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Co-Simulation of the Borehole Thermal Energy Storage at the Solar District Heating System in Brædstrup, Denmark

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ABSTRACT

The solar share of district heating grids with integrated solar thermal collectors can be increased significantly by adding Borehole Thermal Energy Storages (BTES) to the system. The different project stages of such systems should be accompanied by numerical simulations to improve the resulting thermodynamic performance, cost effectiveness and environmental compatibility. While there are simulation tools available for the initial design to compare a great number of variants on a low level of detail, there is no single tool available yet for a highly detailed analysis of the whole system. Especially the modelling of the BTES is usually limited with respect to the accurate consideration of the local (hydro-)geology and resulting environmental impacts. To take the strong interdependencies between all system components into account, while simultaneously allowing for a high level of detail, a coupled simulation approach is used. The above ground heating system is modeled in Modelica, whereas the BTES is modeled with the Finite Element Method in FEFLOW. Both sub-models are run simultaneously. For the assessment and validation of the proposed methodology, operational data from the existing BTES in Brædstrup (DK) is used. Different sampling frequencies for the communication between the two sub-models are compared, considering the resulting computational effort and accuracy of the simulation process. The results demonstrate the possibility to predict the system behavior on a high level of detail, producing valuable information about environmental impacts and performance improvement potentials in advance.

1. INTRODUCTION

Heating amounts to 48 % of the final energy demand in Europe, thus representing the biggest share. Yet, only 13 % of this share is produced by renewable energies, while most of it is still produced by fossil fuels (Fleiter *et al.*, 2017). District heating (DH) grids will play a key role for the future introduction of renewables on a large scale (Susana *et al.*, 2018). An easy and cost-efficient way of lowering the greenhouse gas (GHG) emissions in the heating sector is the utilization of Solar District Heating (SDH). The drawback of this technology is the seasonal mismatch between the high solar yields during summer and the high heat demand during winter. This mismatch can be overcome by seasonal thermal energy storage. The requirements for such technologies are large storage capacities, high storage efficiencies and low specific storage costs. Borehole thermal energy storage (BTES) systems have proven to fulfil those requirements. Compared to other viable technology options, they show low specific costs and the largest storage capacities (Mangold, 2015). While being less dependent on a specific location than aquifer thermal energy storages, the actual location of BTES systems has to be considered carefully. Interactions between the storage and the local geology have a high relevance for the storage efficiency and environmental aspects as well. Therefor a detailed analysis of these interactions should be carried out by numerical simulations. The modelling of BTES systems poses the challenge of combining the large dimensions of the heat dissipation problem in the underground with much smaller dimensions of the heat-transition problem in and around the borehole heat exchangers (BHE). A multitude of models with reduced complexity has been developed for fast simulations, e.g. exploiting the symmetry of the storage and neglecting effects like groundwater flow or a detailed representation of the local geology. This approach might be suited for an assessment of the approximate energetic performance of the storage from a system view, but cannot support information about environmental impacts. For such detailed analysis a 3D Finite Element Method (FEM) model of the storage represents the current state of the art (Mielke *et al.*, 2014). In contrast to this, DH systems are modeled most efficiently by using 1D component representations, e.g. with Modelica (Modelica Association, 2018) or TRNSYS (Solar Energy Laboratory, 2012). To combine the most suited modelling approaches for the underground BTES and the above ground SDH system, a coupled approach can be used, where both subsystems are modeled separately and simulated simultaneously in dedicated simulation tools, exchanging information in prescribed intervals. This approach allows for the utilization of proven software for both system parts, while considering their strong interdependencies. The computational effort is considerably larger though compared to stand-alone simulations with reduced storage models. This limits the method to detailed case studies, where most system parameters are already fixed and excludes large parameter studies. Parameters like the size of the communication intervals between the two simulation tools or the coupling scheme have to be chosen carefully, to find a good compromise between the computational effort and the accuracy of the co-simulation. The presented work shows a co-simulation approach, where the BTES is modeled in FEFLOW (DHI WASY, 2014) and the above ground SDH system in SimulationX (ESI ITI, 2017). FEFLOW is a FEM modeling tool for subsurface heat and mass transport and is commonly used for the simulation of geothermal applications. SimulationX implements the equation-based, object-oriented physical modeling language Modelica and includes components for the modeling of SDH systems in its Green City library. It does not include a BTES model though. The coupling between both simulation tools is implemented via a TCP/IP connection. To verify the co-simulation, monitoring data from an existing SDH plant with integrated BTES in Brædstrup (Denmark) is used.

