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Evaluation of the Potential for Efficiency Increase by the Application of Model-Based Control Strategies in Large-Scale Solar Thermal Plants

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Abstract

This paper presents a systematic evaluation procedure to estimate the potential for performance improvement by applying model-based control strategies in large-scale thermal plants. The evaluation is performed separately for the low-level control which is in charge of the temperatures in the collector fields and for the high-level control which defines the general mode of operation of a plant. In order to evaluate the potential for the low-level control, simulation studies have been carried out, based on the assumption that the individual flows through the collector fields can be controlled separately. This can be achieved by an advanced model-based control which makes use of motor-driven control valves at the inlets of the collector fields. The potential of the high-level control has been evaluated by energy calculations based on measurement data from a typical large-scale solar thermal plant. The evaluation finally identified a potential for efficiency increase in the range of 8% for the low-level control and about 3% for the high-level control.

Keywords:	Performance evaluation; Model-based control; Large-scale solar thermal plant; Solar thermal

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1. Introduction

Control systems for large-scale solar thermal plants are typically hierarchically structured. On a high-level basis a set of rules defines the general mode of operation (e.g. feeding the heat into a district heating network vs. storing it in a local buffer storage) whereas on a low-level basis mainly linear PID controllers control the different temperatures in the plant. Unfortunately, both control levels do not fulfil their tasks in a truly satisfactory way. They neither consider the non-linear and coupled characteristic of such plants (see e.g [2, 3]) nor do they take into account any information on future weather conditions. The available measurement data of different large-scale solar thermal plants clearly reveals that the control systems currently applied show a suboptimal high-level control and especially a poor performance of the low-level control at varying ambient conditions. This leads to significant efficiency losses.

For both, high-level and low-level, control model-based control approaches are regarded as the most promising attempts to solve these problems, since they enable to explicitly consider the physical characteristics or incorporate weather forecast data. The advantages of such advanced model-based control methods over classical methods have repeatedly been demonstrated, e.g. [2-7, 9]. Regarding the high-level control of solar thermal plants, in [6] an analysis of the potential of model predictive control strategies was carried out, concluding that there is scope for increased energy savings by a model predictive control. In [7] this assumption was verified, presenting that the primary energy consumption of solar thermal plants can be reduced by 5% when updating the high-level control strategies; yet such evaluations which give concrete numbers for the improvements by a model-based control method for solar thermal plants are rarely found in the literature. In most cases the description of the improvements achieved by model-based high-level control strategies are rather vague, e.g [3, 5], and the improvements by a model-based low-level control are not considered at all.

For this reason, this paper firstly presents a systematic evaluation procedure to estimate the potential for performance improvement by applying model-based control strategies on both levels (low- and high-level) in large-scale solar thermal plants. To evaluate the potential two reasonable assumptions have to be made: the solar thermal plant is equipped with controllable valves at every inlet of the collector fields, which allow to individually control the collector outlet temperatures, and forecast data for the weather is available. The evaluation of the performance improvement is performed on the basis of measurement data from a typical large-scale solar thermal plant.

2. Investigated solar thermal plant

The investigated plant has a nominal capacity of 2 MW and a collector area of approximately 3,900 m². The collector field consists of 24 parallel subfields which differ in size of their collector area from 96 m² to 174 m². These differences in size have their origin in the optimization of the collector area under the local constraints of the place of installation, as it is often the case for plant installations in urban areas. In order to ensure an adequate flow distribution in the individual subfields to avoid exergy losses by mixing flows with different temperatures, the individual fields are equipped with manually adjustable balancing valves, e.g. [1]. However, perfect balancing of the different subfields can just be achieved for one specific operating condition, typically for nominal load, while deviations of the outlet temperatures occur under all other operating conditions [8]. In order to achieve an adequate flow distribution for every operating condition, servomotor driven controllable valves would be necessary. In order to investigate the potential for improvement by the application of automatically adjustable valves, 7 of the 24 subfields have been recently equipped with controllable valves at their inlet.

