Model predictive control to Maintain ATES balance using heat pump

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Abstract

A rapidly growing amount of sustainable office buildings in the Netherlands is using an Aquifer Thermal Energy Storage (ATES) system. An ATES system uses a well pump to extract cold groundwater for cooling with the use of a heat pump if necessary. An essential condition for optimal ATES operation is the thermal balance of the system. Office buildings typically store much more heat than cold, causing the entire underground slowly to heat up and causing cooling capacity problems on the long term. This is compensated by using cold outdoor air to store additional cold during the winter, called regeneration. Model Predictive Control (MPC) is used to control the amount of regenerated cold to maintain the ATES balance. The key element in the method is the reference model built from Big Data learning by the Building Energy Management System, to calculate the expected behaviour of the system and use it as model for MPC for the heat pump. Using MPC it was possible to keep the ATES in balance over a simulated 20 years period. By using a slight cold surplus as target, the effect of exceptionally warm winters is minimal and extraction temperatures are very constant. For the case study building it can be concluded that MPC, using the developed reference model, is capable of automatically controlling the heat pump and maintaining the ATES balance. Because the case study building type and size is comparable to the majority of the new Dutch office buildings, it is expected that large parts of the method are universally applicable.

Keyword: Model Predictive Control; heat pump; Aquifer Thermal Energy Storage; Big Data modelling

Introduction

In the Netherlands almost all sustainable offices apply heat pumps combined with geothermal ATES systems for seasonal heat and cold storage. By this cooling and heating can be achieved with a relatively low primary energy consumption. Buildings constructed during the last decade have high standards of air-tightness and insulation. As a result, for office buildings which typically have a high internal heat load (heat generated by people, lighting and equipment), the required amount of external heat is relatively low compared to residential buildings. Also as a result the required amount of cooling is significantly higher than that for heating. This leads to a problem as the principle of an ATES system is based on transferring groundwater between two separated storage wells to generate ideally an energy balance between stored heat and cold. During summertime water is extracted from the coldest well and used to cool the building and increasing the water temperature from approximately 8°C to 16°C. The heated water is injected in the warmer well and stored until winter season. During winter the extraction/injection flow is reversed and the heated water (which still has a temperature of approx. 14 °C) is pumped back to heat the building. As a result of this the water is cooled to approx. 6°C and injected in the cold well. A heat exchanger between the groundwater and the building system water is used to avoid direct hydraulic connections between the water flow within the wells and that within the building as they both need their own pressure regime. The storage wells can be located horizontally or vertically spaced to each other. A horizontally spaced system is called a doublet and has the highest thermal capacity because the total length of the well can be used to inject or extract water. A vertically spaced system is called a mono-well, see Fig. 1. A mono-well has less capacity, but is significantly cheaper because only one borehole is needed. Therefor as a case study an office was selected which uses a mono-well system.

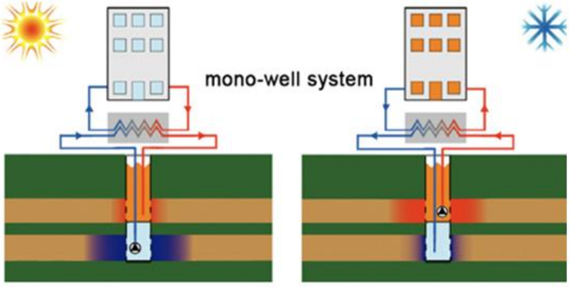

Figure 1. Mono-well ATES systems (modified from IF 2015)

For efficient and profitable application of a mono-well ATES system there are a few boundary conditions, which make the Dutch soil structure particularly suitable. The groundwater level should be relatively close to the ground level, to avoid expensive deep drilling. A large part of the Dutch soil consists of alternating layers of sand and clay, making it likely that a suitable separation layer can be found. Maintaining the energy balance of the wells over a period of 5 years is needed by Dutch regulations, so that there will be no real change of the thermal conditions of the underground effecting the direct environment. However, even if the building operates exactly as intended, this does not imply that the ATES will always achieve a thermal balance. The stored amounts of energy are influenced by climate variations (i.e. warmer winters) or variations in building use (i.e. internal heat load, building occupancy); these are uncontrollable and unpredictable. Therefor ATES-coupled systems are usually combined with possibilities for energy regeneration capacity, which supplies additional controllable amounts of energy to the storage to restore balance. A main challenge is to define how much regeneration is required (because of the uncontrollable part) and how to realize it in the most efficient way. The long-term performance of the ATES system is the cumulative result of all hour-to-hour events, therefore to optimize the total stored energy is to monitor each individual event. The analyzed method used here for this goal is model predictive control (MPC) (Ma et al 2009). MPC is used to control the amount of regenerated cold to maintain the ATES balance over a longer period of years. Key element in this MPC approach is the reference model to predict the expected stored amount and the use of the heat pump. In this article the focus is on modelling the heat pump.

2. Methodology

MPC is not a specific control strategy, but a broad range of methods that all use a (simplified) model of the system for behavior prediction and as input for the control strategy. MPC is a more intuitive (human) way of controlling a system. It is for example easily compared with the decision if we need to bring an umbrella (by using the weather forecast) or the needed force on the brake pedal while driving a car in traffic (by making a prediction of the surrounding cars' behavior and risks) (Robert et al 2011). Conventional controllers only take the past and current situation in account (find an umbrella when it starts to rain and hit the brake when hitting something). Fig. 2 shows the basic principle of MPC with as an essential component the Prediction Horizon stating within how much time form point 'k' the reference trajectory (target state) should be reached.

