Medium Deep Borehole Thermal Energy Storage Systems – Economic and Environmental Impact

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ABSTRACT

Seasonal thermal energy storage in medium deep borehole heat exchanger arrays is a very promising technology for increasing the share of sustainable heat sources in district heating grids, while minimizing the thermal impact on shallow aquifers. However, the integration of a medium deep borehole thermal energy storage system is highly dependent on its interaction with other heating components in the grid. Furthermore, the construction of medium deep borehole heat exchangers is accompanied by additional environmental burdens and large capital expenditures (CAPEX). Hence, their contribution for the mitigation of greenhouse gas emissions as well as the financial implications induced by medium deep borehole thermal energy storage systems are not quantified yet.

In order to pursue these questions, an economic and environmental assessment tool has been developed, which is based on a life-cycle approach (Welsch et al. 2018, Welsch 2019). It is able to consider different district heat generation options including solar thermal collectors, combined heat and power plants, conventional gas fired boilers and MD-BTES systems.

Numerous district heat generation options are analysed under different economic and environmental boundary conditions and reveal the potentials of MD-BTES systems in future district heat production.

1. INTRODUCTION

The energy transition in Germany has mainly focused on the electricity sector so far, although more than 30% of the final energy consumption originates from space and water heating. To reach the climate protection targets, the energy transition has to be extended to the heating sector. District heating (DH) will play an important role in the future heat supply. Consequently, the decarbonisation of DH systems is of utmost interest. There is a variety of sustainable heat sources, which could be exploited to replace fossil fuels in district heat production. However, the strong seasonality of the heat demand results in a strong mismatch between demand and production potential. Therefore, large-scale seasonal thermal energy storage systems are required, which are able to store excess heat in summer from for example solar thermal collectors (STC), combined heat and power plants (CHP) or industrial processes and make it available for heating purposes in the winter with as low heat losses as possible.

Medium deep borehole heat exchanger arrays are a novel concept, which can provide the large storage capacities needed on a DH scale while reaching high efficiencies of more than 80% (Welsch et al. 2016, Schulte et al. 2016a). Moreover, such medium deep borehole thermal energy storage (MD-BTES) systems are able to reduce the thermal impact on shallow aquifers significantly compared to conventional borehole thermal energy storage (BTES) systems by shifting the heat input to less vulnerable reservoirs in larger depth (Schulte et al. 2016b, Welsch 2019).

However, the construction of all BTES systems (medium deep and shallow ones) releases additional greenhouse gas emissions and it constitutes large capital expenditures. Consequently, these implications have to be taken into account when assessing the integration of such systems into DH grids.

Welsch et al. (2018) compare different district heat production combinations including CHP, STC, gas fired hot water boilers (GB) and shallow to medium deep BTES systems on the basis of a life-cycle assessment (LCA) and a life-cycle cost analysis (LCCA). Hence, they do not only consider the operation phase of the system over a time frame of 30 years but also take into account greenhouse gas emissions as well as capital expenditures connected to the production phase of the system.

2. SYSTEM DESCRIPTION

A low temperature DH grid (supply temperature 55 °C as needed in future DH systems) with an annual heat demand of 25 GWh/a serves as a reference case. In total, seven different heat generation combinations (Figure 1) are compared in terms of levelized cost of heat (LCOH) as well as global warming potential (GWP). A GB base-case as well as three combinations adding a CHP, an STC field and a combination of both represent reference scenarios. Three further system combinations include a BTES system assisted by a heat pump (HP), which is needed to provide the required grid supply temperatures. The GB is present in all system combinations in order to cover peak load demands.

In addition to the changes in the general composition of the heat production system, the dimensioning of the single system components is also varied. In the end 9241 different production system designs are modelled and compared. The heating grid itself is assumed to be invariant and thus it is excluded from the considerations.

An energy balance approach is used to determine the heat fluxes between the components and the grid on an hourly basis, which are then used to calculate the gas consumption of the GB and the CHP as well as the cogenerated electricity (Welsch 2019). Moreover, the electricity consumption of auxiliary devises (e.g. circulating pumps) and the HP are also estimated. All these consumption and production data are then used for LCA and LCCA.

