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Interdisciplinary Review of Medium-deep Aquifer Thermal Energy Storage in North Germany

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Abstract

High Temperature Aquifer Thermal Energy Storage (HT-ATES) has developed from a demonstration stage to a mature technology over the past decades. The specific storage capacity costs are lower by a factor of 20 compared to above-ground storage systems. Depending on geology, system configuration and temperature level, medium deep aquifers (approx. 400 m – 1,000 m) enable seasonal heat storage from 1 GWh/a up to 100 GWh/a. Typical heat recovery factors are in between 60 – 80 %. However, only three systems have been built and reached normal operation in Europe. Moreover, although substantial parts of the subsurface in Germany, for example, are suitable for ATES systems, over 10 years have passed since the most recent project has been put into operation.

Despite substantial advantages and a great potential of bridging the gap between constant production and seasonally varying demand, ATES is quite complex and conditional. Critical hydro-geological conditions (e.g. permeability, porosity, mineralisation) as well as relevant ordinances and regulations from the mining and local water authorities should be complied with. In addition, geothermal projects are not always supported by public acceptance as drilling boreholes today is a sensitive and emotional topic.

This contribution deals with an interdisciplinary approach to evaluate all parameters (geology, legal classification, public acceptance, water chemistry, applications/revenue models and drilling technology) affecting a cost-effective operation of ATES systems in North Germany. One main objective is to identify possible locations for ATES in the North German Basin and to derive generalizable success factors. Preliminary results and an overview of the project supported by the Federal Ministry of Economic

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Keywords: Aquifer Thermal Energy Storage (ATES); medium-deep; geological-technical-economic potential

1. Introduction

In order to achieve the policy targets set for the German energy sector, major research and development endeavors are needed, especially in the heating sector due to its large share of end use of energy with 40%. Heat storage is an essential technology with regard to the coupling of electricity and heating sectors since it is not only used to store heat temporarily, but also to reduce conventional peak load, increase the share of renewable heat, and/or enables to make the electricity system more flexible, e.g. through power-to-heat (P2H) concepts.

Aquifer Thermal Energy Storage (ATES) is a relatively low-cost technology for seasonal heat storage compared with other thermal energy storage technologies. The research project described in this paper focuses on medium-deep high-temperature aquifer storage, i.e. around 400m to 1,000m deep [1] and with injection temperatures of 50° C and above. Advantages compared with shallow ATES systems are higher storage and use temperatures and hardly any negative effects on drinking water reservoirs if works, esp. drilling, are done properly. Despite of these positive characteristics, there are only few cases internationally, mostly experimental and demonstration projects. In Germany, there are two projects which have been realized and are still running (Neubrandenburg, Reichstag). Four other projects are in different stages of development: in Berlin (TU campus), Dingolfing (BMW), Hamburg, and Lüneburg (Leuphana campus) (see Table 1a). Internationally, the picture is not that much different (see Table 1b): In the Netherlands, there are many shallow ATES systems, but only few HT ATES plants. Projects in Utrecht and Zwammerdam near Gouda have been closed. Other projects, it seems, have not been gone beyond the state of feasibility studies. The same can be said about the state of HT ATES in other countries. However, it seems that interest in the technology is growing again as an ongoing survey among national associations shows.

Table 1: Overview of medium-deep high temperature aquifer energy storage.

(a) Germany

Project name	Neubrandenburg	Reichstag	BMW	Campus Leuphana	TU Berlin	Hamburg
Location	Neubrandenburg	Berlin	Dingolfing	Lüneburg	Berlin	Hamburg
Implementation date	2004	2000	planned	planned	planned	planned
Project status	in operation	in operation	planned	planned	planned	planned
Depth [m]	1,250	320	500-700	400-450	560	300-390
Rock formation	Upper Postera sandstone	Hettangian sandstone	Lower Bavarian Malm	Upper Eocene (Tertiary)	-	Tertiary
Storage capacity [MWh]	12.000	-	115,000	10,000 (Doublet)	<= 50,000	-
Natural temperature thermal water [°C]	55	19	-	20-25	-	16
Heat extraction [MWh/a]	7,000	2,050	22,700	>1,700	-	25,121
Extraction temperature [°C]	75-80	30-65	-	25-80	5-90	68
Heat injection [MWh/a]	8,000	2,650	25,200	>3,000	-	31,150
Injection temperature [°C]	85-90	70	130	85-90	-	80

Source: Own compilation.

