Opening the black-box: A case study of a borehole thermal storage

Tobias Dokkedal Elmøe, Denmark

The Energy Machines Verification tool (EMV) is a combined hardware/software solution based on physical measurements. A service REST API (REpresentational State Transfer Application Programming Interface) and thermodynamic models of the heat pumps in order to provide online/live transparent performance monitoring of these, as well as perform analysis on historically logged data. Here we present a case study where a combination of this tool and energy-meters are used on an existing plant to de-convolute the system COP and the negative energy balance of a borehole thermal storage (BTES), which may predict, and prevent potential long-scale temperature drops inside the BTES.

Energy Machines (EM) is a leader in the design, implementation and operation of integrated energy systems for buildings. EM uses standardized component designs, which not only reduce complexity for control systems but, more importantly, ensure quality and functionality as the designs consist of reusable and scalable modules. Through simulation platforms, EM is developing digital solutions for heat pump systems. Hence, EM has a key focus on the digitalization of heat pumps and is, in relation to that, also a part of the Danish working group in the HPT Annex 56 on "Digitalization and IoT for Heat Pumps".

Ground source heat pumps, which take advantage of borehole thermal storages (BTES), are some of the most flexible heat pumps which provide high energy efficiency [1]. When designing a new BTES, care must be taken to avoid the dropping of temperatures below freezing. The lifetime of the underground storage is typically designed for 25 years. In practice, this is controlled on-site by dumping excess building heat in free-cooling mode during spring/early summer and excess heat from the hot side into the borehole in warm summer months during active cooling. Thermal energy-meters can be placed around the site to estimate the power going into the boreholes, but they are expensive and in most applications, the energy meters are therefore limited to only measuring the building interface (heating/cooling side).

Here, we present a case study of an Energy Machines (EM) installation located in Sweden, where we wish to investigate the total heating/cooling production from the installation, as well as examine the imbalance between heat storage and heat recovery from the BTES connected to this site. We do this by applying the Energy Machines Verification tool (EMV), in combination with the preexisting energymeters, to open up the "black-box" of the energy flows of the heating/cooling system. EMV relies on multiple, simultaneous measurements of the refrigerant pressure and temperature, as well as a knowledge of the thermodynamic properties of that refrigerant, as illustrated in Figure 1. EMV comes as an optional "out-of-the-box" with all EM installations since the machines already have all the necessary sensors equipped. It functions primarily as an automated real-time cloud service but can also be invoked to analyze historical data and give inputs to energy engineers, building property managers, or others who might have an interest in the performance of their heating/cooling system.

The purpose of this study was to gain more insight into the performance of the EM installation, in particular with a focus on the total heat and cooling production vs the measured heating and cooling from the energy-meters, and the imbalance imposed on the borehole storage. This insight can improve the control of the system to prevent long-term freezing of the boreholes, as well as help, understand the actual system COP.

Case study

The system examined in this case study consists of three heat pumps (HP1, HP2, and HP3), two of which are in parallel, and one which has its heat source connected to the outlet of the two parallel ones. A very basic sketch can be seen in Figure 2. Currently, at the plant, thermal energy-meters are placed at the inlet, measuring $Q_{i,\ building}$, as well as $Q_{o,\ building}$. There are also electrical energy meters measuring the electrical power used for each of the three compressor pairs ($Q_{c,1}$, $Q_{c,2}$, $Q_{c,3}$) (two circuits with two compressors/circuit each per heat pump). With EMV, we can estimate the power to the evaporator and the power released in the condensers. Because of the configuration of the system, only $Q_{i,1}$ and $Q_{i,2}$ need to be determined from EMV, as the input source to heat pump 3 is part of the output from heat pumps 1 and 2.

The EMV algorithm requires input measurements of pressure and temperature throughout the heating cycle,