3. METHODOLOGY

3.1. Finite Element Method BTES Model

The pilot BTES in Brædstrup (DK) was introduced to an existing SDH system in 2012. It comprises 48 BHEs each 45 m deep and is mainly charged by surplus heat of a 18,600 m² solar thermal collector field. (Sørensen *et al.*, 2013) A detailed FEFLOW model was designed by Tordrup et al. (2017). The model's thermophysical parameters were determined by a history matching study using PEST (Doherty, 1994), resulting in a fitted model with six geological layers. Compared to a model which was parametrized by using thermal properties determined by a Geothermal Response Test, the deviation between monitoring data and simulation could be reduced from 12.5 % to 4 %. The BTES model used in the presented co-simulation was designed according to the rules presented by Tordrup et al.. FEFLOW currently does not support a reversal of the flow through arrays of BHEs. Since this is an essential feature of the BTES under investigation, which has 6 legs with 8 BHEs in series each, a plugin had to be developed. The inlets and outlets of the BHE array were dynamically linked to each other during the simulation according to the current mode of operation. During charging periods in summer, the flow through the BHE legs is directed from center to outer BHEs. For discharge periods in winter the flow direction is reversed. The FEM mesh of the created FEFLOW model is depicted in Figure 1.

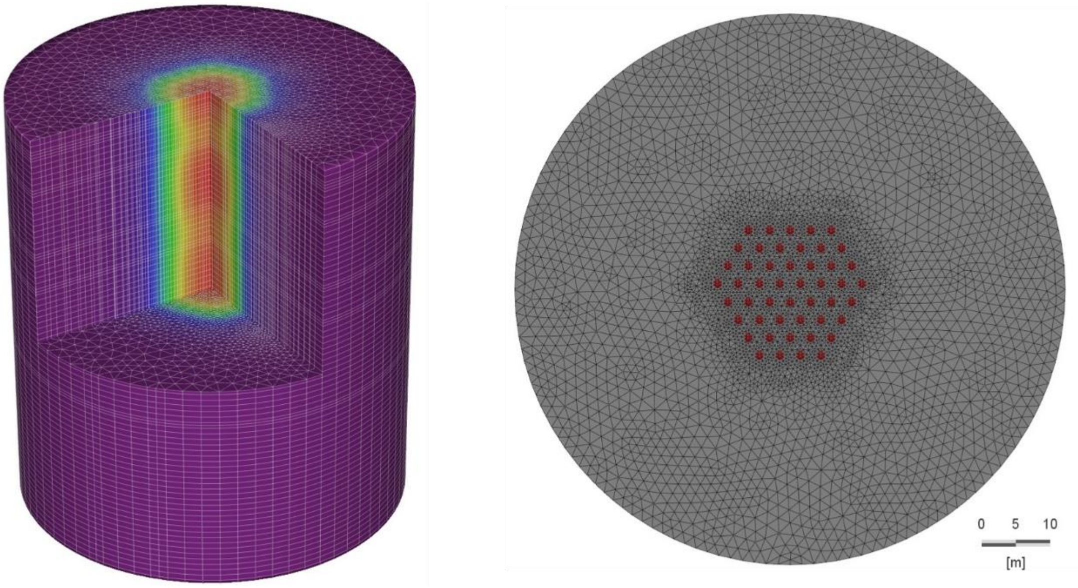

Figure 1: Finite Element Method model of the BTES in FEFLOW (left: 3D view, right horizontal cross section)