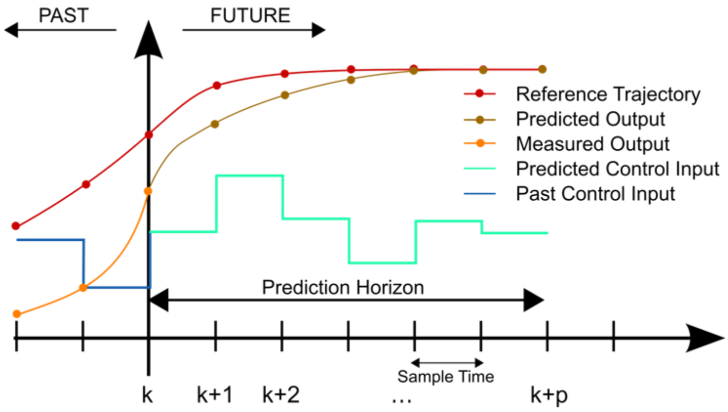

Figure 2. MPC basic principle (Behrendt 2009)

The key element in model predictive control is an accurate reference simulation model. The more accurate this model, the higher the potential of an accurate and good result. The model should be an integral solution for the ATES behavior (the storage), HVAC system performance and heating / cooling loads, because only by analyzing the whole combination a predictive model can be constructed. The model must be capable of adapting to changes in building use or equipment performance. This implies the model should be merely based on data extracted from the building management system (BMS). A model based on this method uses data generated by the building and is not based on static assumptions or calculations. The general modeling concept is: 'Learning from the past how the building will behave in the future'.

This research is based on a case-study building of which the ATES system has a structural yearly surplus of stored heat. This results in cooling problems during summer and high-energy use for regeneration. In the original designs a surplus of cold was expected (Claessen 2013), which makes the case-study interesting. In this research an analysis is made if MPC is capable of maintaining the thermal balance of the ATES heat pump system. A reference trajectory is set on the required amount of stored cold during the winter and MPC is used to control the amount of regenerated energy. If the stored amount of cold deviates from the reference trajectory, the control input or regeneration is adapted to reach the reference trajectory within the prediction horizon. A simulated analysis is performed (not an actual implementation) to check if the suggested MPC method is capable of maintaining the thermal balance. In this article the focus is on modelling the heat pump and its functions.

3. Case study

The developed model is based on a case study on an office which houses approx. 150 employees (Hoving 2015). The building is constructed in 2004 and has a GFA (gross floor area) of roughly 5500 m2. Like a typical ATES coupled system, the HVAC system is designed for low-exergy (Hepbasli 2012) operation (using low temperature (<50°C) heating water and high temperature (>10°C) cooling water). The low temperature heating is needed to reach a high efficiency on the heat pump and the high temperature cooling is needed to directly utilize the cold water supplied by the ATES system. The system is mainly based on heating and cooling via the ventilation air.

The water distribution system transfers the heat and cold from the 'generating components' to the 'distributing components'. Other than conventional building systems, the system in the case study office is quite sophisticated and offers a lot of possibilities to (re)distribute the heating and cooling loads, see Fig. 3. The main generating components are:

The ATES system: always tries to supply water of 12 °C to the building. The maximum heating or cooling capacity of the system depends on the extraction temperatures and the temperature difference over the heat exchanger. During standard operating conditions the ATES system can deliver a rated capacity of roughly 150 kW ([28]) of heating or cooling power for a ΔT of 8K.

The heat pump: The 12°C water supplied by the ATES system can be directly used for cooling, but for heating a heat pump [38] is used. The capacity of the heat pump is ±50 kW, which is enough to provide >90% of the yearly heating energy. The heat pump is a single-stage (on/off) type. Two buffer vessels of 800 liters are coupled to the warm and cold side to provide the heating or cooling when the heat pump is off.

The district heating: The district heating is used to provide peak heating when total heating load is higher than the maximum capacity of the heat pump. It can also be used as backup heating or alternative heating in the (unlikely) case of a cold surplus in the ATES system. The system is connected via a heat exchanger to the district heating pipes which provide water of 90°C. The rated capacity of the system is 120 kW.

The distribution components are separated in central and local distribution. Central distribution is provided via the air handling unit and dependents only on the outdoor temperature and the heating curve. Local distribution is provided on office level and depends on the local heating or cooling load per office. The main distribution components are:

AHU heating/cooling coil: Can be used for both heating and cooling (+ dehumidification) using a change-over principle. For cooling mode the coil is directly coupled to the ATES system. In heating mode the coil is coupled via a heat exchanger to the warm water distribution system.

Local heating/cooling group: The local heating group is the combination of all chilled beam units, duct heaters and floor heating(/cooling) systems.

All components are linked by the water distribution system, which uses various valves and pumps to distribute the water through the building. The general principle diagram of the water distribution system is shown in Fig. 4. The states of the distribution network are defined by the buildings control software. This software is based on a technical description that describes how the system should operate and the model is constructed accordingly.

