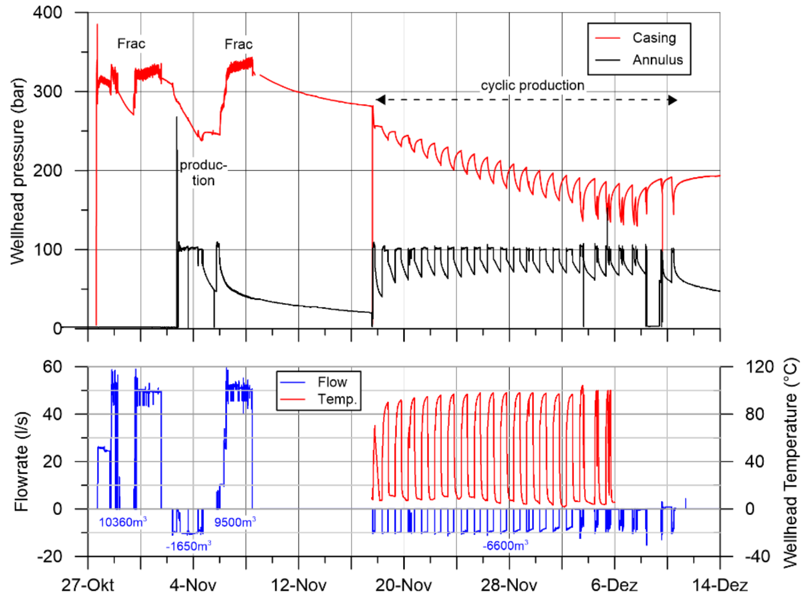

Figure 5: Pressure curves for the Detfurth stimulation and succeeding cyclic production tests in 2003. The wellhead pressure of the cased well (casing) and of the reinjection zone (annulus) are shown. In the lower graph the flowrate and the wellhead temperature are depicted. Negative (positive) rates mean injection (production), respectively. Freshwater at ambient temperature without additives was injected.

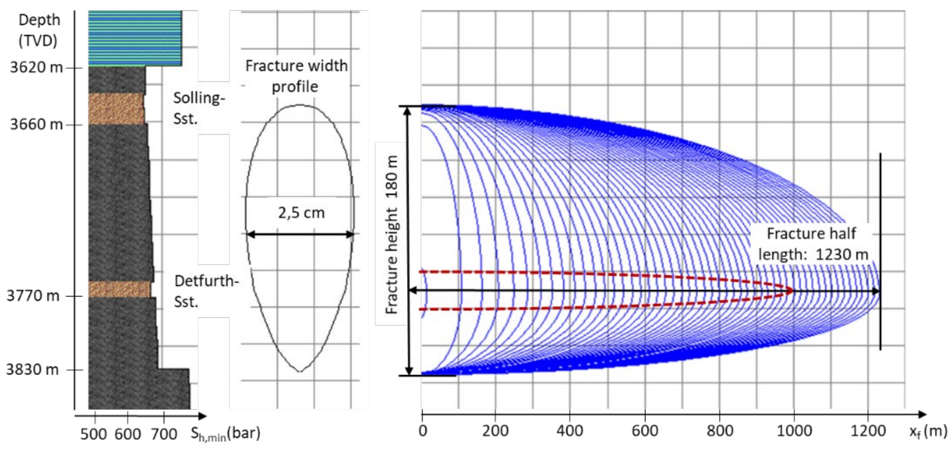

Figure 6: Calculated vertical fracture propagation for the stimulation in the Detfurth sandstone, using the software FIELDPRO™ (co. RESnet). The blue lines show the fracture front in time steps of two hours. The calculation was performed with an injection volume of 20.000 m³ at a rate of 50 l/s and for the minimum horizontal stress profile ($S_{h,min}$) depicted on the left hand side. The fracture width profile is shown for the end of stimulation. The dotted red ellipse symbolizes the area of persisting infinite conductive fracture. x_f: fracture half length.