3.2. Co-Simulation Approach

The focus of the underlying study does not include the assessment of the whole SDH system, but rather focusses on the simulation of the BTES to validate the presented co-simulation approach. Therefore, the inlet temperature and flow rate which are transmitted from Modelica to the BTES model in FEFLOW are not defined by a transient simulation of the above ground components, but real monitoring data is read from timetables. The available monitoring data covers the years 2012-2016 and was retrieved from the SCADA (Supervisory Control and Data Acquisition) system as 5 minutes average values. To increase the numerical stability and decrease the computational effort of the co-simulation, the data was aggregated to hourly values. Additionally, a threshold of 0.1 l/s for the flow rate was applied, to avoid numerical oscillations. Figure 2 shows the implementation (a) and scheme (b) of the co-simulation. At each communication step (CS) the Modelica above-ground model passes the inlet temperature, flow rate, charging direction and the current CS size to the BTES model in FEFLOW, which responds with the according outlet temperature and temperatures at arbitrary observation points. The connection between both software tools is established via the TCP/IP-protocol, which allows for the simulation of the two sub-systems on separated computing environments. The coupling component in Modelica was developed using functionalities from the open source Modelica Device Drivers component library (Thiele *et al.*, 2017). The corresponding part in FEFLOW was realized by a plugin programmed in C++ with the help of FEFLOW's Plug-In and Interface Manager. The CS size is dynamically adapted during the simulation in Modelica, depending on whether the BTES is in operation. This approach allows for large CS sizes during times when the BTES is idle and thus can speed-up the computation significantly. Therefor CS sizes of one day could be chosen for those periods, in contrast to CS sizes of 0.5-4 h during times of operation. Due to the way the serial hydraulic connection of the BHEs is implemented, a restriction for the internal solver time step size in FEFLOW had to be imposed. The outlet temperature of the first BHE in series defines the inlet temperature for the second BHE for the following time-step and so on. An input signal to the array of BHEs hence will take six time steps to propagate to the array outlet for an array with 6 BHEs in series. Accordingly, the maximum time step size in FEFLOW during times of operation is limited to 1/6 of the CS size. Figure 2 (b) shows the scheme of the co-simulation. The Gauss-Seidel scheme was chosen, i.e. a non-iterative and sequential approach. Sequential means that while one sub-system is simulating the CS the other has to wait for the results. Since the computational effort of the co-simulation is strongly dominated by the FEM software, this is no real drawback though. During the co-simulation both software tools calculate their model states ($Y_{model,t}$) for each internal solver time step t. The original time step size control of the solver is left unchanged, but time steps are forced at each CS. An exemplary CS from $t_{CS,N}$ to $t_{CS,N+1}$ is first simulated in Modelica, where the BTES response to the inputs has to be extrapolated. For the underlying study a constant charging or discharging power for each CS proved to be the most accurate approach for the extrapolation. At the end of the CS the current BTES input variables $y_{Mod,N+1}$ ($y_{model,t} \subseteq Y_{model,t}$) are passed to FEFLOW. FEFLOW then simulates the CS and sends back the BTES response $y_{FEFLOW,N+1}$ to Modelica. This process continues until the end of the simulation. The choice of the CS size has a significant impact on the computational effort and the error in transmitted power. Smaller time steps reduce this error, but lead to an increased computational effort.