(b) International

Year	Location/Project Name	Status	Heat Source	(max.) Temperature	Depth
1976	Auburn University, Mobile/AL, USA	E/c	Hot wastewater from power plant	55° C	40 m - 61 m
1982	SPEOS, Lausanne-Dorigny, Switzerland	c	Wastewater treatment	69° C	
1982	Hørsholm, Denmark	D/c	Waste combustion	100° C	10 m
1982	University of Minnesota, St. Paul, USA	E/c		115° C (150° C)	180 m – 240 m
1987	Plaisir, Thiverval-Grignon, France	E/c		180° C	500 m
1991	De Uithof, Universiteit Utrecht, Netherlands	D/c	Combined heat and power	90° C	4 m – 45 m
1998	Hooge Burch, Zwammerdam near Gouda, Netherlands	D/c	Combined heat and power	90° C	
1999	Reichstag, Berlin, Germany	D/iO	Combined heat and power	70° C	300 m
2004	Neubrandenburg, Germany	iO	Combined heat and power	75° C-80° C	1,250 m
2015	Duiven, Netherlands	fs	Waste combustion	>140° C	

c: closed, D: demonstration project, E: explorative project, fs: feasibility study, iO: in operation

Source: Own compilation, partly based on [2].

Against this background, Leuphana University of Lüneburg and GeoDienste GmbH together with GeoEnergy Celle e.V. conduct a research project. The interdisciplinary research team

- Analyzes the geological-technical-economic potential of HT ATES in Northern Germany, defined here geologically as North German Basin.
- Develops a roadmap for research and development.
- Derives recommendations for support policies, especially potential locations for demonstration projects.

2. Identification of suitable storage aquifers

2.1. Significant reservoir characteristics

In order to identify "suitable" thermal energy storage aquifers in a medium-deep range of 400 - 1,000 m, information of detailed formational depth and related temperature levels as well as knowledge of the reservoir's lithology is indispensable. To achieve an economic operation of ATES systems, i.e. a high recovery efficiency (ratio of extracted to stored heat energy), certain requirements will have to be satisfied according to temperature differences and geo-hydraulic properties. Of particular significance seems the transmissibility, which is a product of permeability (the reservoir's hydraulic conductivity) and reservoir thickness.

In general, suitable hydrothermal reservoirs are defined by a minimum thickness of 20 m, a minimum permeability of 250 to 500 mD and an effective porosity of at least 20% [3,4]. Experience has shown – when meeting the above mentioned requirements – circulation rates can be achieved that allow an economically feasible heat extraction.

In case of ATES systems, these constraints have a particular significance with respect to the achievable storage and extraction rates, too. On the other hand, the permeability, in particular, should not be too high in comparison to a development designed exclusively for heat extraction with no storage phase. As already demonstrated by numerical modeling, an exceptionally high permeability has a counterproductive effect on the recoverability of the stored heat [5]. Excessively high reservoir permeability may result in an unwanted rapid dislodgment of the stored heat due to free convection (unhindered buoyancy flow), so that only fractions of it can be recovered during the extraction phase.

Additionally, high differences in stored temperatures and subsurface reservoir temperatures would have a negative effect on the recovery efficiency and sustainability due to thermal dispersion as well.

2.2. Identification process

For the identification of suitable ATES horizons, area- and depth-discriminated data for Northern Germany from already existing cartography and archive data are used (Fig. 1). Within the scope of the presented project the "Information system of reservoir rocks in Germany" [6], GeotIS (geothermal information system for Germany [7]) and structural compendia such as the "Geotectonic Atlas of Northwest Germany" [8] and "Structure of Northeast Germany" [9] are particularly noteworthy. These information systems already enable conclusions on a regional to local scale regarding depth and reservoir temperatures.

In addition, we will have to estimate and, where possible, appoint geo-hydraulic parameters using literature data (e.g. residual thickness and lithological facies maps) as well as borehole data (bore logs, geophysical logs and in situ tests. However, up to now it is still unsettled how very meaningful but confidential data of the petroleum industry could be incorporated in this study. Maybe some of these borehole data may be used partly anonymized.