After the frac operation and a nine days shut-in period a cyclic production test was commenced. Its main objective was to study the hydraulic performance of the created fracture at different pressure levels. As a side effect it provided information for the option of mechanical energy storage.

During the intermittent production test a total volume of about 6.600 m^3 of water was produced back from the fracture and directly reinjected via the annulus, into the calcareous arenite formation. During production the flowrate was stabilized at 10 l/s by adjusting a choke valve. Because of technical problems the test was terminated after 15 cycles. The wellhead pressure of about 190 bar measured at the end of the final shut-in period was close to the initial overpressure in the Detfurth sandstone and would have allowed to produce significantly more of the injected water. Hence, a significant fraction of the mechanical pump energy of about 180 MWh$_{me}$ needed for the frac operation could have been recovered if a turbine with generator would had been installed in the production line.

Another important test was performed in 2004 (Fig. 7). In this test about 2.600 m^3 of freshwater at ambient temperature were injected and produced back completely within five production periods. Again, the produced water was directly injected into the calcareous arenite formation via the annulus. This test provided valuable insights in the fracture performance at a pressure level significantly below the fracturing pressure (Tischner et al., 2020) and, besides, about the storage option. Diesel driven pumps were used for the injection. However, for evaluating the option of mechanical energy storage, it is assumed here that the pumps were electrically driven. On the production side it is assumed that a water turbine in combination with a generator converts the hydraulic energy of the flowback to electric energy. A conversion efficiency of 80 % was assumed for the conversion of electric to hydraulic energy and vice versa. This means the theoretical maximum for the storage efficiency is 64 % just due to the twofold energy conversion.

In the injection phase the pressure reached 320 bar, approximately the same value as in the frac operation, meaning some reopening and ballooning of the preexisting fracture. In the production periods the wellhead pressure dropped from about 290 bar at the beginning of the first production period to about 140 bar at the end of the last production phase (Fig. 7). Taking the averaged pressure and flow rate for each individual production period and applying the mentioned conversion efficiency, a fictive electric energy of 11 MWh$_{el}$ could have been regained (Tab. 2). This amounts to about 40 % of the electric energy needed for injection.

In the described test water with a mean density of 1,05 kg/l was produced (increasing from 1,0 kg/l to about 1,1 kg/l), whereas freshwater with a density of 1,0 kg/l was injected. In a realistic cyclic scheme the same water would be used repeatedly and the density of the injected and produced water would be the same. Correcting the injection pressure for the corresponding density effect, by assuming a density of 1,05 kg/l, the efficiency would be a few percent higher (see table 2).

During each production period the fluid temperature at the wellhead increased up to about 90°C, despite of the fact that 2600 m³ of water with a temperature of about 5°C had been injected a few days before (undisturbed reservoir temperature: 145°C). The amount of extracted thermal energy was 83 MWh refered to a reference temperature of 60°C (see table 2). From an economical and ecological point of view thermal energy should be used in combination with the storage scheme.