The plant is supplemented by a heat pump as well as a buffer storage with a volume of 64.6 m³. Several local consumers are connected to the buffer with a connection power of 505 kW. In addition, there is the possibility of feeding into a district heating network (DHN). Thus, there are several heat sinks (feed to the DHN, direct feed into the buffer storage, indirect feed into the buffer storage via the heat pump). The consumers are always supplied from the buffer storage, which can also be recharged from the DHN if a lack of solar energy occurs. Except for the heat pump the investigated plant can be considered as a typically modern large-scale solar thermal plant. A schematic representation of the investigated plant is shown in Figure 1.

3. Evaluation method

The basis of the evaluation is a comprehensive analysis of measurement data from the solar thermal plant depicted in chapter 2, finally leading to a classification of the operating conditions on a daily basis. In doing so, half of a year is investigated and separated into several categories. Each category is subsequently represented by a so called model day. These model days describe the average day of the different categories with respect to energy quantities and ambient conditions.

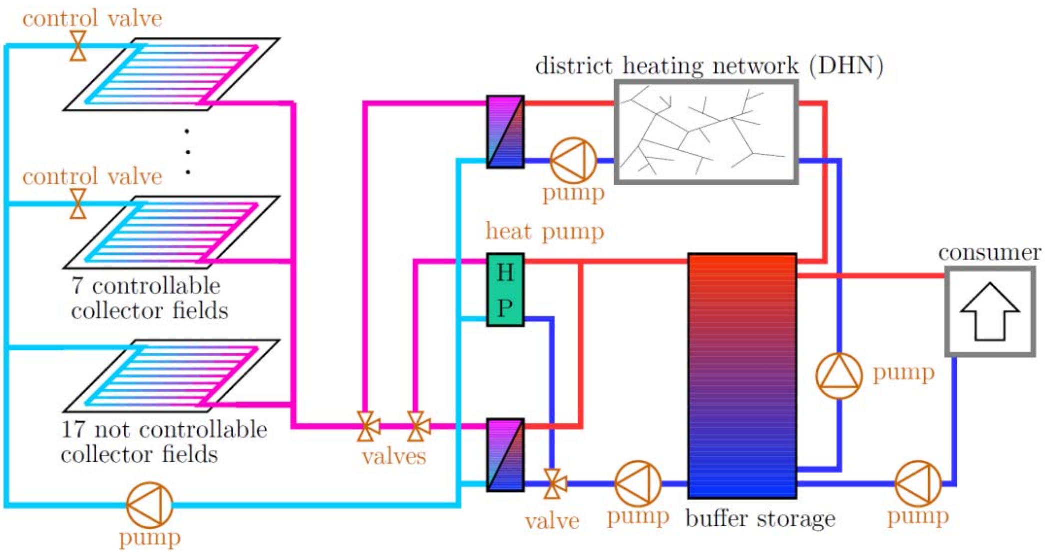

Figure 1. Schematic representation of the investigated plant

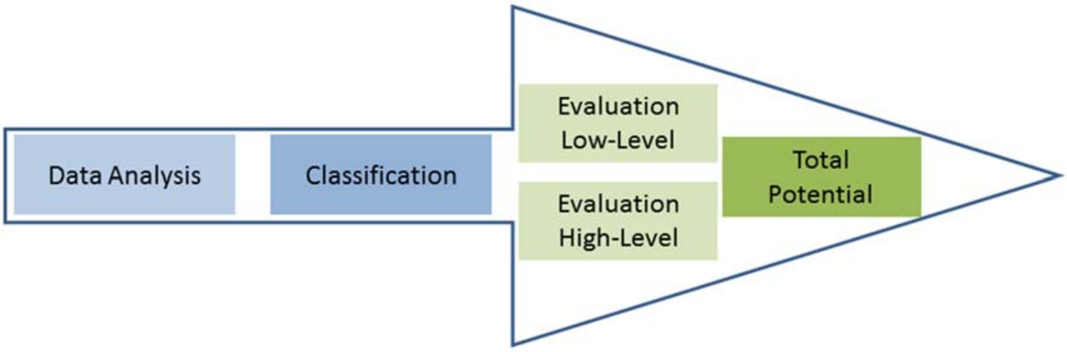

Figure 2. Steps of the evaluation procedure

Table 1: Main categories for the classification of days within the investigated period