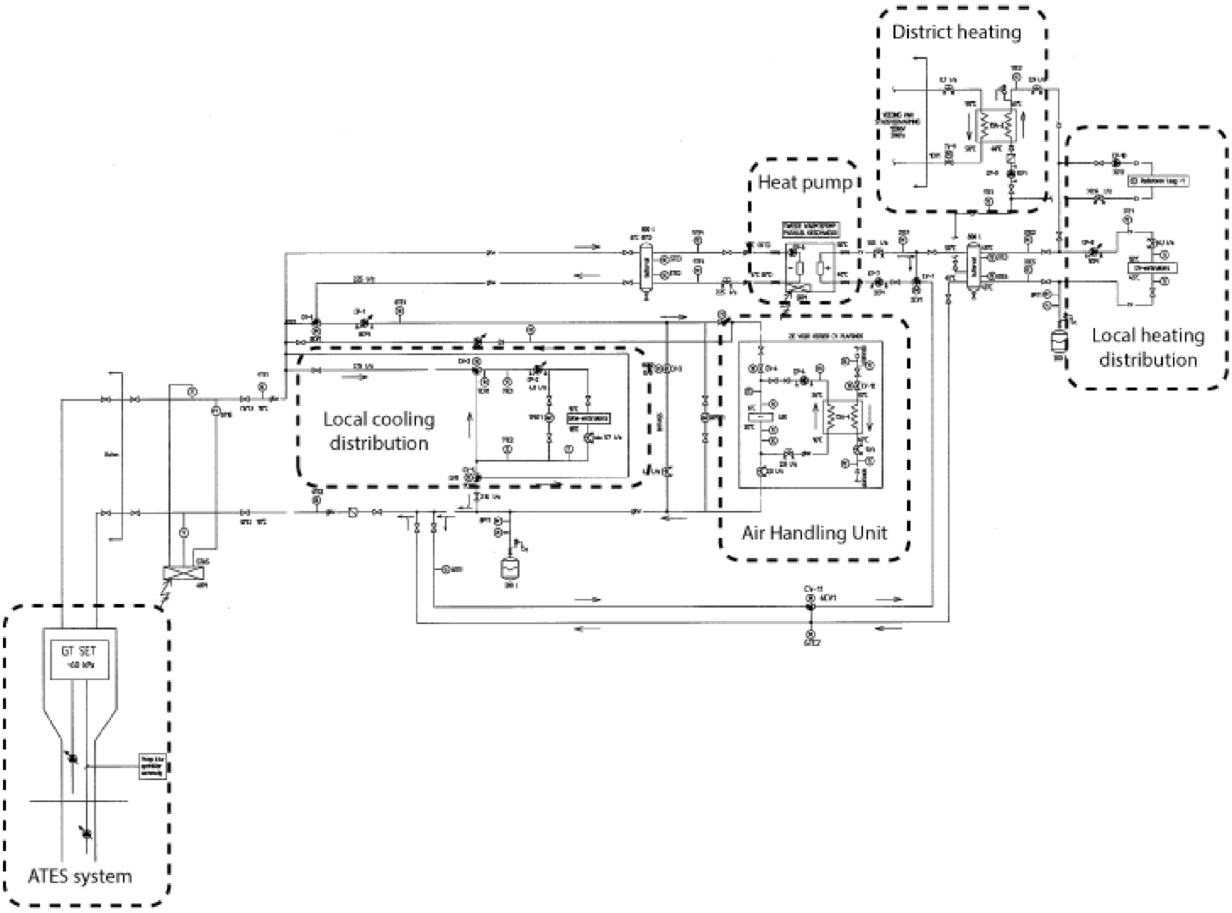

Figure 3 - Principle diagram water distribution

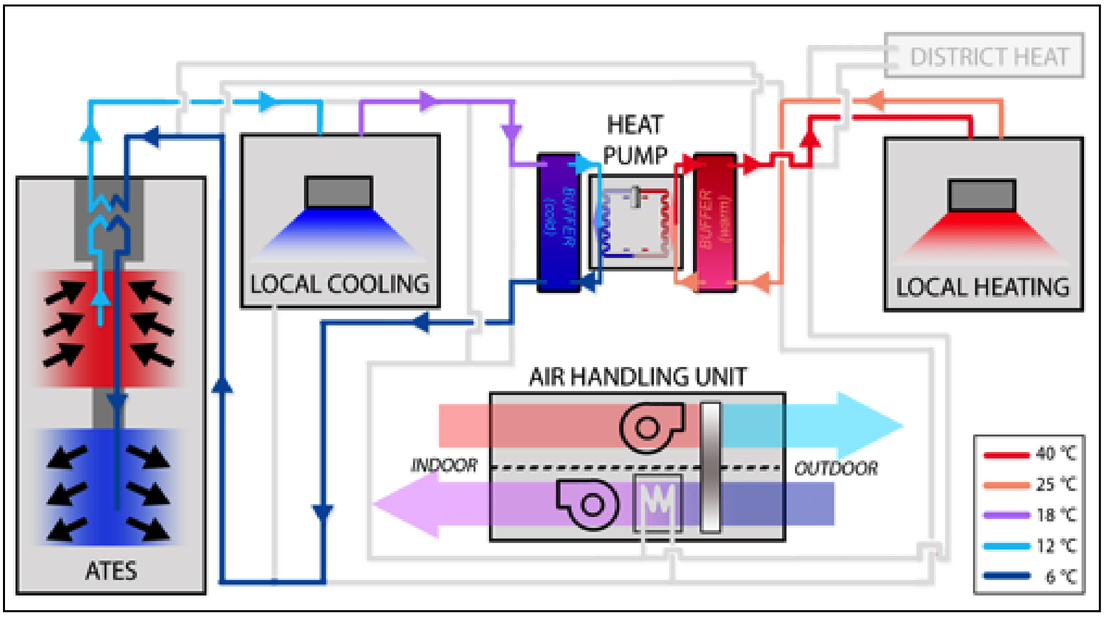

Figure 4. Simplified basic principle diagram water distribution

4. Heat pump simulation method

The influence of the HVAC system on the ATES system can be simulated using methods for three main subsystems: the air handling unit, the local heating groups and the heat pump. As all heating components do only influence the ATES via heat pump, the summed load of all heating components is sufficient for simulations (without analyzing the separate parts).