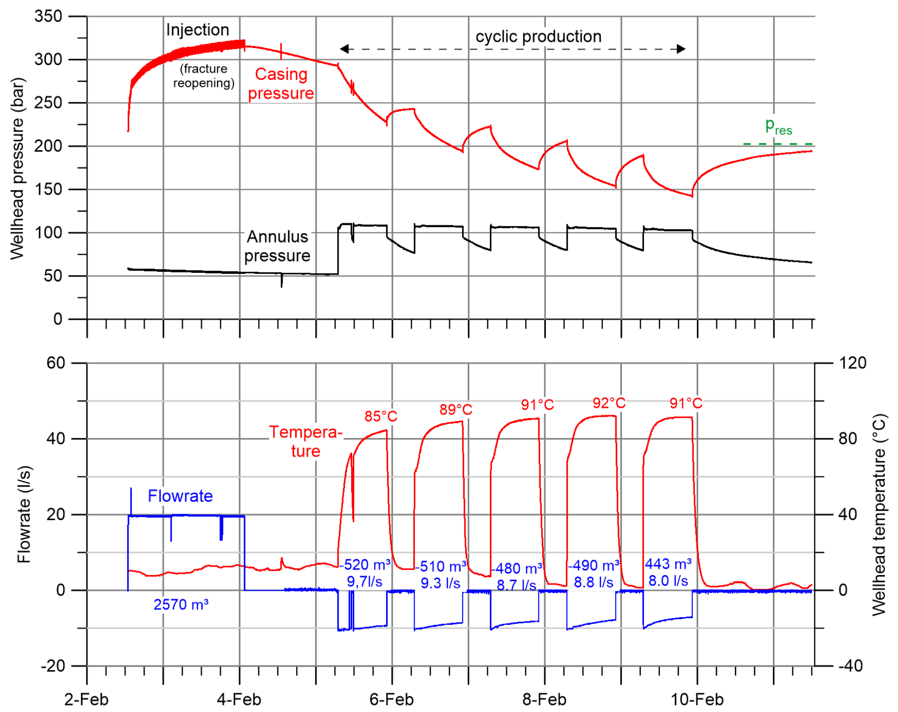

Figure 5: Pressure, flowrate and temperature for an injection test with freshwater followed by cyclic production in the Detfurth formation in 2004. The wellhead pressures of the cased well (casing) and of the reinjection zone (annulus) are shown. In the lower graph values are given for the injected/produced water volume and for the mean flowrate in each phase, as well as for the maximum wellhead temperature at the end of each phase. Negative (positive) rates mean injection (production), respectively. The static wellhead pressure for the produced water at a density of about 1,1 kg/l is indicated (green line)

Table 2: Energy balance for the test shown in figure 4. The values for electric energy are calculated ones. In the test diesel pumps were applied and no electricity was produced. The values in brackets are valid if water at a density of 1,05 kg/l would had been injected instead of freshwater (see text).

No.	Process	Energy (MWh)	Explanation
1	Injection, mechanical	-21,7 (-20,3)	Mechanical pump energy for the injection with 19,8 l/s for 36 h at an averaged pressure of 305 bar (285 bar); mechanical power: 604 kW_{me} (570 kW_{me})
2	Injection, electric	**-27,1 (-25,3)**	Potential electric energy needed for injection at an efficiency of transforming electric to hydraulic energy of 80%
3	Production, mechanical	13,4	Mechanical turbine energy of production (5 phases á 15 h at a rate of 8-10 l/s), based on the averaged values for flow and pressure for each individual production phase
4	Production, electric	**10,7**	Potential regain of electricity at an efficiency of transforming mechanical to electric energy of 80%
5	Thermal energy extraction	82,7	Potential gain of thermal energy in the five production periods based on an averaged flowrate of 9 l/s, a production temperature of 90°C and an assumed cooling to 60°C. Mean thermal power: 1,1 MW_{th}

4. THERMAL ENERGY EXTRACTION

The observations at Horstberg demonstrate that the thermal energy of the produced fluid is much higher than the mechanical energy recovered during flow back (Tab. 2). Therefore, it makes sense to combine the storage of mechanical energy with using the heat of the produced water. Numeric simulations were carried out in order to quantify the long term thermal output of the fracture in Horstberg according to the scheme that is shown in figure 7. Unlike to the performed cyclic test in which water at ambient temperature was injected, an injection temperature of 60°C was assumed here for simulation. In a practical operation a higher injection temperature of 60°C is more realistic and corresponds to the usual return temperature in heating networks. For more details about the numerical simulations see Sulzbacher and Jung (2010).

According to the simulations, the temperature of the produced water decreases slightly from about 105°C in the first cycle to about 90°C after 25 years of continuous cyclic operation (figure 10). Based on the temperature development and an assumed constant flow rate of 10 l/s while producing, the thermal output was calculated to 1,3 MW_{th} in the beginning and to about 0,8 MW_{th} after 25 years. The calculated thermal output is therefore a bit higher than the one in the performed test (Tab. 2).

But in the simulations the temperature was calculated at the fracture inlet whereas the values in table 2 refer to wellhead conditions. Including thermal losses along the wellbore, which could be reduced by technical means, there is a good agreement between the experimentally derived thermal output at the wellhead and the calculated one.