By means of an iterative feedback approach, long-term storage/extraction scenarios for different temperature levels will be simulated with numerical modeling software package FEFLOW (Figure 1). Model boundary conditions are limited by the previously identified variability of geo-hydraulic characteristics and possible supply structures. Feedback from the numerical simulations should elucidate which general framework promises the highest possible recovery efficiency for the medium-deep storage horizons of Northern Germany in question.

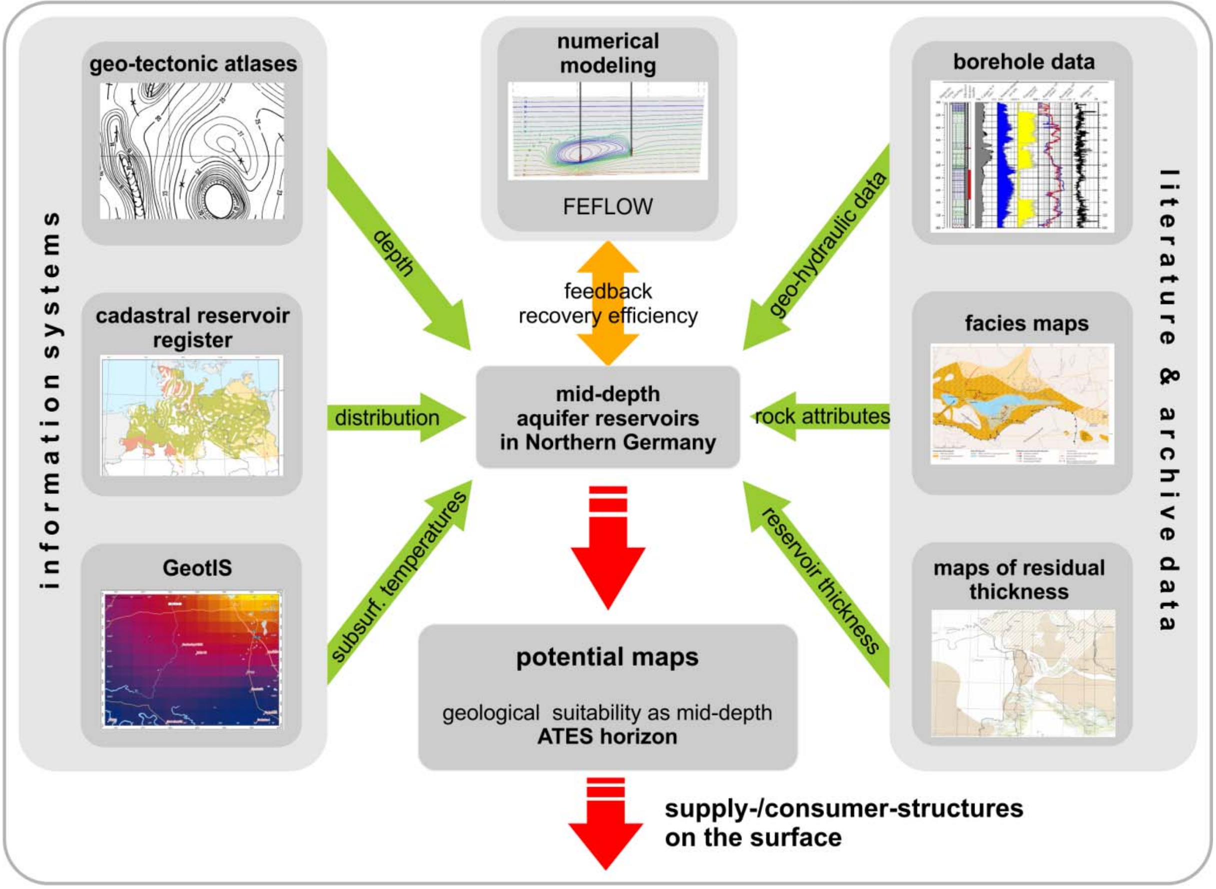

Figure 1: ***Identification process to determine the most suitable thermal energy storage aquifers in Northern Germany.***

2.3. Outlook

As a result, the applicability of the geological subsurface as well as the recovery efficiency for medium-deep storage aquifers will be presented area-differentiated in a GIS-based environment preferably as so-called potential maps. Therefore different storage temperatures and rates have to be categorized and implemented in the feedback process. This requires a thorough research for possible surplus heat supply and consumer structures.