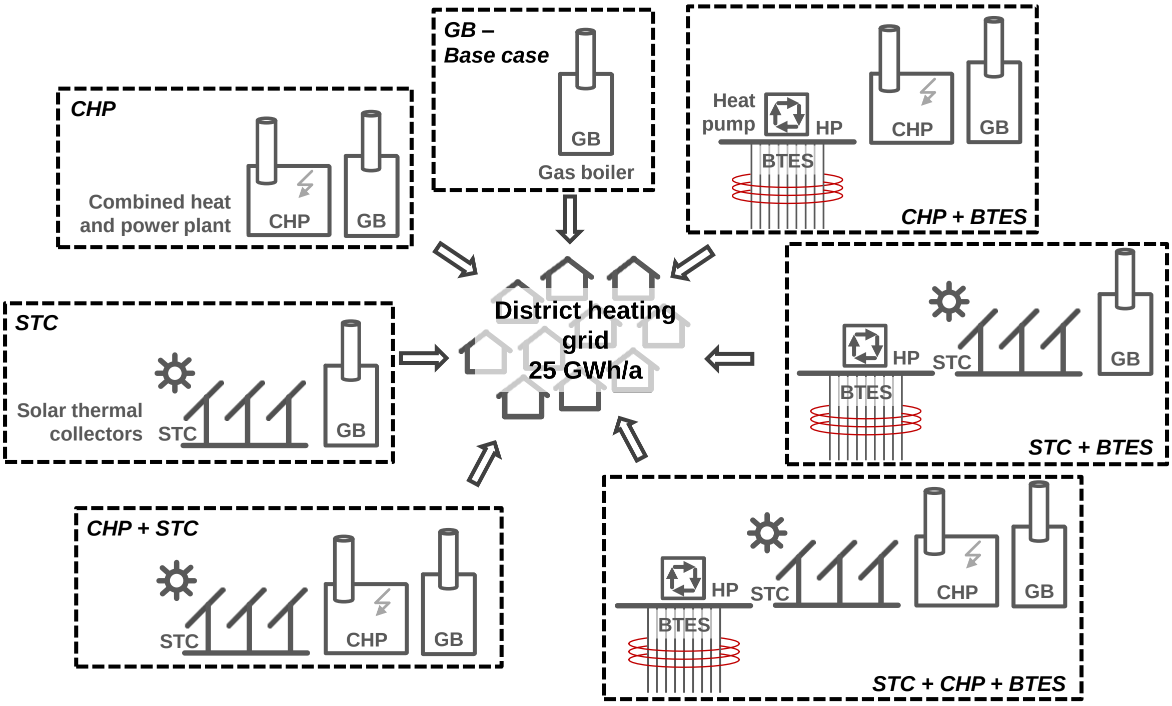

Figure 1: System combinations taken into account (modified after Welsch et al. 2018).

3. ECONOMIC AND ENVIRONMENTAL SCENARIOS

The LCA and the LCCA rely on environmental and economic boundary conditions specifying energy prices as well as the emission factor for the grid electricity. The latter is important as the considered system receives GWP credits for replacing grid electricity by excess cogenerated electricity. Moreover, the economic boundary conditions also define potential subsidies that apply.

Welsch et al. (2018) compare four different economic and environmental scenarios (Table 1). The first is a business-as-usual (BAU) scenario in which all the factors were kept constant on a present-day level. The second is an evolution (EVO) scenario, which considers an increase in the energy prices as well as a decrease in the emission factor of the grid electricity due to a growing share of renewables in the grid mix. For each, the BAU and the EVO scenarios, a sub-scenario (SUB) is defined, where current German subsidies for cogenerated electricity as well as for the construction of STC and heat storage systems are taken into account.

Table 1: Economic and environmental scenarios taken into account (modified after Welsch et al. 2018).

Scenario	Gas price [ct/kWh]	Electricity base price for CHP feed-in [ct/kWh]	Electricity price for industry [ct/kWh]	Emission factor grid electricity [g/kWh]	Subsidies included
BAU **(Business As Usual)**	3.08[1]	3.66[2]	13.08[3]	532[4]	✗
BAU SUB	3.08[1]	3.66[2]	13.08[3]	532[4]	✓
EVO **(Evolution)**	Projected[5] ↗	Projected[5] ↗	Projected[5] ↗	Projected[5] ↘	✗
EVO SUB	Projected[5] ↗	Projected[5] ↗	Projected[5] ↗	Projected[5] ↘	✓

[1] average gas price for industry in Germany 2015 (Statistisches Bundesamt, 2017)

[2] 3.16 ct/kWh average price for baseload power at the EPEX spot 2015 (European Energy Exchange AG, 2017) plus 0.5 ct//kWh for avoided grid charges

[3] average value for 2015 (Statistisches Bundesamt, 2017)

[4] current German electricity mix (IINAS, 2016)

[5] trends from Schlesinger (2014)

4. RESULTS

The study represents a multi-objective optimization problem. On the one hand, the LCOH shall be minimized, on the other hand, the GWP shall be minimized as well. As illustrated in Figure 2, these two objectives compete against each other: for a particular combination of district heat generators the system design with the lowest LCOH is usually not the system design with the lowest GWP. However, it is possible to define so-called Pareto fronts. Proceeding from a system design that lies on such a front, one objective cannot be further improved without impairing the other objective. For each system combination the Pareto front is determined. Moreover, three characteristic system designs are identified on each Pareto front. These are the minimum heat cost design, the minimum GWP design as well as a compromise solution, which represents a good trade-off between both objectives.