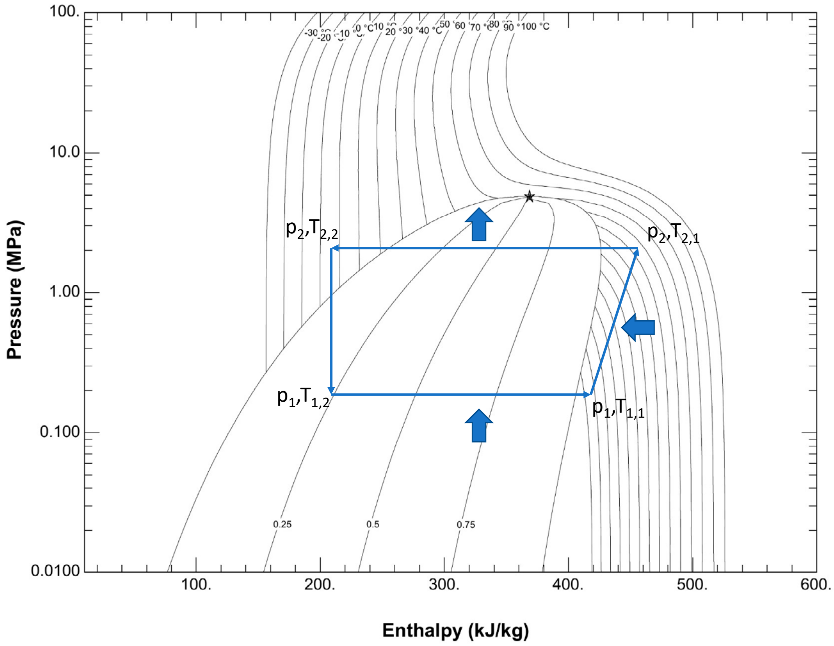

Figure 1. p-h diagram for R410A, showing the thermodynamic cycle of the heat pump, indicating the necessary measurements of the temperatures/pressures for EMV. Energy Machines heat pumps have all relevant sensors installed per default, so the EMV option can be enabled without additional installations required.

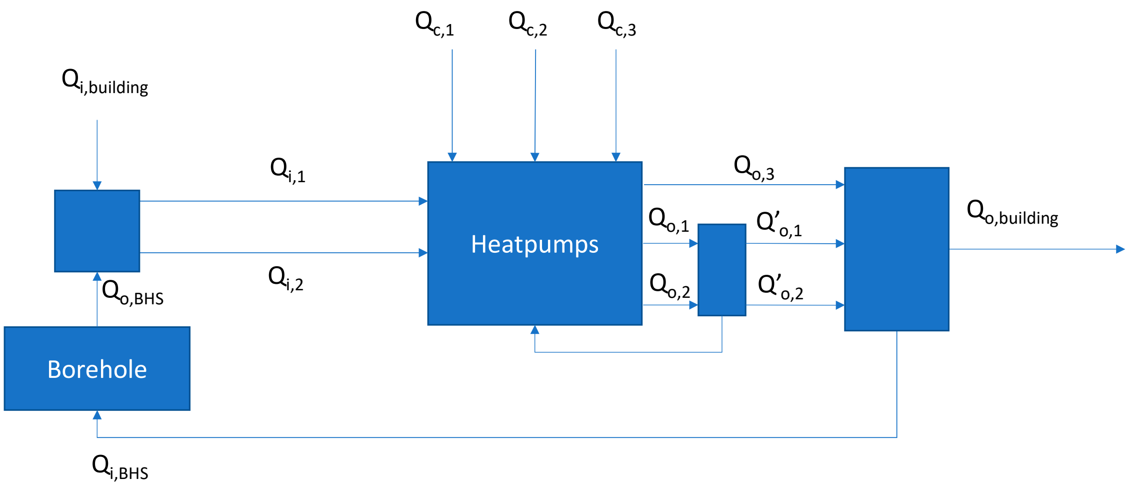

Figure 2. Sketch showing the heat flows in the system. Energymeters monitor the building energy flows ($Q_{i,\ building}$/ $Q_{o,\ building}$), while electricity meters measure the compressor powers ($Q_{c,1}$ to $Q_{c,3}$), and EMV is used to calculate the heat source $Q_{i,1}$ and $Q_{i,2}$. Some output energy from HP1 and HP2 is recycled as input to HP3. Energy balances can then be used to determine $Q_{o,\ BHS}$ and $Q_{i,\ BHS}$, the outlet and inlet from the borehole storage, respectively.

which are logged with 1-minute resolution and are available using our energymachines.cloud platform, which logs and monitors all EnergyMachines installations. Figure 3 shows the energy flows in terms of heating and cooling in the system, as an example of the output data from EMV. Many more outputs can be derived, such as COP, refrigerant flow and compressor efficiency, which given the right data analysis, may help diagnose/predict potential performance issues.