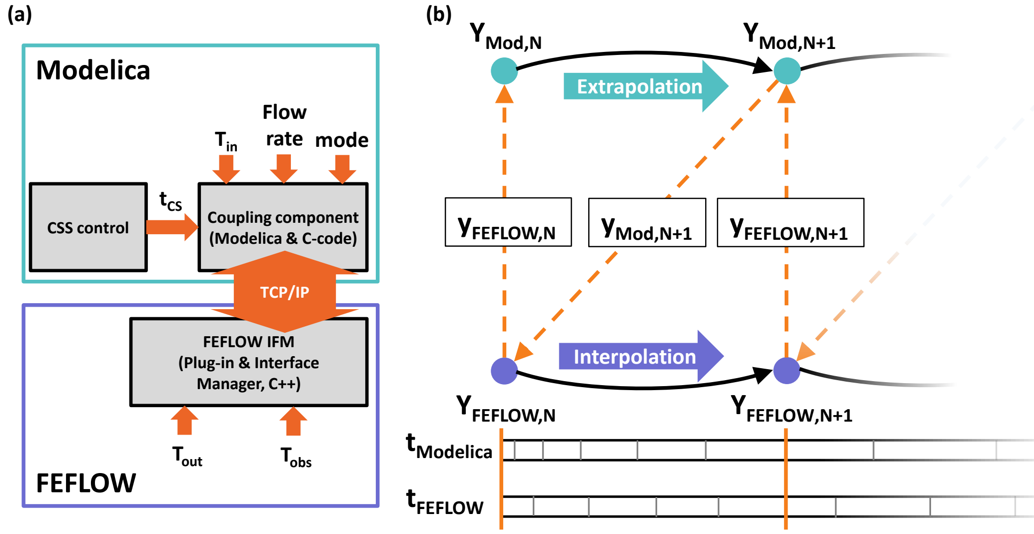

Figure 2: Implementation (a) and scheme (b) of the Co-Simulation

4. RESULTS

4.1. BTES Energy Balance

The simulated period covered the years 2012-2016 with a duration of 1,684 days. Four co-simulation scenarios with different CS sizes were simulated, ranging from 0.5 to 4 hours. Figure 3 shows the overall energy balance of the BTES as recorded by the monitoring system and the co-simulation runs. The co-simulation results are in very good accordance with the monitored data for the first charging period, but deviate increasingly for the succeeding charging cycles. As stated by Tordrup et al. (2017) the BTES was operated under steadier conditions during the initial charging periods compared to its later operation, resulting in a decreasing fit between the model and the monitored data. While the BTES was initially charged by several pulses with constant flow rates, the flow rate was much more fluctuating later on. Accordingly, the problem is not inherent to the co-simulation approach itself, but rather one of the underlying FEFLOW model. Six different geological layers were modeled and parametrized by a parameter estimation process, using data of the first 510 days of operation. A repeated parameter estimation study with the incorporation of the more recent monitoring data could possibly further improve the quality of the model.