3. Legal and Legally Relevant Chemical and Public Participation Issues

3.1. Relevant fields of law

While the geology determines the physical potential for underground storage in specific locations, the legal framework restricts activities in certain areas, has an impact on project costs and determines the remuneration to a large extent. There are several legal fields which are relevant for ATES projects in the planning and building phases and during operation:

- Regional planning legislation is generally applicable for underground uses [10-13; different opinion: 14], even if it has been developed for different applications. This legal field is currently under development and may gain more prominence in the future due to the diffusion of heat pumps and other underground uses.
- Mining and water laws are the most relevant fields during the planning and building phases and will be discussed in more detail below. Regulatory approval affects other fields like immission, conservation, and soil protection law. In addition, developers have to adhere to requirements from building law and waste legislation. Certain risks may arise from public participation for which see sub-section 3.4.
- Remuneration is to a large extend determined by regulations, i.e. energy law (see 4.3). In addition, liability issues may play a role during building or in the operation phase.

3.2. Mining and water laws

The mining and water laws play the biggest role when an ATES project is realized. The Federal Mining Act adjusts the raw material extraction and drills into the soil. It adjusts for example the exploration, the extraction and the treatment of freehold resources and freely mineable resources. The question is whether ATES projects extract resources or not. Water is not a resource (sec. 3(1) Federal Mining Act, BBergG) but geothermal heat and the other energy sources generated during its extraction shall be deemed freely mineable resources (sec. 3(3) BBergG). This includes also the geothermal energy of the water. One requirement is that the geothermal heat is a natural occurrence [15]. The question is whether geothermal heat of natural occurrence is used or not. The affirmation of the existence of a resource leads to the need of mining authorizations. An exploration license is required for exploring freely mineable resources, and an extraction license or mining proprietorship is required for extracting freely mineable resources (sec. 6 BBergG). On the other side drilling holes which exceed 100 meters in depth require a notification and the authority in charge decides whether an operation plan is necessary or not (sec. 127(1) BBergG). An underground storage site means an installation for subterranean, containerless storage of gases, fluids and solid matter, with the exception of water (sec. 4(9) BBergG). The geothermal heat itself is not covered by this regulation.

For the use of water the Federal Water Act requires a permit or an approval. An approval gives the owner a stronger legal position but you cannot get it for every type of usage. It is more difficult for the authority to revoke an approval (only because of the reasons named in sec. 49(2) no. 2-5 Administrative Procedure Act, VerwVerfG). Introducing substances into waters is a usage which needs a permit (sec. 9(1) no. 4 Federal Water Act, WHG). Otherwise, drillings could be measures that tend to cause harmful changes to the physical, chemical or biological properties of the water, either permanently or to an extent that is not merely inconsiderable (sec. 9(2) no. 2 WHG). Therefore, a permit is necessary as well. Withdrawing groundwater or pumping to the surface needs a permit or an approval (sec. 9(1) no. 5 WHG). During the warming of the water it could be necessary to use inhibitors. In this case you need a permit for introducing substances into the water (sec. 9(1) no. 4 WHG). After the warming of the water it has to go back into the ground. This could be seen as discharging groundwater or guiding to the surface, then a permit or an approval would be necessary (sec. 9(5) no. 4 WHG). But it could be also be seen as introducing substances into waters; in this case a permit is necessary. For the legal admissibility it matters whether it is expected that the usages cause harmful changes for the waters which are not compensable or avoidable with terms and conditions or not (sec. 12(1) no. 1 WHG). Thereby the authority has a scope of discretion. In case of the duty to submit an operation plan, the competent mining law authority decides on the grant of a permit in consultation with the competent water law authority.

Overall, two issues arise at the intersection of legal requirements and economic feasibility which will be further analyzed through interviews with authorities: the choice of procedure – where operators have a choice – or the practice of mining law authorities and the interaction of mining and water law authorities. First discussions have shown that the administrative practice differs significantly between the federal states, partly depending on the relative sensibility of groundwater issues in certain areas.

