

Optimal Operation of Ground Coupled Heat Pump Systems: Should We Take the Seasonal Time Scale into Account?

Stefan Antonov¹, Clara Verhelst², Lieve Helsen³

*Department of Mechanical Engineering, KU Leuven
Celestijnenlaan 300A, post box 2421, B-3001 Heverlee, Belgium*

¹stefan.antonov@mech.kuleuven.be

²clara.verhelst@gmail.com

³lieve.helsen@mech.kuleuven.be

Abstract

Optimizing the control of a ground coupled heat pump system requires consideration of the building dynamics as well as of the borefield dynamics. The former is important to satisfy thermal comfort and to assess the heating and cooling loads. The latter is important to determine the efficiency of heat pump operation and passive cooling (bypassing the heat pump in cooling mode). While the time constants of the building range from hours up to days, the dynamic range of a borefield is up to multiple years. Within an online optimization framework such as model predictive control, it is computationally expensive to include the entire dynamic range from the hourly time scale to the (multi)annual time scale. The question arises to which extent the long term time scale influences the optimal system operation. This paper addresses this question for a hybrid ground coupled heat pump system with a backup gas boiler and a backup (active) chiller for a cooling dominated office building. To this end, the optimal operation – found by solving the optimal control problem for a prediction horizon of one year – is compared to the operation obtained with model predictive control with a receding horizon of 1 week. The results show that the operation with the 1-week horizon is identical to the one found with a 1-year horizon. This indicates that for the considered system there is no optimization potential at the seasonal time scale. The study shows that seasonal thermal energy storage is not an optimal control strategy for the specified system.

Keywords – hybrid ground coupled heat pump systems; seasonal underground thermal energy storage; model predictive control; optimal control;

1. Introduction

Ground coupled heat pump systems are ideally suited for buildings requiring both heating and cooling. The heat injected to the borefield in summer recharges the borefield for the heating season. Or, to put it the other way around, heat extraction in winter cools down the borefield such that one can make more use of passive cooling in summer. One of the important questions to be resolved is how to operate the system when the building heating and cooling loads are imbalanced. Should we prevent borefield

thermal buildup in the case of a cooling dominated building? Should we restrict the use of passive cooling in order to balance the annual heat injection and extraction loads? Is it advantageous to extract more heat by the heat pump during the heating season, in order to have a colder borefield at the start of the cooling season? Should we inject more heat than strictly necessary during the summer in order to have a higher borefield temperature at the start of the heating season? Should we take into account the seasonal variation and the intra-day variation of the chiller coefficient of performance?

Research on the optimal operation of GCHP systems is a relatively new area, which has gained interest with the up come of hybrid ground coupled heat pump (HyGCHP) designs. Those have a lower investment cost than conventional designs since the borefield is sized to cover only the heating or the cooling demand entirely, depending on which of the two is smaller. The downside is that the HyGCHP systems are more complex to operate since it should be additionally decided when and how to use the backup heating or cooling device.

In this study, we adopt an optimal control framework to address these questions. This approach radically differs from the approach adopted in most studies in two ways.

First, in most studies the controller is defined by a set of heuristic rules with a number of tunable control parameters. Its influence on the system performance is assessed by multi-year system simulations in a dedicated simulation environment such as TRNSYS. The control is fine-tuned by varying the set of rules and/or by tuning the corresponding control parameters. This fine-tuning can be done through a trial-and-error-approach, which can be relatively time-consuming, or through a derivative-free optimization tool such as GenOpt [1]. The drawback remains, however, that the control settings can only be optimized within a limited subset of possible control actions, defined by the chosen set of heuristic rules. The optimal control framework, by contrast, allows defining the control action at each point of time such that the control objectives are optimally met, under the constraints given.