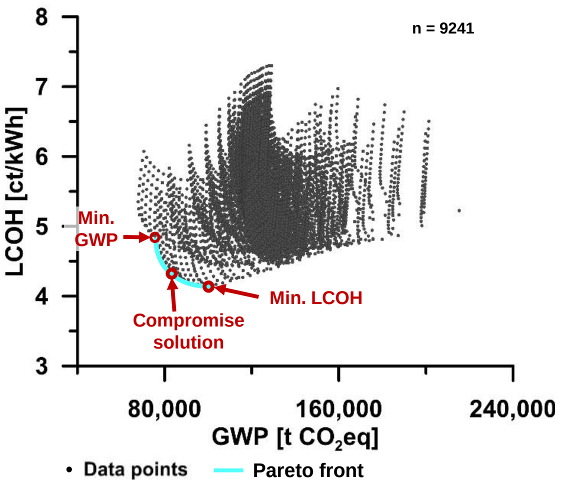

Figure 2: Identification of characteristic Pareto efficient system designs (modified after Welsch et al. 2018).

Figure 3 illustrates that the results differ significantly for the four economic and environmental scenarios. As expected, in the BAU-scenario the GB base-case represents the system design with the highest GWP and the lowest LCOH. All other combinations reduce the GWP in parts significantly, but this comes at a price. When including subsides (BAU SUB), system designs that achieve comparatively high GWP reductions become cost-effective. However, the most cost-effective system designs all include a large CHP. This indicates, that subsidies benefit CHP over STC- and BTES-based system designs. This situation considerably changes, when increasing energy prices are assumed in the EVO scenario. A general increase in the heat cost can be observed, however, in particular the fossil-based system designs are affected. Moreover, the assumed growing share of renewables in the grid electricity production results in declining GWP-credits for the replacement of grid electricity by cogenerated electricity. Consequently, the CHP-based system designs perform much worse in terms of GWP mitigation than in the BAU-scenario. Now, heat production systems that are composed of a large STC-field, a large BTES system as well as a small CHP for the self-provision with electricity achieve high GWP reductions while already being economically competitive. When taking subsidies into account (EVO SUB), such system designs are capable of also significantly reducing the heating costs. Compared to the best compromise solution without any seasonal heat storage system, the integration of an MD-BTES system reduces the GWP by more than 30%, while concurrently reducing the LCOH by approximately 5%.

5. CONCLUSIONS

The results of the study (Welsch et al. 2018) reveal that the economic as well as the environmental impacts of different district heating concepts are both highly dependent on the assumed financial and economic boundary conditions. Moreover, the results demonstrate the high economic competitiveness of MD-BTES in combination with solar thermal collector fields, when supposing a very likely increase of energy prices in the future. Furthermore, the combination of solar energy and seasonal storage exceeds the greenhouse gas mitigation potential of combined heat and power plants by far, when assuming a very likely decrease in the emission factor of the grid electricity mix.