The installed heat pump has a very straightforward on/off design, which makes its behavior easily predictable. The simulation method is based on two components: efficiency and compressor electricity use.

The Coefficient of Performance (COP) of a heat pump is the ratio between produced heat and the added electric energy. It depends on the temperature difference between the cold side (evaporator) and the warm side (condenser). The theoretical efficiency is determined using the Carnot efficiency (eq. 1). The actual achieved COP is a factor of the Carnot COP. This factor is called the irreversibility factor (k) (eq. 2).

$$\mathrm{COP}_{carnot} = \frac{\bar{T}_{warm}}{\bar{T}_{warm} - \bar{T}_{cold}} \tag{1}$$

$$k = \frac{\mathrm{COP}_{actual}}{\mathrm{COP}_{carnot}} \tag{2}$$

The temperatures are in degrees Kelvin and the mean values are calculated using the Logarithmic Mean Temperature Difference (LMTD) method. The k-factor varies as function of both COP’s, depending on the heat pump design. Every heat pump is designed for an optimal temperature range, where it achieves the highest k-factor.

The electricity use of a heat pump depends on the amount of work the compressor performs. When the ΔT between condenser and evaporator increases, the required pressure for the gas to condensate increases. This increases compressor load and so electricity use. Figure shows the schematic overview of the heat pump and buffer vessels.

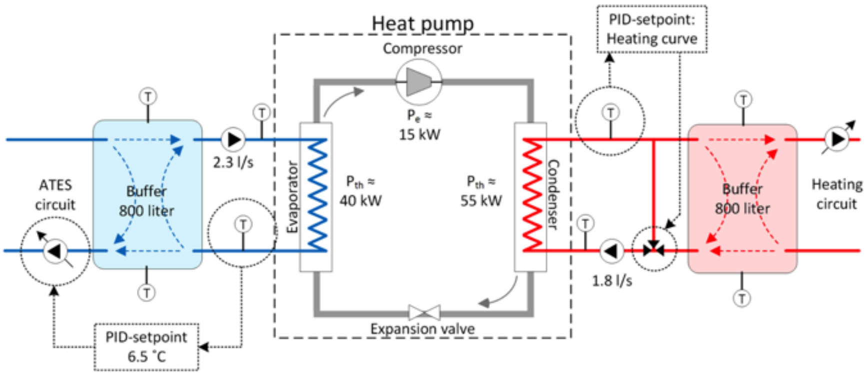

Figure 5 - Heat pump system diagram

The cold (ATES circuit) water flow through the cold buffer vessel is PID-controlled to keep the return temperature on the evaporator side at 6.5 °C. The ΔT over the evaporator is roughly 4 °C, so the mean evaporator side temperature is 8.5 °C. The flow over the ATES circuit is slightly lower than over the heat pump circuit, because of the larger temperature difference (12°C / 6.5°C for the ATES circuit versus 10.5°C / 6.5°C for the heat pump circuit). Because the flow over the heat pump is higher, the supplied temperature to the ATES circuit can be safely assumed to be also 6.5 °C. Using this assumption the ATES circuit flow can be calculated using equation 3.

$$q_{heatpump}[l/s] = \frac{\mathrm{P}_{hp,evap}}{(\mathrm{T}_{ATES} - 6.5) * 4.2} \tag{3}$$

Because the evaporator side temperature is assumed to be constant (at 8.5 °C), the condenser side temperature is the only variable of the heat pump behavior. The condenser side temperature is controlled by a heating curve and a PID-controller. The PID controls the 3-way valve in the supply water, which recirculates a part of the heated water to reach higher supply temperatures. The ΔT over the condenser is roughly 7°C. The heat pump is started when the upper buffer temperature sensor drops below the heating curve temperature and stops when the bottom buffer sensor gets above the heating curve temperature. This causes a variable condenser side temperature during this start/stop cycle. In the beginning the supply temperature is approx. 7 °C below the heating curve and the return temperature is equal to the heating curve. At the end of the cycle the supply temperature is nearly equal to the heating curve and the return temperature is 7 °C above the heating curve. It is assumed that the average condenser temperature over a cycle is equal to the heating curve.

5. Data analysis

In this section the data extracted from the BMS is analyzed to find the needed data fits. The used dataset contains the data of 2013 and values are filtered on steady state operation (>2 time samples) without the first value (to exclude startup effects). Fig. 6 shows the k-factor is decreasing at higher Carnot COP's. This (correctly) indicates the heat pump is optimized for (high ΔT) heating use instead of being a cooling machine. The k-factor is fitted using equation 4.