Category	Description
winter (W)	no feed into DHN, buffer charge from DHN to cover local heat demand
summer (S)	feed into DHN, no buffer charge from DHN to cover local heat demand
transition (T)	all days not falling into categories *winter* or *summer*, e.g. feed into the DHN or buffer charged from DHN, or neither

In the next step, the potential for improvement is evaluated separately for both low- and high-level control. For the low-level control this is done by simulation studies using a simplified dynamic simulation model. The model has been parametrized with plant data and uses the ambient conditions of the investigated odel day as input variables. In order to evaluate the potential for efficiency improvement of the low-level control, the solar yields achieved with two different operating modes are compared for all model days previously defined. In the first case PI controllers with their parameters optimally adjusted to the measurement data provides the control signals whereas in the second case the control signals are generated by a stochastic optimization routine. In both cases, model days, where mostly the heat pump was operating, are excluded from the evaluation process, since in many practical applications no heat pump is present.

For the evaluation of the high-level control, thermal energy calculations are performed separately for the different categories. Because of the more simple procedure, compared to the simulation studies carried out for evaluating the low-level control, every day of the respective categories can be taken into account and not just the corresponding model days. The improvements achievable by an improved high-level control either result from adjusting the temperature levels or improving the buffer management. Because of restrictions of the temperature levels a much higher potential lies in the buffer management. This is the reason why the presented method is focussing only on the buffer management, finally leading to monetary savings, not because solar yields are increased, but since they are used more economically and losses are reduced. The savings of three improved strategies for the buffer management are evaluated which then leads to the potential for improvement of the high-level control.

The evaluation procedure is shown in the Figure 2; the single steps together with their respective results will be described in more detail in the following sections.

3.1. Data analysis and classification

In a first step, high quality measurement data from the plant described in section 2 was analysed. The data was recorded over the period of half a year (29.01.2015 to 31.07.2015) with a sampling time of one minute. The dataset corresponds to a third of an astronomical winter season, an astronomical transitional season (spring), and two thirds of the astronomical summer.

In order to classify the data, the respective energy quantities of the different sources and sinks were analysed for each day (direct buffer charge, buffer charge through heat pump, buffer charge from DHN, feed into DHN and consumption of the local consumers from the buffer storage). Based on this analysis a first categorization of the days in three main categories was obtained, where the categories are described in Table 1. Although these main categories are labelled as seasons for the sake of simplicity, their categorization is only carried out on the basis of the energy quantities.

Next, these main categories are divided into subcategories based on meteorological parameters (ambient temperature, mean intensity of the global solar radiation and its fluctuation). This leads to three subcategories (*poor*, *cloudy*, *sunny*) per main category where all combinations except *W-cloudy* occurred in the measurement data. A short description of the subcategories can be found in Table 2.

In the following step a representative model day for each subcategory is selected based on the average solar yield. If the selected model day is significantly different from most days in the subcategory regarding the course of the heat flows or the global solar radiation, an adjoining day is chosen. This was the case for the subcategories *T-cloudy*, *T-poor* and *W-poor*. The investigated period, divided into subcategories with the sorted energy quantities, including the average solar yield and the respective model day is shown in Figure 3. The average solar yield is marked with a horizontal line, the model day with a vertical line. Most of the days fall in the category *S* although the investigated dataset includes only two thirds of the astronomical summer. This is because the classification into main categories is based on energy quantities and not astronomical seasons. Typically the solar yield is increasing with the subcategories from *cloudy* to *sunny*. However, it can happen that, for example, the solar yield of a *poor* day with a relative high and continuous solar radiation is higher than of a *cloudy* day with a higher but more fluctuating solar radiation. The categories with the smallest solar yield (*W-poor* and *T-cloudy)* mostly consist of days where the heat pump was operating.

3.2. Evaluation of the low-level control

The low-level control is in charge of the different temperatures in the collector field. The evaluation of the control is done by comparing two operating modes by means of simulation studies. In the following section the simulation model used, the two operating modes compared and the results of the simulation studies are presented, finally leading to the overall potential for improvement of the low-level control.