Second, most studies on HyGCHP operation assume that the building heating and cooling demand profiles are given [2]. The opportunities at building side for peak shaving and load shifting to minimize the energy cost, for instance, are thus not deployed. In this study, the control is optimized from an integrated building perspective, including the thermal dynamics at building side. This allows the controller to further reduce energy cost by shaping the heat and cold production profile based on the installed capacity of the different heating and cooling devices, the electricity price profile, and the available opportunities for (active or passive) thermal energy storage at building level. A relevant integrated system approach for optimal operation of a HyGCHP system with solar thermal energy storage is presented in [3].

In this study we apply the proposed optimal control framework approach to a HyGCHP system in a cooling dominated office building with concrete core activation (CCA). The first results presented in [4] show that the heat pump and passive cooling are used in base load. The backup heating and cooling devices are only used when the heating and cooling demand can not entirely be covered by the heat pump, respectively by passive cooling. The backup heater is switched on when the borefield fluid outlet temperature reaches its minimal value (close to 0°C, depending on the calorimetric fluid used), while the backup chiller is switched on when the borefield fluid outlet temperature reaches its maximal value (close to the cooling supply water temperature). These results were obtained by solving the optimal control problem for a representative year with a control time step of 1 hour. An important observation made was that, despite the one-year prediction horizon, we did not directly observe an attempt to use the borefield as a seasonal storage device. The results suggest that the optimal operation is governed by the short term dynamics – defined by the building time constants – only. This hypothesis is tested in this paper.

In this paper we present:

- the optimal control problem formulation (section 2)
- the results obtained by MPC with a receding time horizon (section 3.1)
- the evidence that seasonal storage is not an optimal control strategy for the considered HyGCHP system (section 3.2)

2. Methods

2.1 System description

The investigated system comprises an office building equipped with concrete core activation (CCA) which is fed by primary and back-up heating and cooling installations: ground coupled heat pump (HP), ground-coupled heat exchanger for passive cooling (PC), back-up gas-fired boiler (GB) and back-up air-coupled active chiller (CH). The ground-coupled devices are connected to a borefield (BF) of vertical borehole heat exchangers (BHEs), which do not thermally interact with each other. The hybrid ground-coupled heat pump system is sized to 3600 m² of office area conditioned by the use of a borefield of 17 BHEs with a depth of 120 m each, which are not able to cover entirely the cooling dominated loads of the building, therefore, the back-up installations should also be utilized.

2.2. Optimal control problem (OCP)

The operation of the system is determined by solving an optimal control problem, which minimizes an objective function over a specified prediction horizon and satisfies constraints. The objective function represents the operational cost of the HyGCHP as given in (1).

$$J = \sum_{i=1}^{N_p} \left[C_{EL}(i) \frac{\dot{Q}_{HP}(i)}{COP_{HP}} + C_{GAS} \frac{\dot{Q}_{GB}(i)}{\eta_{GB}} + C_{EL}(i) \frac{\dot{Q}_{PC}(i)}{\eta_{PC}} + C_{EL}(i) \frac{\dot{Q}_{CH}(i)}{COP_{CH}} \right] \Delta t_i \quad (1)$$

In (1) \dot{Q} is the heat flow delivered to- or extracted from the CCA by the device indicated in subscript, COP stands for coefficient of performance of the device indicated in subscript, η is the efficiency of the device indicated in subscript, C_{EL} – the time varying electricity price, C_{GAS} – the gas price, N_p – the prediction horizon length and Δt – the discretization time step. The constraints represent mainly a dynamic integrated system model, office building thermal comfort margins and boundary conditions. The integrated model of the HyGCHP system incorporates dynamic models of the building and the borefield, and static models of the heating and cooling devices. The model is described in detail in [4] and reused as such in the current study with the improvement that a 6th-order state space model from [5] represents the BHEs in the current investigation, instead of the 3rd-order model used previously.

Note that the COPs of the HP and the PC are assumed constant, i.e. independent of the borehole fluid temperature. This approximation has significant computational benefits since it results in a convex instead of a non-convex optimization problem. This approximation has been shown to be justified within the considered fluid temperature range and for the system studied [6].