A summary of the COP, heating- and cooling energies can be seen in table 1, which is estimated by EMV, and

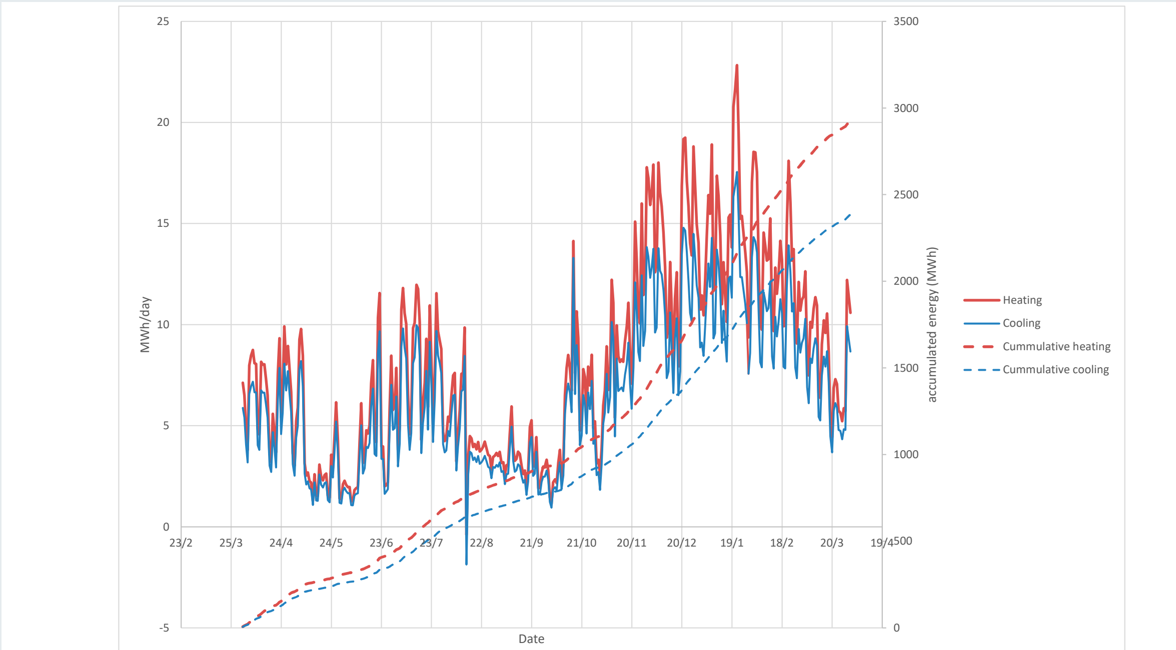

Figure 3. Heat (bold solid, red lines) and cooling (solid, blue lines) energy delivered per day (in MWh, left axis), as well as the accumulated energy (from start, broken lines right axis).

Table 1. Accumulated values for the case studied system calculated by EMV using temperature/pressure sensors located around the heat pump refrigerant circuit(s).

Heating energy delivered at condensers +subcoolers [MWh]	Cooling energy delivered at evaporators [MWh]	COP heating	COP cooling
2928	2385	5.01	4.09

COP was calculated from the total compressor energy used, which was measured by electrical meters to be 584 MWh.

Table 2. Accumulated values for the case studied system calculated energy meters located at the building interface (heating/cooling).

Measured heating energy delivered to building	Measured cooling energy delivered from building	COP heating	COP cooling / COP cooling energy balance
1815	699	3.10	1.20 / 2.10

COP was calculated from the total compressor energy used, which was measured by electrical meters to be 584 MWh. The energy balance is not fulfilled using energy meters alone because the borehole contributes significantly to the cooling energy delivered to the evaporators. COP cooling, therefore, has to be corrected for this (1.20 vs 2.10).