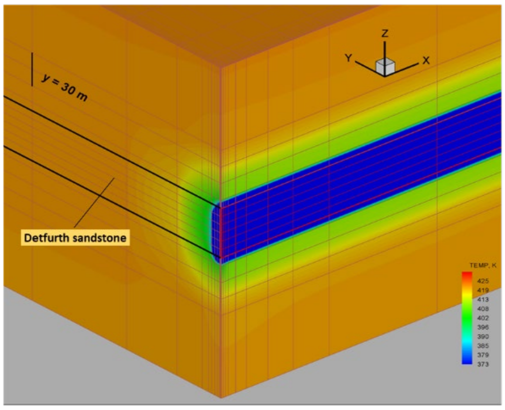

Figure 9: Geometry for numeric thermo-hydraulic simulations of a repeated cyclic injection and production scheme according to the schedule and flowrates in figure 7. The red framed area shows the infinite conductive fracture in the vicinity of the well. The temperature distribution after the first injection phase of the first cycle is shown. Figure modified after Sulzbacher and Jung (2010).

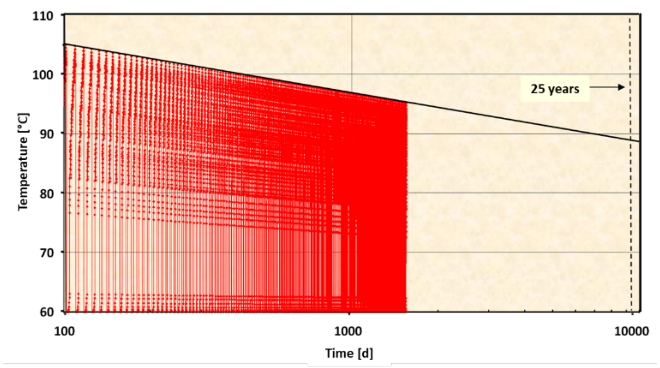

Figure 10: Temperature evolution at the fracture inlet in repeated cyclic injection and production tests according to the schedule and flowrates in figure 7 and based on the geometry shown in figure 9. Figure modified after Sulzbacher and Jung (2010)

5. MECHANICAL ENERGY STORAGE IN MULTIPLE FRACTURES

The capacity and efficiency of mechanical energy storage can be improved if multiple fractures are used. In a multiple fractured system and for an even distribution of the injected fluid the whole system behaves similar to a closed reservoir. During injection the fluid movement is restricted, and the energy is predominantly stored as elastic energy in the rock and in the water between the fractures. Figure 11 shows an example for a reservoir exploited with ten parallel fractures, on the bases of which efficiency calculations were made.

Table 3: Rock, well and fluid parameters for the calculation of mechanical energy storage via multiple fracs (figure 11).

Reservoir		Fractures		Well and fluid	
Boundaries	no (infinite acting)	Number of fractures	10	Static well head pressure	200 bar (at fluid density of 1,1 kg/l)
Thickness	20 m	Half length	500 m	Well radius	0,011 m
Transmissivity	0,03 Dm	Conductivity	infinite	Wellbore storage	$5*10^{-5}$ m³/Pa
Porosity	0,05	Lateral distance	200 m	Dynamic fluid viscosity (water)	$5*10^{-4}$ Pa*s
Total compressibility	$1*10^{-9}$ Pa^{-1}				

It is supposed that water is injected evenly in the fractures and later produced back again evenly. The rock, well and fluid parameters for the calculation are assumed according to data and test results at the well Horstberg (table 3). It has to be noted that after the frac operation in 2003 the reservoir height is larger than the thickness of the Detfurth sandstone alone, corresponding to a slightly higher transmissivity and a lower mean porosity. The calculations are purely hydraulic and were performed using the Software "Saphir" of co. Kappaengineering. To account for the fracture opening and ballooning a high apparent wellbore storage was assumed. But the wellbore storage has little impact on the pressure curve. In the frac operation 2003 a considerably higher wellbore storage (up to 10^{-3} m³/Pa) was derived (Jung et al. 2005).