2.3. Solving the OCP over one year: Short And Long Term Optimization (SALTO)

The optimal operation of the system is described in [4] as a result of a Short and Long Term Optimization (SALTO) and is recomputed for the case with a 6th-order BHE model to serve as a reference for the current investigation. The SALTO method computes the optimal annual control profiles of the system by minimizing annual operation cost, satisfying thermal comfort requirements, and maintaining thermal balance of the ground. For that purpose the optimization is performed over a prediction horizon of 1 year which is discretized with a 1 hour time step. One of the questions which are answered in the current study is whether the SALTO profiles could be reproduced with model predictive control based on prediction horizons of realistically shorter time scale.

2.4. Solving the OCP over a shorter time frame: MPC with receding horizon

MPC includes the same optimal control problem (OCP) formulation as the one used in the SALTO method [4], but the receding horizon approach is applied. This means that the annual control profiles for the HyGCHP system are obtained by solving the OCP repeatedly for a finite prediction horizon N_p . The first iteration is computed starting with the states of the system model

being initialized to the end-values from the SALTO solution. This way we can judge to which extent the solution found by MPC will deviate from the optimal and cyclic solution of the SALTO.

The investigated prediction horizon for MPC is 1 week. This specific length is chosen to be comparable to the time needed for the slowest thermal transient processes in the building to converge. A prediction horizon of 3 days (which is not presented here) has been shown to be too short. The discretization time step is 1 hour (as in the SALTO) and the first 24 samples (1 day) of each solution are applied for open loop control of the system. As in the SALTO, no model mismatch is implemented in STMPC, thus the system model described above is used for both controller model and to represent the controlled HyGCHP system.

2.5. Analyzing the impact of seasonal storage through a modified SALTO

An additional simulation experiment is performed to evaluate the system performance in the case the ground is actively used as a seasonal storage device for cold. To force the SALTO to make use of this seasonal storage capacity, we penalize active chiller use by a scaling factor $\alpha \gg 1$ in the cost function (2):

$$J = \sum_{i=1}^{N_p} \left[C_{EL}(i) \frac{\dot{Q}_{HP}(i)}{COP_{HP}} + C_{GAS} \frac{\dot{Q}_{GB}(i)}{\eta_{GB}} + C_{EL}(i) \frac{\dot{Q}_{PC}(i)}{\eta_{PC}} + \alpha \cdot C_{EL}(i) \frac{\dot{Q}_{CH}(i)}{COP_{CH}} \right] \Delta t_i \quad (2)$$

The solution of the SALTO with this modified cost function will be characterized by seasonal cold storage through additional heat extraction from the ground during winter and using the stored cold during summer. Due to the modified cost function (α) the system operation cost will be different. The corresponding annual system operation cost (post-computed without α) is compared to the solution obtained with the original SALTO.

3. Results and Discussion

The results presented in this paper are described in two steps. Firstly, the system performance obtained with short term MPC (STMPC) is compared to the one obtained with the SALTO. Secondly, the use of the borefield for seasonal cold storage is evaluated. The latter will allow us to clarify why it is possible to follow the optimal SALTO profiles with a STMPC strategy.

3.1. Comparison of STMPC and SALTO

The results for operation of the HyGCHP system controlled by STMPC are compared to the reference results obtained by SALTO by the following performance indicators:

- annual system operation cost
- annual thermal discomfort

- borefield temperature difference over a one-year period, evaluated at the different ground nodes
- annual heat/cold delivered to the building by the different devices
- annual net heat transfer with the borefield (heat extraction minus heat injection)

The third indicator above allows us to quantify the magnitude of borefield thermal build-up. For SALTO, the latter is by definition zero – it is implied by optimization constraints that the ground temperatures have annually cyclic values. For STMPC this may be different, since that long term performance criterion is not imposed in the OCP formulation. Additionally, the annual net heat transfer with the borefield and the total annual heat/cold delivered by the different installations are discussed. The results are shown in Table 1.