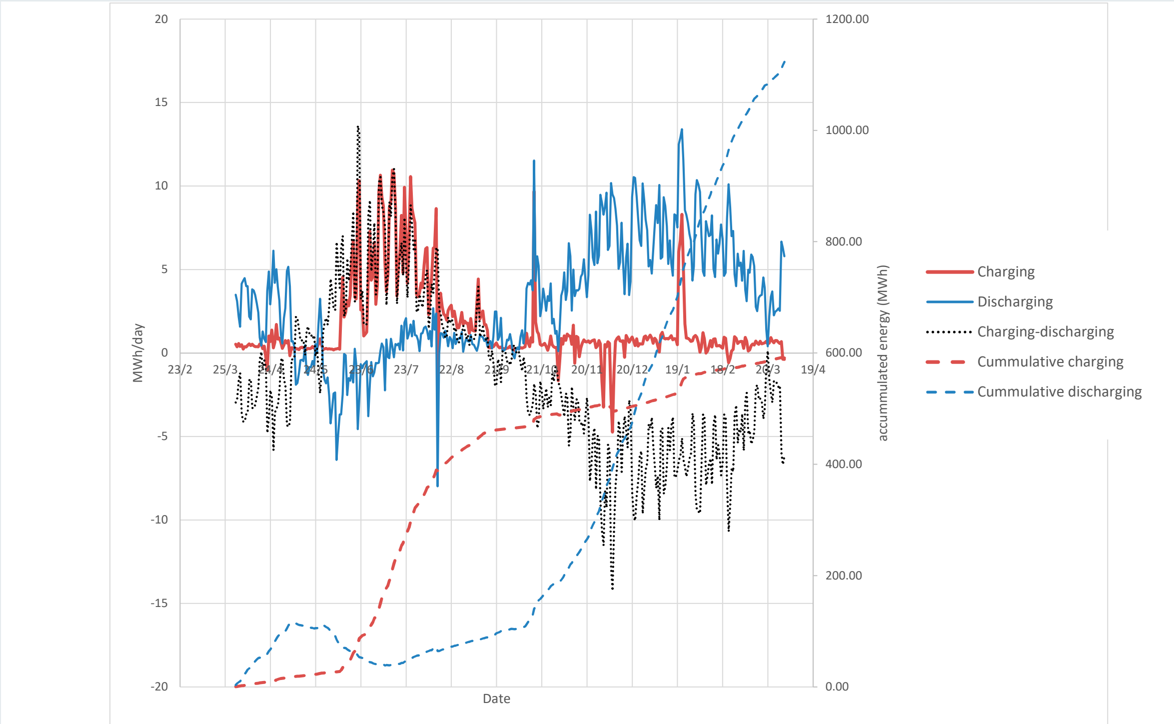

Figure 4. Borehole charging per day (left axis) from hot side (bold solid red line), discharging on the cold side (solid blue line) and the difference between the two (dotted black line) over a year of operation. In late spring, discharging is negative because of free-cooling, dumping energy back into the borehole from the cold side. During summer, charging is positive because of the active cooling demand of the building, which is when the heat pumps are mainly switched off. During autumn and winter, the borehole is discharged. Overall, the heat balance is negative, with higher discharging than charging (broken lines, right axis), not accounting for the self-charge .from the rock surrounding the borehole).

similarly in table 2 using energy-meters only. A clear distinction can be seen. First of all, the energy estimated by energy-meters is much lower, and this obviously leads to a much smaller COP. This is particularly more clear for the cooling side since the difference between cooling energy determined by EMV and energy meters is much greater. The reason for this difference is the borehole storage, as well as the fact that some output energy from HP1 and HP2 is used as input energy for HP3 (cf. Figure 2). The result illustrates the difficulty in reporting a system COP, mainly because of the borehole storage but also because of heat recycling inside the system.

To gain further insight, we will combine the EMV results with the energy-meters (thermal+electrical) and use energy-balances that can be set up from Figure 2, which are shown in eq. 1 and 2. Figure 4 shows the borehole storage charging/discharging calculated by EMV, energy-meters, and eqs. 1-2. The figure reveals how the borehole is charged by free-cooling from the cold side in early spring, then via active-cooling from the hot side during the summer, before being discharged in autumn and winter to increase system performance by increasing the evaporator temperature. Overall, the energy-balance is negative, leading to a decrease over time in borehole temperature. Nevertheless, the borehole will also "re-charge" through the surrounding rock, which requires more detailed analysis using so-called "g-functions" [2]. This analysis was not done in this study.

Conclusions

The Energy Machine Verification tool (EMV), which comes as an optional part of any Energy Machines installation, offers energy engineers, building property managers, or anyone with interest in the performance of their integrated energy system, a way to analyze results and gain insights into the "black box" of the energy system. In the case study above, the focus was on determining the system COP from the heat pumps, as well as investigating the energy flows to and from the borehole over a season of operation. Such knowledge can help the operators improve the operation and control of the integrated energy system to prevent potential future borehole freezing, as well as give them information on the current and seasonal performance of that system.

TOBIAS DOKKEDAL ELMØE
Energy Machines ApS
Belgium
tobias.dokkedal.elmoe@energymachines.com
https://doi.org/10.23697/j1x8-r288