Table 2: Subcategories for the classification of the days within the main categories

Subcategory	Description
poor	low global solar radiation and low ambient temperature
cloudy	medium to high, fluctuating global solar radiation and moderate ambient temperature
sunny	medium to high, continuous global solar radiation and moderate to high ambient temperature

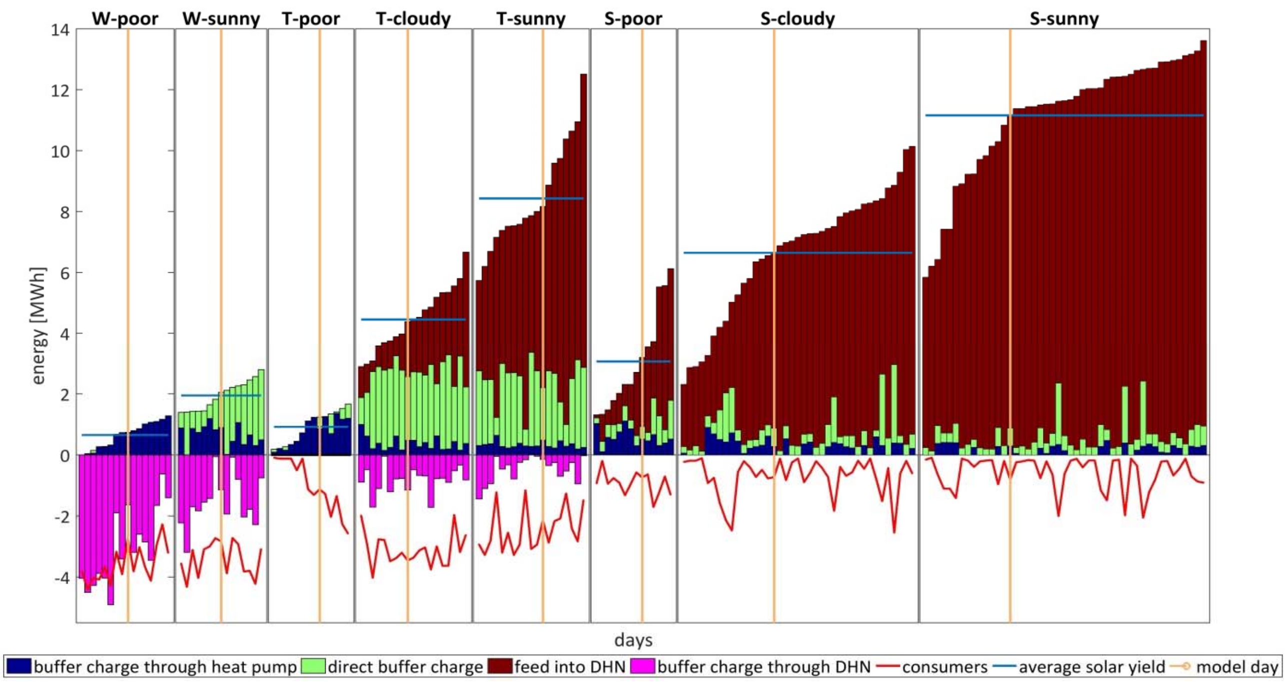

Figure 3. Investigated period divided into eight categories with their corresponding sorted, daily energy quantities. The average solar yield of each category is marked by a horizontal line and their representative model day is marked by a vertical line

Simulation model

For simulation a simplified model of the plant is used, consisting of three differently sized collector fields, as they occur in the investigated plant. Each collector field is described in a simplified way as a flow-through tube and is discretized to equally-sized fluid elements. In the time-discrete simulation, each fluid element then takes up a certain amount of energy and thus is heated in dependence of the external conditions (ambient temperature, global radiation) and the collector efficiency. The time a fluid element needs to pass through the collector field and the final temperature it can reach both depend on the velocity of the fluid and the size of the collector field. To limit complexity, the velocity can only be set to discrete values in the simulation. This is no significant limitation for sufficiently fine spatial and temporal discretization. An advantage of this simple discrete model is that dead times, which occur in real collector fields but are often neglected by simplified models, can be described accurately. The dead time describes the delay between the change of an input variable (e.g. the inlet temperature) and the resulting change of a corresponding output variable (e.g. the outlet temperature).