3.3. Legally and ecologically relevant water chemical and microbiological aspects

From a legal perspective, aquifer thermal energy storage often is only possible if there are no adverse effects on otherwise used water resources. Specific adverse ecological effects of medium-deep ATES are not known so far. Monitoring data exists for example from ten years of operation of an aquifer heat storage installation located in Berlin. Bacterial community changes (however reversible), total cell counts, live cells counts and indicators like total inorganic and organic carbon and nitrogen species show low variability. PH and conductivity also do not change significantly, so do the very low heavy metal concentrations present [22].

In principle, possible thermal or chemical influences on resources that are connected to vegetation or surface ecosystems or used for drinking water production should be excluded. For medium-deep ATES, there is only negligible thermal influence on shallow groundwater bodies and the root zone of surface ecosystems. However, corrosion and clogging may play a role and are significant with respect to costs and stable operation (see 4.2.). During drilling and completion of the wells, state-of-the-art techniques have to be employed to avoid mixing with shallow groundwater layers. Thus, tightness of the wells has to be checked and approved. Chemical alteration must be avoided during drilling and by adequate well construction. Furthermore, liquid and solid wastes containing high salt and heavy metal concentrations must be adequately collected in a sludge pit and disposed of properly.

Following these guidelines, ATES does not have ecologically adverse effects. Temporal changes of microbial communities and water chemistry due to changes in temperature and traces of oxygen may occur, but due to limiting oxygen and organic matter availability, usually no significant growth of pathogenic microorganisms is possible. Also, during monitoring of aquifer storage installations, for example in Berlin, concentrations of heavy metals and other possibly polluting substances did not change in ten years of operation.

3.4. Public participation and social acceptance

Finally, formal requirements with regard to public participation may be of importance in the planning phase. In this area, legal prescriptions, considerations from political science (participation), and social acceptance meet. In the following, we restrict our description mainly to findings with regard to the latter field.

In some circumstances, environmental impact assessments are required (UVPG, UVP-V Bergbau) which include formal processes of public participation. From a legal systematic perspective, public participation for larger-scale projects like HT ATES systems seems to be desirable. Similar conclusions can be drawn from (normative) democracy theory. However, it constitutes a risk for project developers: Formal processes may lead to delays or even put the whole project at risk. This indicates that there is a tension between changing legal requirements and project developers' demands. But even if no public participation is legally required, these problems may arise in case there is a lack of social acceptance.

Public reactions to infrastructure projects have been a subject of intensive research going from description of and explanations for the so-called NIMBY ('not in my backyard') effect, over more differentiated analyzes of factors influencing social acceptance to literature on social conflicts arising in the context of technology development. Problems with social acceptance have been reported especially from southern Germany following cases of induced seismicity in Basel and Landau, less so from Northern Germany. Research has shown that deep and shallow geothermal energy, hydraulic fracturing ("fracking"), Carbon Capture and Storage (CCS), or mining inspire "primordial fears" in people living next to the plants [16,17]. It is highly likely that these fears will be transferred to ATES projects even if this may be technically unjustified. Therefore, communication strategies should not only include knowledge transfer, as they often do, but also consider the diverse publicities [18].

4. Identification of economically viable solutions

Besides the identification of suitable geological formations and analysis of the legal framing of HT ATES projects, the project team discusses the decisive factors for arriving at economically viable solutions. Even if a project is financially supported by the state or a local government, these subsidies should be minimized. Therefore, it is essential to identify economically efficient and effective solutions. Due to the large share of costs related to drilling, the selection of appropriate drilling technologies and their development plays an important role (see 4.1). Besides, there are several water chemical and microbiological (see 4.2) and legal issues (see 4.3) to be taken account for, and the suitability of a location from an economic point of view highly depends on the presence of an appropriate heat supply and demand (see 4.4).

4.1. Selection of the drilling technique

ATES are open systems. Thus, the storage is naturally given. As a result, there are no costs for the plant itself beyond the above-ground installations and the drill hole (including pumps). Therefore, costs for drilling make up a major part of overall costs for HT ATES projects. The selection of the optimal drilling technology depends on geological depth, characteristics of the layers above the reservoir horizon, and necessary diameter of casings. Generally, different drilling methods are suitable for the relevant depth of 400 m to 1,000 m – from air lifting over wireline coring to rotary drilling.