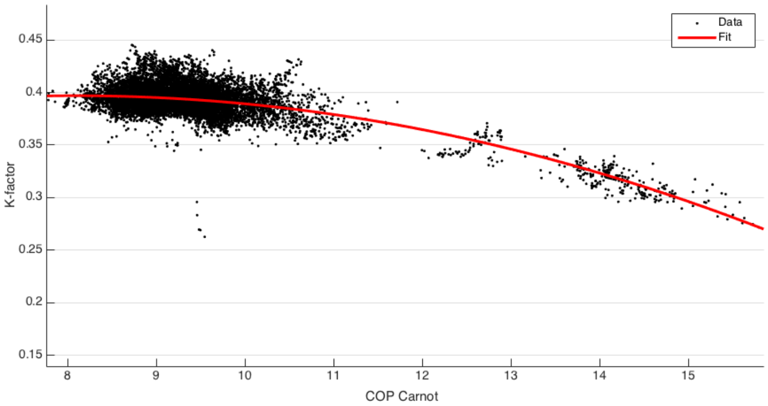

Figure 6 - Heat pump K-factor / irreversibility factor

$$\mathrm{k} = -0.0021 * COP_{carnot}^{2} + 0.034 * COP_{carnot} + 0.259 \ \ (\mathrm{R}^2\text{: } 0.949) \tag{4}$$

Fig 7. shows the heat pump electricity use. The electricity use is reconstructed from the difference between heating and cooling capacity. The actual electricity use can be higher, because of energy losses and auxiliary energy use (pumps, electronics). As predicted, the electricity use (proportional to the compressor load) increases at lower COP's. The graph is fitted using equation 5.

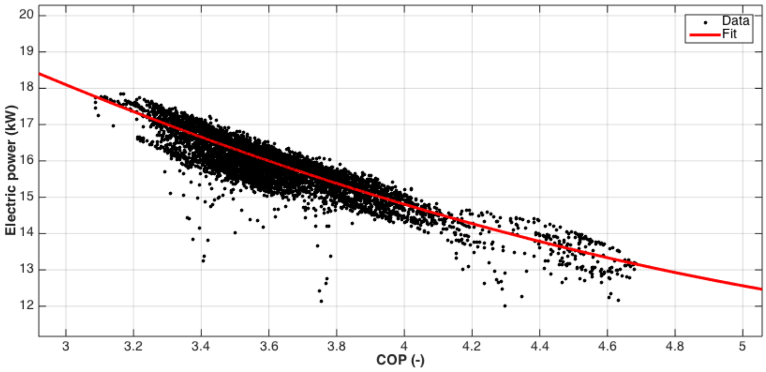

Figure 7 - Electricity use heat pump

$$\mathrm{P}_{el} = 0.523 * COP^2 - 6.95 * COP + 34.3 \quad (\mathrm{R}^2\text{: } 0.81) \tag{5}$$

Fig. 8 shows the measured mean condenser temperature and the heating curve. In the heating mode (-5°C to 15°C) the temperature varies ±5°C. In cooling mode the temperature is 5°C higher than expected. The deviations are mainly caused by leaking of the 3-way mixing valve in the condenser circuit (Figure 5).

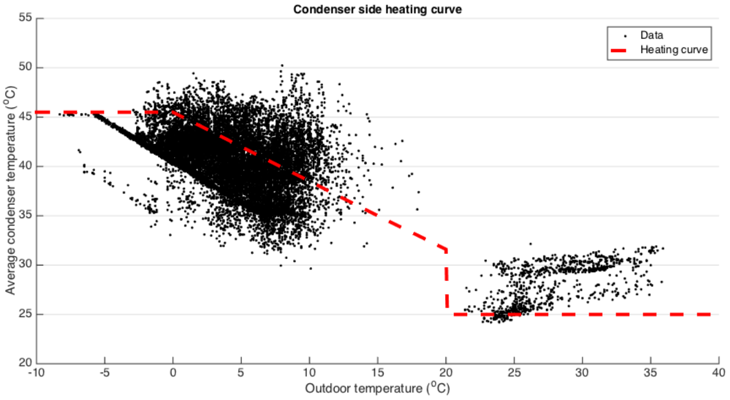

Figure 8 - Heat pump heating curve analysis

Using the derived equations the behavior of the heat pump can be calculated in five steps:

1) The condenser temperature derived from the heating curve and outdoor temperature
2) The Carnot COP calculated from the mean condenser temperature and the assumed evaporator temperature of 8.5 °C
3) The actual COP calculated using the k-factor equation
4) The electricity use calculated based on the actual COP
5) Using the electricity use and actual COP the heating and cooling capacity can be calculated

As shown in Fig. 8 the main inaccuracy of this calculation is caused by the mismatch between condenser temperature and heating curve. For that reason only step 2 to 5 are evaluated. Fig. 9 shows the results of the simulation versus the actual measurements. The measured values are filtered on steady state operation (>2 time samples) and a mean evaporator temperature within 1 °C of the assumed 8.5 °C. The simulated curves on average match the measurements, but with a scattered distribution.