Table 1. Comparison of system performance factors resulting from STMPC to the corresponding factors resulting from SALTO

	SALTO	STMPC	Increase	Increase (%)	
Annual operation cost (€)	3806.94	3807.99	+1.04	+0.03	
Annual thermal discomfort (Kelvin hours)	80.87	79.93	-0.95	-1.17	
Ground temperature difference after 1 year (°C)	Node 1	0.00	0.07	+0.07	—
	Node 2	0.00	0.36	+0.36	—
	Node 3	0.00	0.11	+0.11	—
	Node 4	0.00	0.06	+0.06	—
	Node 5	0.00	0.03	+0.03	—
	Node 6	0.00	0.01	+0.01	—
Heat pump (kWh _{th})	5.11E+04	5.10E+04	-5.29E+01	-0.10	
Gas-fired boiler (kWh _{th})	0.00E+00	1.76E-11	+1.76E-11	—	
Passive cooling (kWh _{th})	1.20E+05	1.23E+05	+2.30E+03	+1.91	
Chiller (kWh _{th})	2.01E+04	1.85E+04	-1.64E+03	-8.15	
Annual net heat transfer with the borefield: extraction-injection (kWh)	-7.79E+04	-8.02E+04	-2.35E+03	-3.01	

It can be seen in Table 1 that for the three performance indicators – energy cost, thermal discomfort, ground temperature difference – the difference between STMPC and SALTO is negligible. STMPC is marginally more expensive (0.03%) and provides slightly more thermal comfort than SALTO, but it also slightly rises the ground temperatures. The thermal energy delivered by the heat pump is equal for both cases, and neither the use

of the gas-fired boiler is changed. STMPC however makes slightly more use of the passive cooling, and less use of the chiller. The results in Table 1 give a global annual estimation of the similarity of the system behavior with different control strategies. The annual performance indicators reveal no major differences between SALTO and STMPC.

It is also important to present the degree of similarities throughout the year. More specifically, we need to verify whether there is a potential for optimization on a seasonal time scale, or not. To this end, the profile for the borefield loads obtained with STMPC (1-week prediction horizon) is compared to the operation profile of the SALTO (one-year prediction horizon). The difference between both profiles on a weekly basis is presented in Figure 1. The presence of a seasonal control strategy could be detected in this graph as a deviation from zero.

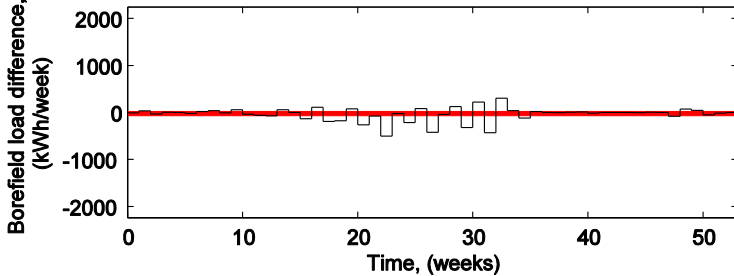


Figure 1. Difference between the borefield load profiles obtained with STMPC (receding prediction horizon of 1 week) and SALTO (one year prediction horizon). The zero-line is indicated in red.

Figure 1 shows that the differences between the two borefield load profiles do not represent a pattern related to the inter-seasonal time scale. Instead, the differences occur in particular weeks and cancel each other within neighboring weeks, which is caused by the short term prediction horizon of the STMPC. This means that the STMPC tends to reproduce on the long term the system behavior given by the SALTO. The remaining differences in weeks 21, 23, 25, and 27 show the slightly higher share (1.9 %) of passive cooling when STMPC is applied, which leads to a minor increase of the ground temperatures.

The annual profile of the office zone air temperature (T_z) is given in Figure 2. The fact that the optimal solution from SALTO is reproduced by the STMPC implies that the borefield heat extraction during the heating period, by means of heat pump heating, is not more than strictly needed to satisfy the thermal comfort requirements. T_z is kept close to the lower comfort bound. No additional heat extraction during winter is observed to store cold in the ground for use during summer by means of passive cooling in order to decrease the usage of the less efficient chiller. The question arises whether seasonal storage is physically impossible for the specified system or

whether it is possible but financially disadvantageous. This is investigated in the next section.