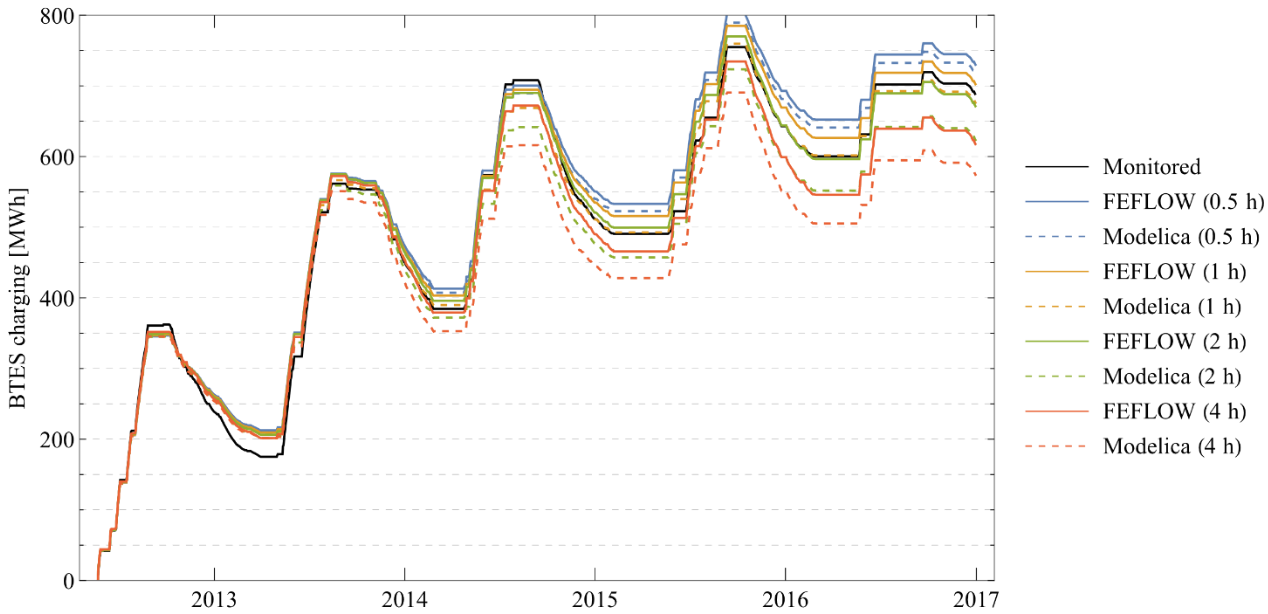

Figure 3: Energy balance of the Brædstrup BTES from monitoring data and simulations

4.2. Co-Simulation Transmission Error and Real-Time Factor

An important measure for the quality of a co-simulation is the transmission error (Eq. 1). As mentioned above, the error is generally smaller for shorter CS sizes (Welsch *et al.*, 2017). Figure 4 shows the average error in the transmitted power between FEFLOW and Modelica for charging and discharging periods. The negative numbers imply that the extrapolation in Modelica underestimates especially the charging power compared to FEFLOW.

$$\Delta Q_{transmitted} = \frac{Q_{th,Modelica} - Q_{th,FEFLOW}}{Q_{th,FEFLOW}} \tag{1}$$

For all observed scenarios the error is smaller during discharging periods. This might be due to the fact that the charging power is strongly depending on the power of the solar thermal collectors, which shows large variations during the course of one day. In contrast, the discharging power is mainly defined by the much steadier operation of the heat pump. Overall, the operation conditions of the BTES in Brædstrup pose a challenging task for the presented co-simulation approach. Input variables like the flow rate and temperature were highly fluctuating and the operation of the storage was switched on and off frequently. For a steadier operation of the BTES the transmission error can be expected to be significantly lower.

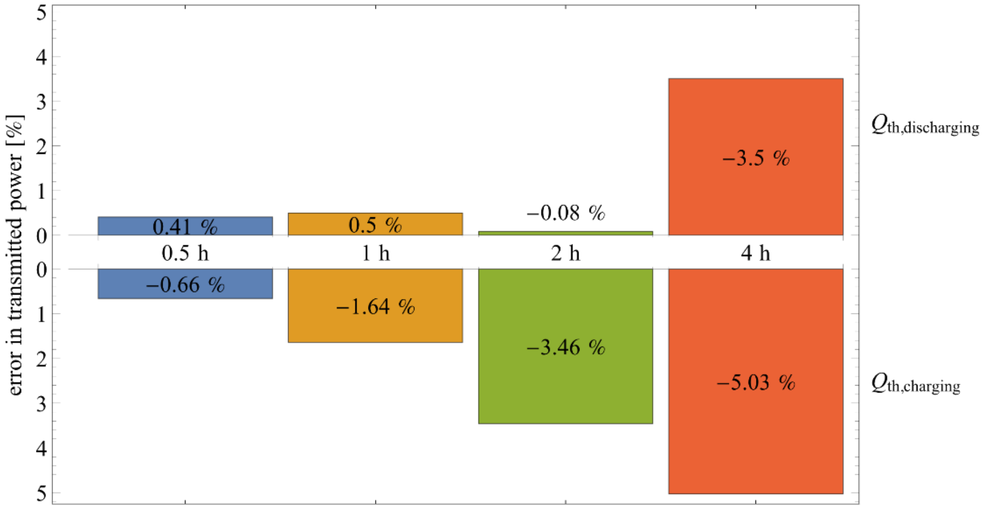

Figure 4: Average deviation of the energy balance between FEFLOW and Modelica during charging and discharging periods for different communication step sizes.