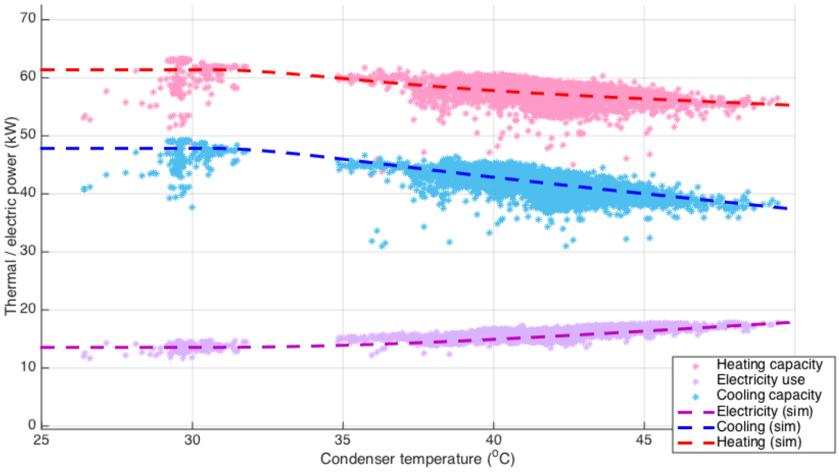

Figure 9 - Heat pump performance at variable condenser temperature

From analysing the amount of stored heating and cooling energy without regeneration of the case study building, it became clear that it has a structural surplus of stored heat. This makes the stored amount of heat the leading input variable for controlling the amount of (compensating) regenerated cold. The amount of heat stored in the summer season must be compensated by the amount of generated cold in the winter season. Therefor the MPC method is only evaluated during winter season than there are two sources of cold: cold generated by the heat pump and by regeneration. The cold generated by the heat pump is influenced by the heating load of the building, which is coupled to the outdoor temperatures and is uncontrollable. The amount of regeneration is influenced by the setpoint temperature below which the regeneration is active and is there for controllable. The higher the setpoint, the higher the probability that regeneration must be used. As a result the amount of regenerated cold is manageble by increasing or decreasing the chance on outdoor temperatures below the setpoint. Combined, this means the total amount of stored cold becomes controllable.

The storage goal is the required amount of stored energy at the end of the winter. There are two approaches to define the storage goal: keeping the energy balance around zero or maintaining a certain amount of stored cold as energy buffer. Both methods reach a yearly balance, but the difference is found in the offset of this balance. Because the building thermal summer conditionsdepends largely on the ATES' cold-water storage for its active cooling, it makes sense to store additional cold water to improve reliability. For this simulation an energy balance of minus 100 MWh is used as target for the end of the winter. This value is arbitrary, but can be argued using the assumption of a typical cooling load (per summer) of around 100 MWh.

The implementation of this method has two steps. First the amount of regeneration, needed to reach minus 100 MWh at the end of the winter (using a reference winter dataset), is calculated. The curve of the stored amount of energy (using the result of this calculation) is stored as 'goal curve'. Using the 'actual weather dataset', the building is simulated and the progress of the storage is compared to the (reference) storage curve. Every first day of the week, the reference weather dataset is used to calculate the needed setpoint to get back on the goal curve.

This section gives an example of application of the method for three years. First the goal curve is defined and next the MPC implementation is showed. As reference winter dataset the winter of 2008-2009 is used, as this winter is the most recent 'reference climate year' (Imsirovic and Molenaar 2011). By simulating the energy stored during the winter as function of the regeneration setpoint, the graph of Fig. 10 is plotted.

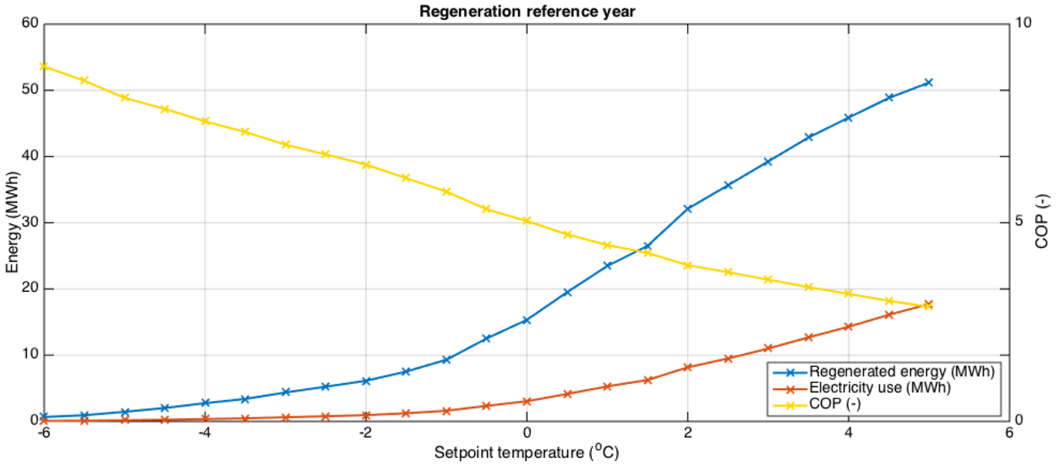

Figure 10. Regeneration curves after reference winter

The amount of cold stored by the heat pump during the reference winter is 88.1 MWh. If for instance the energy balance is +21 MWh at the start of the winter, 121 MWh of cold must be stored to reach the goal of -100 MWh. If the amount of cold stored by the heat pump is distracted, 121 – 88 = 33 MWh is left which must be generated using regeneration. As visible in Fig. 10 the setpoint temperature should be 2°C. If the reference model is simulated using the setpoint of 2°C/ and starting at 21 MWh ATES balance, the reference curve shows indeed an ATES balance of -100 MWh at the 1th of April, see Fig. 11.