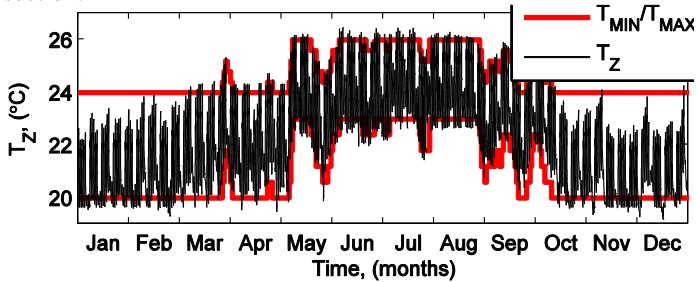


Figure 2. Office zone air temperature profile resulting from SALTO (similar for STMPCC)

3.2. Evaluation of seasonal storage

The office zone air temperature profile as resulting from a SALTO with modified cost function penalizing chiller operation (2) called tuned SALTO is presented in Figure 3 and can be compared to the profile from the original SALTO (Figure 2). It can be seen that during the heating period T_z is kept as close as possible to the upper comfort bound in the case of tuned SALTO. This is a consequence of the additional heat extraction from the ground in order to use the stored cold during the cooling period. This seasonal behavior can be clearly seen in Figure 4, which presents the difference between the two borefield load profiles (for tuned SALTO and SALTO) on a weekly basis, and compared to Figure 1. The presence of a seasonal control strategy appears in Figure 4 as a deviation from zero.

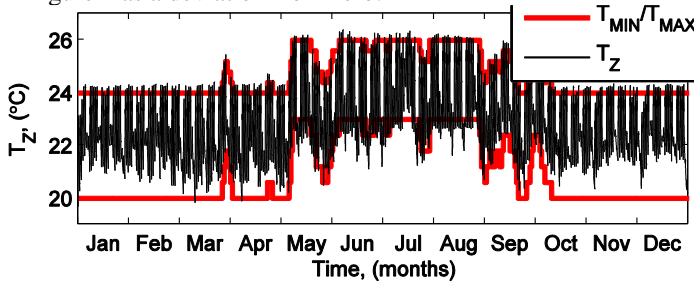


Figure 3. Office zone air temperature profile resulting from tuned SALTO

To enable a quantification of the difference between the two solutions differences in global annual heat factors are tabulated in Table 2. The results show that the total delivered heat by heat pump operation is doubled in the tuned SALTO solution. The corresponding borefield heat extraction provides the opportunity to increase the amount of passive cooling and thus decrease the chiller use, which is highly penalized in the cost function (2).

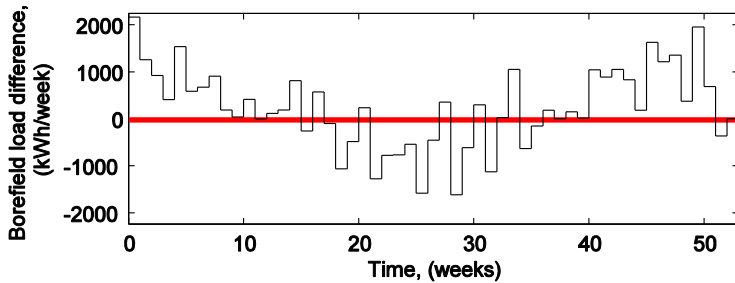


Figure 4. Difference between the borefield load profiles obtained with tuned SALTO (with penalized active chiller operation – factor α in the cost function (2)) and original SALTO

Table 2. Differences in some key factors when comparing the results from the tuned SALTO (with seasonal storage) to the results from the original SALTO