The second important indicator of a co-simulation is the computational effort or real-time factor. Shorter CS sizes considerably increase the computational effort, leading to a higher real time factor (see Figure 5). For a CS size of 1 hour the co-simulation took about 1 second of computational time to simulate 1 hour. Since the computational effort for FEM simulations is rather high, especially if additional time-step restrictions are imposed by the Co-Simulation scheme, it is important to carefully consider the trade-off between a low error in transmission and a small real-time factor. The choice should be made by regarding the desired accuracy, the volatility of the transferred variables, the necessary number of simulations runs and the length of the simulated period. If the information about the simulated system is on a high level of detail and certainty, the quality of the co-simulation should match this by a high accuracy. Accordingly, the desired accuracy can be lower for systems with higher uncertainties, reducing the computational effort. BTES systems for seasonal storage are usually operated under rather steady conditions. They are often connected to buffer storages, which even out the daily fluctuations of solar thermal production or the heat demand. Certain conditions, like a direct feed of solar thermal energy, can necessitate shorter CS sizes though.

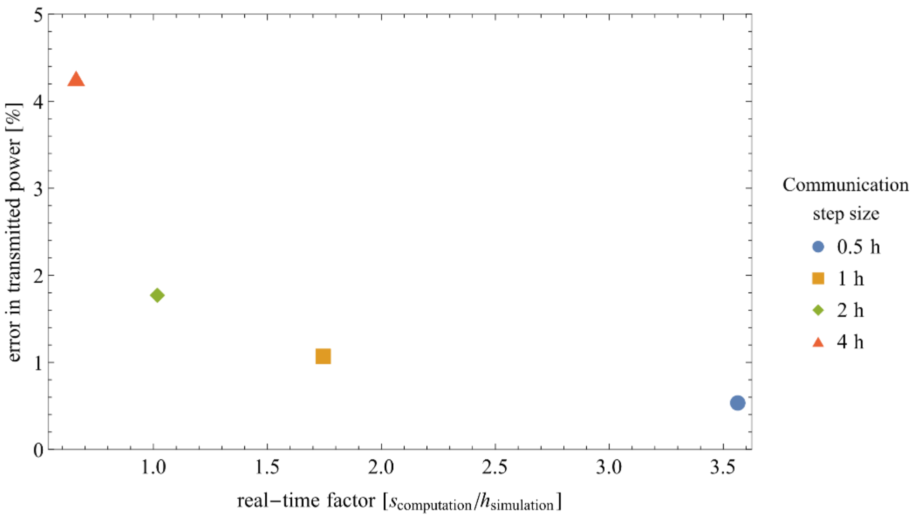

Figure 5: Co-Simulation real-time factor and relative error in transmitted energy for different communication step sizes.

An important parameter for system simulations is the temporal discretization of input data. For dynamic simulations of heating systems, intervals of one hour are used most frequently. As mentioned above, the data which was retrieved from the SCADA system in Brædstrup originally had a discretization of 5 minutes, but was aggregated to hourly values. A CS size of one hour therefor constitutes a good compromise between the error in transmission and the computational effort, keeping the error at approximately 1 % for the presented study.

5. CONCLUSIONS

A methodology for the co-simulation of BTES models in FEFLOW and district heating models in Modelica was developed and successfully applied. The coupling between the two software tools is realized via the TCP/IP protocol. A plugin for FEFLOW was developed to add coupling functionalities and the possibility to dynamically reverse the direction of flow through the BTES. To allow for an adaptive control of the CS size a new Modelica type was created. The developed methodology was assessed using real monitoring data from the SDH plant in Brædstrup, which contains a BTES. The impact of different CS sizes on the error of transmitted power and the computational effort were compared. During times when the BTES was operated, the CS size was set to a fixed value between 0.5 to 4 hours, while CS sizes of up to one day were used for idle periods. For the presented study, CS sizes up to one hour yielded in a good agreement between simulation and monitoring results. For a CS size of one hour, the average BTES power was approximately 1.6 % lower in Modelica compared to FEFLOW during charging and 0.5 % higher during discharging. For all observed scenarios the error was smaller during discharging periods, since inlet fluid temperatures and flow rates during those periods were steadier. Future studies should investigate additional CS size control schemes, with different step sizes during charging and discharging periods to increase the accuracy of co-simulations. Additionally, the scope of future studies should include further SDH system components to validate the overall approach of co-simulation of SDH with integrated BTES.

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