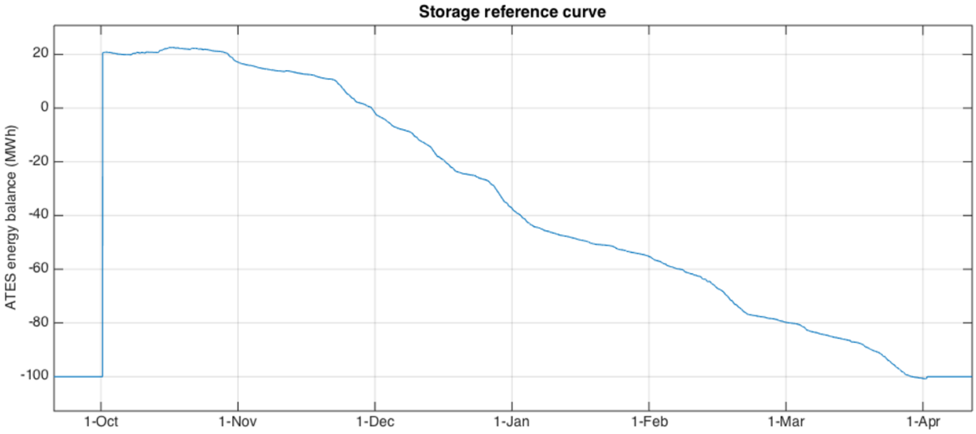

Figure 11. Storage reference curve example

This curve is the target curve for the MPC model. Every first day of the week, a simulation the prediction horizon of 4 weeks is simulated (similar to Fig. 5) to determine the setpoint at which the target curve is met after 4 weeks. If the actual winter is warmer than the reference winter, the setpoint increases to compensate for the less generated cold by the heat pump (and vice versa for a colder winter). Fig. 12 shows the results of three years of MPC simulation. As clearly visible in the last year, the setpoint is 4°C (max. value) when the actual stored energy is above the goal curve and -5°C (min. value) if too much cold is stored. If the curves match, the setpoint lays between these values.

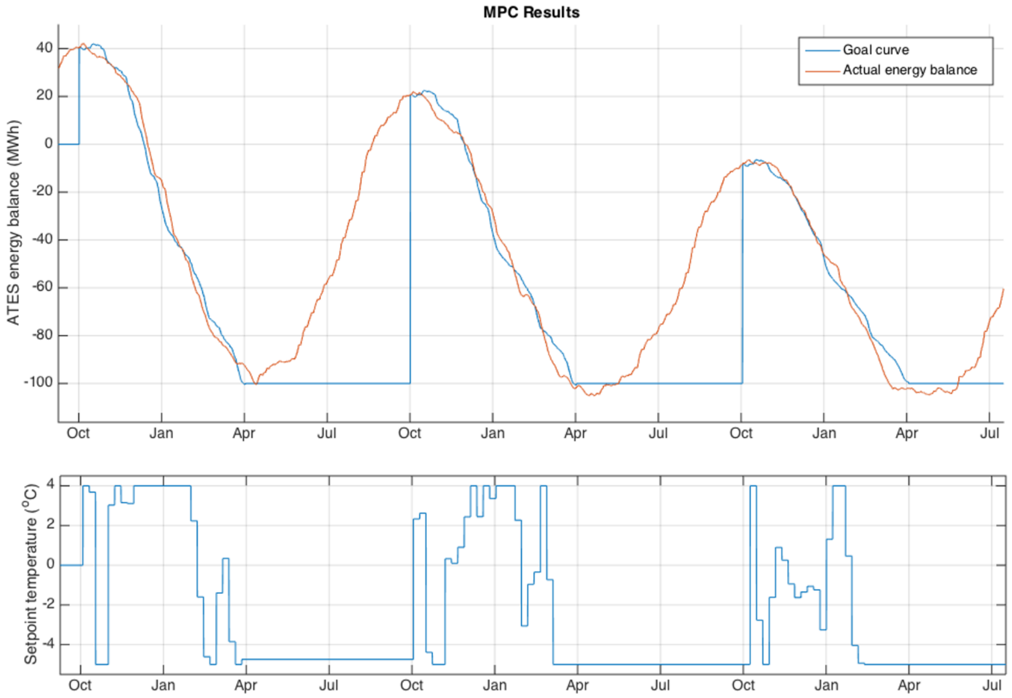

Figure 12. MPC energy storage simulation and setpoint temperatures

To test if the method is capable of maintaining the ATES balance over a longer period, a dataset of 25 years is used. The dataset is collected from a nearby weather station (‘De Bilt’) (KNMI 2015) and data from 1990 until 2014 is used. The result is shown in Fig. 13.