	Load increase (kWh _{th})	Load increase (%)	Cost increase (€)	Cost increase (%)
Heat pump	+2.95E+04	+58	+859	+69
Gas-fired boiler	+0.00E+00	—	0	—
Passive cooling	+1.22E+04	+10	+404	+23
Chiller	-5.50E+03	-27	-149	-18
Heating (HP+GB)	+2.95E+04	+58	+859	+69
Cooling (PC+CH)	+6.66E+03	+5	+255	+10
Heating + Cooling	+3.62E+04	+19	+1114	+29
Net heat extraction from the BF	+2.46E+04	+58		
Net heat injection to the BF	+1.22E+04	+10		

With tuned SALTO the cooling demand is covered with almost only passive cooling, however, the total amount of cooling is increased with 5 % compared to the optimal (original) SALTO. Since the maximal power rate of passive cooling is limited by the borefield properties and the prevailing temperatures, passive cooling is started in advance to operate longer at less power, which slightly increases the total cooling load.

On the other hand, and more importantly, only half of the additionally extracted heat from the borefield (BF), by increased heat pump operation during winter, is used for passive cooling during summer, as additional heat injection to the borefield (Table 2). The other half of the ‘stored cold’ is ‘dissipated’ to the far field ground. Hence, for the considered soil properties, the efficiency of the underground cold storage, which could be defined as the ratio of the additional heat injection to the additional heat extraction from the borefield, is only 50%. The results show that chiller usage is a cheaper strategy (original SALTO) than storing cold into the ground (tuned SALTO, 29% more expensive system operation – Table 2). This observation confirms

the previous findings that there is no optimization potential at the seasonal time scale, eliminating the need for a long term prediction horizon within the optimal control problem for the specified system. This is the reason why an STMPC can follow the system operation profiles resulting from the original SALTO.

4. Conclusions

There is no need to account for long term effects in the optimal control of the studied HyGCHP system. STMPC, which optimizes HyGCHP operation over a short term horizon, is sufficient. There is no potential for seasonal underground thermal energy storage in the optimal operation of the considered HyGCHP system. The usage of the back-up chiller is a cheaper alternative, which could be started at any time and can be controlled with a short term strategy. The seasonal cold storage in the ground is less efficient because the main part of the stored cold is lost in the far field before it could be used. For long term optimal operation of the system the STMPC should have a prediction horizon, which is as long as the largest time constant at building side. A long term constraint in the controller of the investigated system is not needed to achieve ground thermal balance or to guarantee long term sustainable performance. For the considered HyGCHP system the ground is naturally recharged from the far field. Future research will broaden the scope of the study towards other HyGCHP designs.

Acknowledgment

The research work of the authors is framed within the research project entitled “Black-box model based predictive control of ground coupled heat-pump systems”, funded by the Research Foundation Flanders (FWO).

References

- [1] L. Peeters. Water-based heating/cooling in residential buildings. Towards optimal heat emission/absorption elements. PhD thesis, KU Leuven (2009)
- [2] F. De Ridder, M. Diehl, G. Mulder, J. Desmedt, and J. Van Bael. An optimal control algorithm for borehole thermal energy storage systems. *Energy and Buildings*. 43(10) (2011) 2918–2925.
- [3] R. Franke. Integrierte dynamische Modellierung und Optimierung von Systemen mit saisonaler Wärmespeicherung. VDI Verlag, Düsseldorf (1998)
- [4] S. Antonov, C. Verhelst, and L. Helsen. Control of Ground Coupled Heat Pump Systems in Offices to Optimally Exploit Ground Thermal Storage on the Long Term. In: *Proceedings of Innstock 2012, The 12th international conference on energy storage, Lleida, Spain, 16–18 May 2012*. ISBN: 978-84-938793-4-1
- [5] C. Verhelst and L. Helsen. Low-order state space models for borehole heat exchangers. *HVAC&R Research*. 17(6) (2012) 928–947
- [6] C. Verhelst. Model Predictive Control of Ground Coupled Heat Pump Systems in Office Buildings. PhD thesis, KU Leuven (2012)