Intermediate conductor pipes and their cementations have to be included in the planning process in order to minimize problems during the drilling process like sloughing or hollowing and resulting stiff drill strings. Completion elements have to be dimensioned according to local conditions regarding temperature, pressure, corrosion and leak-tightness. This includes filters, blocking installations, and wellhead completion. For the drilling depths analyzed here, tired mobile drilling rigs or fixed constructions can be used. Usually, the latter are more expensive than the former. However, fixed installations may be required by some authorities. In addition, differences in the effectiveness of the drilling process have to be considered in the decision for mobile vs. fixed drilling rigs.

4.2. Cost-related chemical and microbiological aspects

Generally, corrosion and scaling processes are more relevant technically than ecologically. They are frequently observed in geothermal and aquifer storage wells and above-ground installations. Deep groundwater layers often show high salinity which needs to be considered during selection of construction materials to prevent corrosion. Alterations in pressure and temperature leads to solution and precipitation of different minerals, predominantly calcium carbonate (calcite and aragonite) and iron minerals. Calcite scaling mainly occurs in the warm well and at hot heat exchanger surfaces due to its lower solubility at elevated temperature and is often limiting maximum injection temperatures, which have to be determined during planning by water chemical modelling. It can also occur due to degassing of carbon dioxide, e.g. due to pressure changes.

To prevent gas exchange with the atmosphere, the wells are kept pressurized under nitrogen. Filters in the above-ground installation are used to retreat fine sand and clay fractions as well as precipitating mineral particles. However, traces of entering oxygen will often lead to iron precipitation and reduction of injectivity and productivity of both warm and cold wells.

Microbial processes can also influence the occurrence of calcium carbonate and iron scales, but their influence on the sulfur redox cycle is far more important. Sulfate reducing as well as sulfur oxidizing bacteria (SRB and SOB) may also reduce injectivity and productivity of wells, but may further lead to microbial corrosion (MIC). MIC involves several processes: At lower pH, hydrogen from abiotic corrosion of steel may be used by SRB, thus promoting corrosion at the cathode. Furthermore, sulfide may react with ferric iron to form elemental sulfur, which is extremely corrosive also for stainless steels, and acts like a catalyst [19,20]. Biofilms, which can accumulate nutrients, act like a protective layer and "home" of a diverse microbial community, the pH may be reduced and thus enhanced corrosion may occur. This is even more pronounced if SOB oxidize sulfide and produce sulfuric acid, for which they can use traces of oxygen entering the system, or nitrate [21].

SRB can strive completely without oxygen, but like SOB and biofilm-forming bacteria they need organic material, as they are heterothrophic organisms. Middle-deep aquifer waters are normally very low on organic matter and other nutrients, which will limit their growth. However, there are several cases where SRB developed in aquifer thermal energy storage installations [21,22]. Different theories exist how organic matter could be provided for SRB growth in middle-deep aquifer groundwaters. Basically there are two possibilities: More or less "fossil" organic matter is mobilized from the sediment due to increased temperature [21], or primary production of organic matter takes place by autotrophic bacteria, for example the iron oxidizing and carbon dioxide assimilating *Gallionella ferruginea*. *Gallionella* spp. can use traces of oxygen (in the ppb range), live at very low nutrient concentrations and produce highly bioavailable organic carbon [23]. The primary production of *Gallionella* biomass however is very slow, but after years of operation enough biomass may accumulate to form a basis for the development of biofilms, SRB and SOB and thus lead to MIC and other problems like reduced filter lifetimes and reduced injectivity and productivity of the wells [19,22].

There are different methods for the regeneration and cleaning of wells, however not all of them are always effective [21]. A focus should be put on preventive measures. As these problems may develop during operation and, unlike abiotic processes, cannot be modelled and anticipated during planning, monitoring of the water quality is needed to enable early countermeasures and thus reduce costs. A continuous monitoring of pH, redox potential, conductivity, dissolved oxygen and temperature can be used to monitor ferrous iron activity, buildup of ferric iron scales and SRB activity [22].