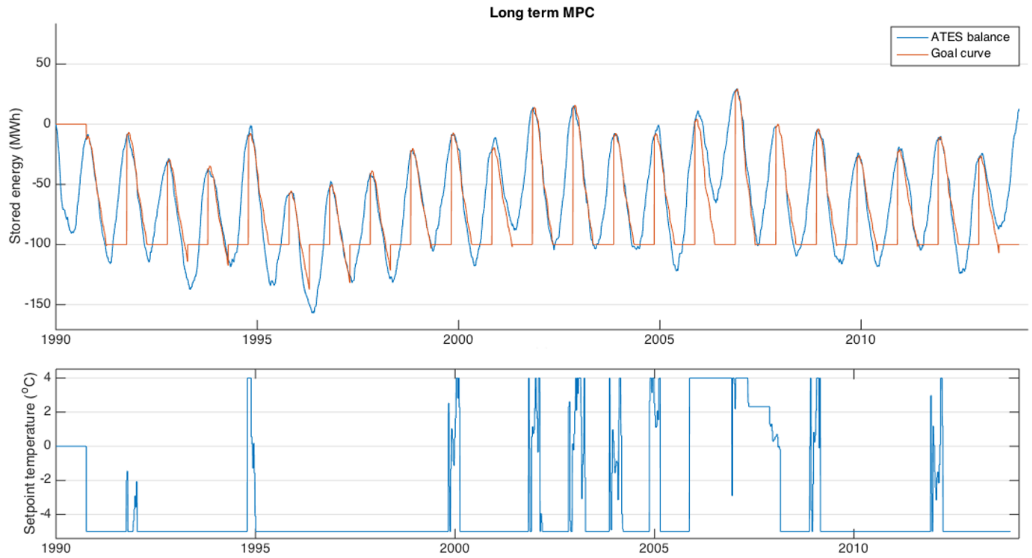

Figure 13. Long term MPC simulation

The graph shows that in the first half of the simulation hardly any regeneration is needed. The stored amount of cold is often even larger than the storage goal, even without regeneration. If this is a structural problem, a regeneration method to store additional heat should be developed. After 2005 an example is visible of the opposite problem. Two warm summers combined with a soft winter that cannot supply enough cold to reach the storage goal. On average however, the MPC method proved to be capable of maintaining the ATES balance over a longer period.

6. Discussion and conclusions

In the Netherlands now a days an almost standard solution for more sustainable office buildings is the use of heat pumps in combination with ATES. Because the case study building type and size is comparable to the majority of the new Dutch office buildings, it is expected that large parts of the method are universally applicable for future designs. The heat pump simulation method is based on reconstructing the elementary characteristics of the heat pump (k-factor and electricity use). This method is applicable to all single stage (on/off type) heat pumps. Although this method simulates how the heat pump behaves when active, it does not define for what period the heat pump is active. The analysis of the heat pump data and development of this simulation method reveals a key challenge for this way of modeling. To predict the behavior of a component, the component itself has to behave predictable. The cyclic on/off behavior of the heat pump can be simulated using a much shorter time interval (for example 10 seconds), but with the logged 8-minute data it is difficult to analyze the short-term fluctuations. Nevertheless, the general behavior of the heat pump showed to be predictable as function of the condenser temperature. The actual effect of the large condenser temperature variations showed to be minimal, because the capacities do vary only a few percent within a 5°C range of condenser temperatures.

The modeling results are based on historical data instead of manufacturer specifications. The methods proved that data analysis is a powerful tool for reconstructing relations of underlying physical phenomena and the construction of simulation models. To successfully apply these methods, three conditions must be met:

- Sensor accuracy. The actual accuracy of used temperature sensors is currently ±1K, which is not accurate enough for these methods. Installation of more accurate sensors (±0.1K) and periodically calibration is required.
- Minimize assumptions. Placement of more flow sensors in the system increases simplifies modeling and increases model robustness.
- Dataset coherence. As the logging of all sensors in the building takes around 5 minutes which means that for the statistical average, the supply and return temperature of a HVAC part are measured 2.5 minutes apart. For an accurate dataset, logging should be done within a few seconds.

The used method for MPC (Hoving 2015) was relatively simple as the main goal was to show that even using something unpredictable as the weather as input, it is still possible to control the use of the heat pump, regeneration and the resulting amount of stored energy in the ATES. The presented results are intended as a 'prove of concept' and do not pretend to be the best possible method.

References

Claessen, R. N. H., 2013, Improving the accuracy of ATES system design predictions, MSc Thesis TU Eindhoven.
Hepbasli A., 2012, Low exergy (LowEx) heating and cooling systems for sustainable buildings and societies," Renewable and Sustainable Energy Reviews 16(1):73–104.
Hoving J.H.K., 2015, Maintaining ATES Balance using continuous commissioning and model predictive control, Masterthesis TU Eindhoven, Eindhovven, Netherlands
IF, 2015, IF Technology, www.iftechnology.nl.
Imsirovic F. and Molenaar R., 2011, Comfort in tijden van klimaatverandering, TVVL Magazine 10: 4–6.
KNMI, 2014, Uurgegevens van het weer in Nederland, http://www.knmi.nl/klimatologie/uurgegevens/selectie.cgi.
Kousksou T., Bruel P., Jamil A., El Rhafiki T., Zeraouli Y., 2014, Energy storage: Applications and challenges, Solar Energy Materials and Solar Cells 20(1):59–80.
Kranz S., Frick S., 2013, Efficient cooling energy supply with aquifer thermal energy storages, Applied Energy 109: 321–327.
Ma Y., Borrelli F., Hencey B., Packard A., Bortoff S., 2009, Model Predictive Control of thermal energy storage in building cooling systems, Proceedings of the 48h IEEE Conference on Decision and Control (CDC) held jointly with 28th Chinese Control Conference.
Robert H., Bars R., Schmitz U., 2011, Predictive Control in Process Engineering, Wiley.