The pressure curves for two different schedules but the same total volume (21.600 m³) are shown in figure 12. Due to the interaction between the fractures the pressure inclines almost linearly, like in a closed reservoir. During shut-in little fluid loss is observed and the pressure remains nearly constant. Thus, in this case the duration of the shut-in period is only little sensitive to the storage efficiency. While producing the pressure drops almost inversely to the incline before. Unlike to the pressure characteristics in an aquifer (see figure 2) the pressure does not drop significantly below the static wellhead pressure. Because of the linear and inverse pressure characteristics the mechanical storage efficiency is very high, see table 3. Under these conditions the efficiency for the storage of mechanical energy reaches about 90 %.

The overall efficiency from power to power almost reaches 60 % and is therefore about 20 % higher than in the cyclic test at Horstberg (table 2). Mainly, the conversion losses from power to mechanical energy and vice versa limit the overall efficiency.

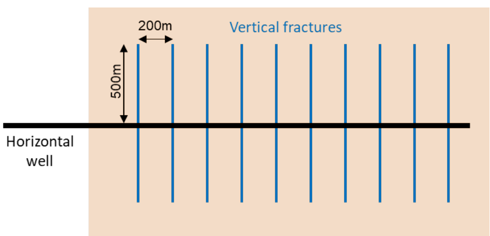

Figure 11: Improved storage concept: multiple fracs originating from a horizontal well section (top view).

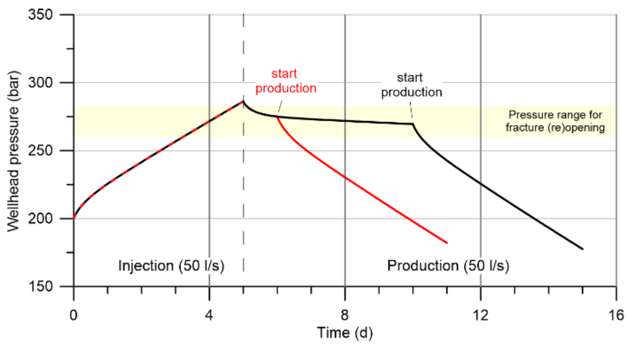

Figure 12: Wellhead pressure for the injection/production of 21.600 m³ (5 days á 50 l/s) of water in and out of a multiple fracture system - see figure 11. Calculations made fortwo different interim shut-in periods (red: 1 day; black: 5 days).

Table 3: Mean pressure p and mean mechanical power P_{me} for the injection and production phases in figure 12 as well as corresponding mechanical and electric energy (W_{me}, W_{el}). η_{me} and η_{el}: efficiency of storage related to mechanical and electric energy. Negative numbers mean production of energy.

phase/scenario	p (bar)	P_{me} (MW)	W_{me} (MWh)	W_{el} (MWh)	η_{me}	η_{el}
Injection	248,3	1,24	149,0	186,2		
Production (1d shut-in)	223,1	-1,12	-133,9	-107,1	0,90	0,58
Production (5d shut-in)	218,3	-1,09	-131,0	-104,8	0,88	0,56

6. DISCUSSION

The experiments at the test site Horstberg show, that significant amounts of mechanical energy can be stored in artificially fractured rock. The storage efficiency is essentially dependent on a large and highly conductive fracture. The fracture serves as pathway for the water from the borehole to the formation and simultaneously as water storage. In low permeable rock water injection at significant flowrates is only possible via a large and highly conductive fracture. The fracture opens and widens while injecting and its storage capacity increases. While producing the pressure decreases slowly due to the large fracture storage capacity, and the pressure does not significantly drop below the static reservoir pressure. During operation and due to cyclic injection of cool water the rock matrix around the fracture cools down and shrinks. As result of both mechanisms, the continuous operation at a high pressure level and the cooling of the formation, there are good chances that the conductivity of the fracture will be maintained or even improved during long term operation. In Horstberg, an infinite conductive fracture was observed even significantly below the static reservoir pressure. If limitations of the fracture conductivity occur, these will primarily arise in the near wellbore region due to tortuosity or twisted fracs, for instance, if the wellpath is not aligned properly in the stress field. However, there are technical means available (deep penetrating perforation, acid treatment,..) and good chances to overcome near wellbore restrictions, if those restrictions arise.