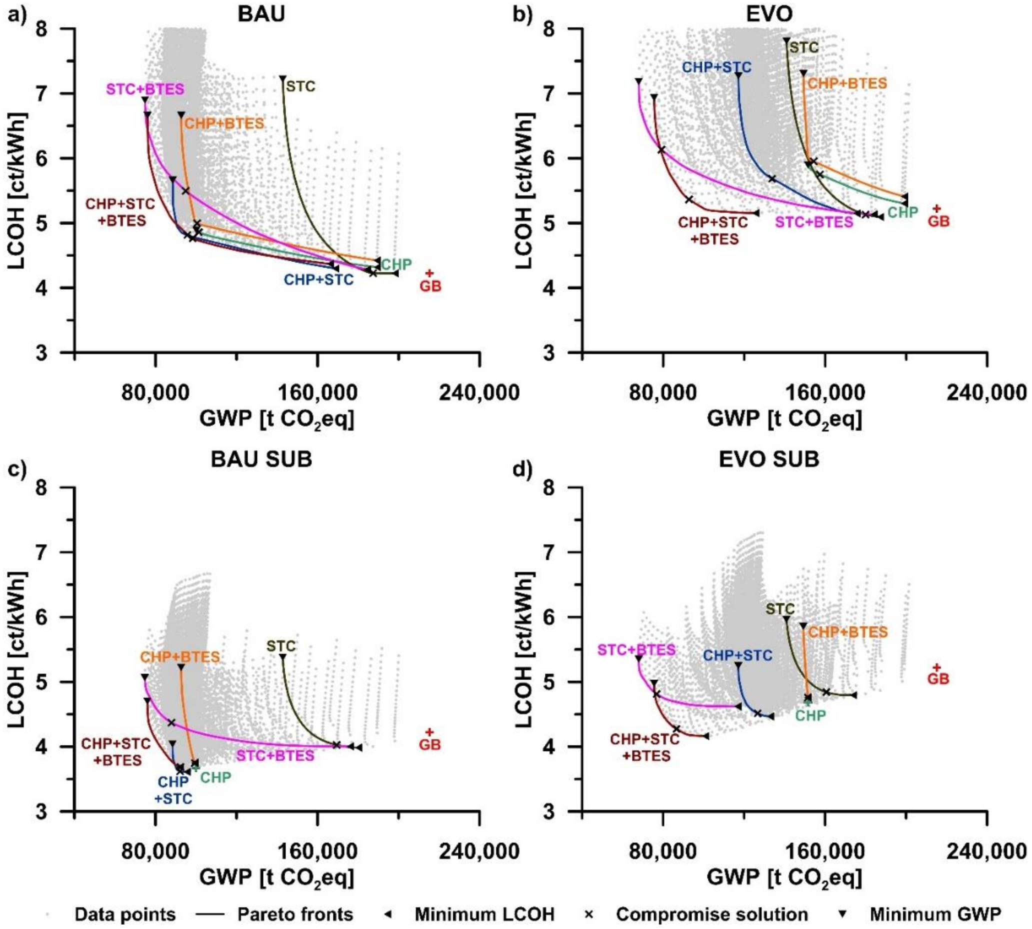

Figure 3: Comparison of Pareto fronts for the different system compositions for (a) scenario BAU, (b) scenario EVO, (c) scenario BAU SUB and (d) scenario EVO SUB (Welsch et al. 2018).

REFERENCES

European Energy Exchange AG. Quarterly Prices According to CHP Law, https://www.eex.com/en/market-data/power/spot-market/kwk-index, (2017).

IINAS: GEMIS - Globales Emissions-Modell Integrierter Systeme - model and database, version 4.93, in *International Institute for Sustainability Analysis and Strategy*, ed., (2016), Darmstadt.

Schlesinger, M., Hofer, P., Kemmler, A., Kirchner, A., Koziel, S., Ley, A., Piégsa, A., Seefeldt, F., Straßburg, S., Weinert, K., Lindenberger, D., Knaut, A., Malischek, R., Nick, S., Panke, T., Paulus, S., Tode, C., Wagner, J., Lutz, C., Lehr, U. and Ulrich, P.: Entwicklung der Energiemärkte – Energiereferenzprognose, Projekt Nr. 57/12, (2014).

Schulte, D.O., Rühaak, W., Oladyshkin, S., Welsch, B. and Sass, I.: Optimization of Medium-Deep Borehole Thermal Energy Storage Systems, *Energy Technology*, 4, (2016a), 104‐113.

Schulte, D.O., Welsch, B., Boockmeyer, A., Rühaak, W., Bär, K., Bauer, S. and Sass, I. Modeling insulated borehole heat exchangers, *Environmental Earth Sciences*, 75, (2016b), 1‐12.

Statistisches Bundesamt: Daten zur Energiepreisentwicklung: Lange Reihen von Januar 2000 bis Dezember 2016 (2017), Wiesbaden.

Welsch, B., Göllner-Völker, L., Schulte, D.O., Bär, K., Sass, I. and Schebek, L.: Environmental and Economic Assessment of Borehole Thermal Energy Storage in District Heating Systems, *Applied Energy*, 216, (2018), 73-90.

Welsch, B., Rühaak, W., Schulte, D.O., Bär, K. and Sass, I.: Characteristics of medium deep borehole thermal energy storage, *International Journal of Energy Research*, 40(13), (2016), 1855‐1868.

Welsch, B.: Technical, Environmental and Economic Assessment of Medium Deep Borehole Thermal Energy Storage Systems. Dissertation, *Technische Universität Darmstadt*, (2019).

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