4.3. Energy law aspects

Within the energy law framework, specific regulations could arise regarding financial support. These affect in particular the combination of aquifer heat storage tanks with combined heat and power plants (CHPs), in this case with a block heat power plant. The latter is regulated in sec. 1, 2 no. 14 of the cogeneration bill (KWKG) and is therefore considered to be a CHP. The subsidies for cogeneration are defined in sec. 6 KWKG which also contains guidelines for plants that are not supplying the public utility infrastructure with power. The individual rebate is regulated in sec. 7 KWKG and depends on the respective CHP's percentage of power output. It varies from 3.1 to 8 cents/kWh.

The duration of the subsidy payment is dependent on various criteria as regulated in sec. 8 KWKG:

- Firstly, it is taken into consideration whether the CHP is new, modernized or retrofitted.
- Secondly, the plants are distinguished according to their percentage of combined heat and power output.
- Lastly, it is discriminated between their full load hours.

A special directive can be found in sec. 9 KWKG for new CHPs with an electric cogeneration output of up to 2 kW.

It is a moot point whether the aquifer is considered to be a heat accumulator as defined in sec. 22, 23 KWKG. According to sec. 2 no. 33 KWKG, the heat accumulator has to be a technical appliance that is able to temporarily store available heat and which includes all technical mechanisms for charging and discharging. Strictly speaking, the aquifer itself is not ‚technical'; however, the mechanisms for charging and discharging are. Its classification therefore needs clarification to enable the possibility of funding.

Further eligibilities for financial support exist according to electricity taxation law. Up until a nominated output of 2 MW, CHPs are exempt from paying electricity tax which is usually as high as 2.05 cents/kWh (sec. 9 StromStG). This applies to every kWh of electricity that is used in proximity – either in own consumption or delivered to nearby properties.

According to sec. 53a of the energy tax law (EnergieStG) it is also possible to receive a full exemption from paying any energy tax if:

1. the plant is highly efficient in accordance with Appendix III of Guideline 2004/8EG and any following updates and
2. the degree of capacity for the relief period amounts to a minimum of 70%.

However, the full tax relief is only granted for the period during which the CHP is being written off in accordance with specifications of sec. 7 income tax law (EStG).

It is uncertain whether in addition to the CHP the aquifer is also included. There is furthermore the possibility of an energy tax refund with regard to the acquisition of fuel (natural gas 0.55 cents/kWh, liquid gas 6.06 cents/kg, light fuel oil 6.135 cents/l).

4.4. Heat supply and demand

Besides the analysis of drilling technology and processes, chemical problems and their solutions, and legal aspects that influence the projects' cash flows, the economic viability calculations are based on the analysis of suitable applications, i.e. adequate heat sources (heat supply) and heat sinks (heat demand). We suppose that locations where industrial waste heat can be stored seasonally without any or with only minor investments and later fed into an existing heating grid provide for favorable preconditions for HT ATES projects. It has to be examined in every case for concrete local conditions if the level of temperature suffices for the use in industrial processes or existing district heating grids for the supply of private households. The combination of HT ATES with existing CHP power plants is known from cases like Neubrandenburg. CHP units can either be better used to capacity or used for power-driven operation (instead of heat-driven operation). Besides, heat from plants which convert excess power into heat (P2H) could be stored seasonally. Finally, the ATES system could be used to store excess heat from distributed heat plants in the neighborhood. Seasonal storage of excess heat from solar thermal power plants is known from shallow ATES systems in the Netherlands [24]. The authors have not found any applications in combination with large solar thermal plants and HT ATES, though. Bundling heat from different distributed sources may be a concept which has to be considered in this regard, but is technically complex and costly.

Subsequent to expert interviews, the project team will define typical applications (heat sources and sinks). The technical system and cash flows will be modeled using TRNSYS. Results from the FEFLOW modeling of geological processes are introduced into the TRNSYS simulations. Load profiles are taken from a load profile generator programmed in MATLAB.

5. Instead of conclusions: expected results of the research project

The geological, chemical and microbiological, legal, technical, and economic perspectives on HT ATES projects described above will be bundled into four different "products":

- maps showing the geological-technical-economic potential for medium-deep ATES in Northern Germany;
- a technology roadmap illustrating needs for further research and development and visions for future applications;
- a selection of potential sites for demonstration projects; and
- further recommendations for public support policies.

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