The larger the fracture is, the more water can be stored in the fracture and its close surrounding and the more efficient the storage is. Vice versa it means, that low permeable rock could be advantageous for this concept. In low permeable rock large fractures can be created at little water losses in the surrounding rock matrix. Further, overpressure reservoirs are preferable for this storage concept. The higher the static overpressure in the reservoir is, the more energy can be stored for the same amount of water. Beyond, a high static overpressure enables the complete back production of the injected water at elevated pressure and the optimal regain of energy. Overpressure reservoirs seem to be widespread in deep sedimentary basins (see chapter 2). At the test site Horstberg the static overpressure at the wellhead is 140 bar (230 bar) if natural formation water (fresh water) is in the wellbore.

By creating multiple fracs originating from a horizontal well the storage capacity and the storage efficiency can be increased significantly. The technologies for drilling horizontal wells and for creating multiple fracs are well established in the oil and gas sector. However, the fluid distribution between the different fracs might be a challenge. Even if the same stress conditions were encountered at all frac positions, there remains a serious risk that a single fracture takes almost all of the injected water. Hydromechanical investigations, testing and fluid distribution measurements are necessary in order to predict and to observe the fluid distribution between the fracs. Potentially, technical means like zonal isolation, sliding sleeves or casing patches shall be deployed for controlling the fluid distribution.

In practice, there are technical and geological limits for creating and operating fractures for storage. In particular, it has to be ensured that the fracture propagates only within predefined layers and does not interfere with other reservoirs or active faults. For that reason a seismic monitoring of the fracture propagation is desirable or even mandatory.

At the well Horstberg a massive waterfrac operation and several production and injection tests were carried out with only a few minor seismic signals being detected by a shallow seismic network (Orzol et al. 2005). Similarly, in the North German Basin the occurrence of noticeable seismic events in relation to frac operations or fluid injections is unknown. The geological structure of this basin, comprising thick sedimentary layers including clay and salt, seems to suppress the occurrence or propagation of seismic signals. Hence, in the North German Basis the seismic risk due to cyclic injection and production for mechanical energy storage is very low. On the other hand this means that for observing the frac propagation deep seismic observation wells in a short distance to the storage reservoir are necessary.

A limitation may arise due to friction along the wellbore. In a deep well fully cased with a 7” casing, as in Horstberg, a flow rate of 50 l/s generates a pressure drop of about ten bar along the borehole length of about 3800 m. A significantly higher pressure drop is likely not acceptable and hence, the storage power (pump power) is limited to about 1 MW_{me}. Higher flowrates require a larger borehole diameter. For example, for otherwise similar conditions as in Horstberg, but a 9 5/8” casing, flow rates of more than 100 l/s would be acceptable.

Water that is produced out of the deep fractured underground contains salts, dissolved solids and dissolved gases. In Horstberg water with a salinity of more than 50 g/l was produced a short time after the freshwater injection in the cyclic tests. If saline water gets in contact to the atmosphere at surface, scales of iron oxides and other minerals can form. Reinjection of water containing scales can cause serious hydraulic problems due to clogging at the fracture inlet or in the reservoir. Therefore, the interim storage of the produced saline water in contact to the atmosphere requires additional means for filtering and treating before reinjection. An option to avoid scaling problems could be the storage in closed tanks at surface under a protective gas atmosphere (nitrogen). A third option would be the storage of the produced water in a shallow permeable aquifer of a second well. Those storage aquifers must be significantly deeper than aquifers used for drinking water. At the test site Horstberg potential storage aquifers below drinking water reservoirs occur at the depths of about 400 m (Neuengammer sand), 600 m (Brussel sand) and at about 1.100 m (calcareous arenite). For large areas of the Northern German Basin aquifers that could potentially be used for the storage of the produced saline water are known. If the water is stored in the underground, the storage capacity is not limited by place or tank volume. Besides, the contact to the atmosphere can be excluded, reducing the risk of scale formation. On the other hand storing of water in the underground leads to additional pressure and energy losses due to the injection in and production out of the aquifer. The decision about the most suitable method for the interim storing of the produced water should be made site-specific, balancing the relevant geochemical, technical and financial aspects.

The temperature of the produced water in the cyclic tests of Horstberg reached more than 90°C, although freshwater at a temperature of about 5°C was injected shortly before. These results and the corresponding numerical simulations reveal that the thermal energy potential can be higher than the mechanical energy potential. The utilization of the accompanying heat potential is therefore important, but leads to a spatial restriction of potential project sites. Heat generation has to take place close to customers and heating grids, that means in general close to urban areas.

Heat generation in parallel to mechanical energy storage could cause another difficulty. Heat can be extracted only when water is produced and, at the same time, power is generated. But the demands for heat supply and for power production usually differ in time. To decouple both applications timewise, the storage of heat could be an option. If a shallow aquifer is used for the interim storage of the produced water, this aquifer is heated up due to the injection of the warm/hot water. By drilling another well into the warmed area of this shallow aquifer, heat can be extracted out of this well when heat is required, independently on power generation.

The proposed conversion of electric energy and its storage as mechanical energy in the underground has to compete with other storage options, mainly with battery storage, which is currently in the focus of energy suppliers.

The system efficiency of modern battery storages can be higher than 90 % (Zablocki 2019). Compared to that, the maximum efficiency of the fracture storage is lower, but may reach about 60 % (table 3) which is in turn considerably higher than the about 30 % of a power to power cycle using hydrogen or methane as chemical storage medium (Ausfelder et al. 2015). The capacity of large battery storages is in the range of some 100 MWh_{el} (VDI 2021) and thereby in the same range as potential fracture storage systems, see table 3.

The advantages of fracture storing could be the costs and its independence on valuable raw materials. The investment costs for batteries are in the range of 200 USD/kWh (George 2020; Schmidt et al. 2017). Accordingly, a battery storage facility with a capacity of 100 MWh_{el} demands about 20 Mio. USD of investment. If, on the other hand, an abundant deep gas well will be recompleted and fractured for storage some 5-10 Mio. USD of investment seems to be sufficient, including surface equipment and a shallow well for water storage. Moreover, fracture storage relies only on local resources and is almost independent on the import of valuable or critical raw materials (Li, Co, Ni,..), a great advantage, but hardly quantifiable.

The northern part of Germany is a focus region for the expansion of wind energy. Here, many new wind parks are under construction or in the planning phase. New power transmission lines have been built for transporting the power to the south and the need for power storage close to its generation increases. In parts of North Germany mature or abandoned gas fields exist. Their wells could get a second life and could be reused for fracture storage at moderate costs. Finally, deep overpressure formations are known in parts of the North German Basin. These four points: wind energy expansion, increasing need for power storage, existence of old or abandoned deep wells and occurrence of overpressure reservoirs are good arguments for the development of this fracture storage concept in the northern part of Germany.

7. CONCLUSION

The results from test site Horstberg and the presented further investigations indicate that the storage of mechanical energy via the injection of water in artificially fractured rock could be a promissing option for energy storage in the underground. It could be competitive or complementary to other storage options like battery storage.

As for any new technology experiences have to be collected in practice. A good starting point to demonstrate this concept would be the secondary use of an already existing deep well. Then, first experiences can be gained at moderate investment costs. Low permeable and overpressure formations should be the target for storage. In deep sedimentary basins, like the North German Basin, natural overpressure as well as low permeable rock are widespread. Those regions could be well suited for demonstrating this storage concept.

The thermal utilisation of the cyclically produced hot water, in parallel to energy storage, would be an additional benefit. However, this would mean that potential project sites should be located close to a heating grid and customers.

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