Furthermore, it is assumed that the flow through each field can be controlled individually. The individual control of the flow through the collector fields is most desirable for fields of different size, in order to achieve the same outlet temperature of the collector fields and to avoid exergy losses by mixing flows with different temperatures at all operating conditions.

Simulation settings

The orientation (south) and the tilt angle of the collector fields (45°) were determined from the investigated plant and the collector efficiency parameters were taken from the respective data sheet of the installed collectors.

The collector areas, the masses of fluid contained in the collector field as well as the hydraulic lengths of the three collector fields were adjusted to the real plant. Furthermore, the maximum simulated fluid velocity was adjusted in order to achieve similar throughput times as they occur at the investigated plant. This is important because the long throughput times, as they always appear in such plants, are one of the main challenges for their control.

The external conditions (ambient temperature, global radiation) were taken from the respective model day which should be examined. Regarding the dominant operation mode of the day the inlet temperature of the collector fields as well as the desired outlet temperature were set to typical, constant values. For the four model days where the heat was fed predominantly into the DHN (*T-sunny* and all *S* categories) an inlet temperature of 60°C and a desired outlet temperature of 80°C were used. For the two model days where the heat was fed mostly directly into the buffer storage (*W-sunny*, *T-cloudy*), an inlet temperature of 40°C and a desired outlet temperature of 76°C was chosen. The two model days where mainly the heat pump was operating (*W-poor*, *T-poor*) have been excluded from the evaluation.

The evaluation was performed following strict guidelines. For example, if a minimal required outlet temperature to feed into the DHN is not reached, the heat cannot be used. For this reason, the heat flow can be zero, even if a collector field has already reached the target temperature, but the mixed temperature of all the collectors is still lower. On the other hand, a sufficient temperature can be achieved also when a single collector provides an insufficient outlet temperature. The final result of the simulation is the total solar yield achieved with the two operating strategies respectively. Thus, the improvement theoretically achievable by an optimized control compared to a conventional control can be calculated.

Operating modes

For the evaluation for the potential for efficiency improvement two operating modes, standard control and optimized course of the actuating variables were compared.

<u>Standard control – PI controllers</u>

PI controllers represent the most frequently used controllers in industrial processes as well as in solar systems (see [2]). In some cases these controllers are enhanced by integrating static energy balance calculations to improve their performance. However the most common control modes for large scale solar systems are still just only PI-controllers. The values of the factors (K_p, K_i) for the proportional and integral components of the controller have to be adjusted according to the control task. In order to be able to start from an optimally adjusted PI control, the best values for K_p and K_i for each day to be examined were determined by means of exhaustive search (for sufficiently finely divided value ranges). For each field one PI controller was used to control the outlet temperature by changing the velocity of the fluid through the collector field. This configuration setting would be impossible for practical application, but it guarantees the best result, which can be achieved by PI controllers for the respective conditions. In practice, the parameters of PI controllers are set once during commissioning by running different test cycles or even just by rules of thumb.

<u>Optimized course of the actuating variables – Stochastic optimization</u>

Stochastic optimization is not directly a control strategy. Strictly speaking, the profiles of the external input

Table 3: Improvement per category as well as the total improvement of solar yield through an optimized low-level control

Category	Solar yield [kWh]	Improvement [%]	Improved solar yield [kWh]
W-poor	20,878	-	20,878
W-sunny	58,532	10.97	64,953
T-poor	25,828	-	25,828
T-cloudy	169,344	19.28	201,994
T-sunny	320,500	5.01	336,557
S-poor	85,774	32.00	113,222
S-cloudy	518,364	13.11	586,322
S-sunny	1,049,108	4.15	1,092,646
total	2,248,328		2,442,399
total improvement	**8.63%**		

variables (disturbance variables) which cannot be influenced by the control are used to determine the best possible course of the actuating variables. This is justified by the fact, that this course could also have been generated by a suitable model-based control (for example from a model predictive control with very good forecasts).

During optimization the course of the actuating variables is adapted in such a way that the solar yield becomes as large as possible. Since for a generally non-convex problem, such as the present one, it can never be guaranteed that the global optimum has actually been found, thus the optimization provides only a lower bound for the existing potential for improvement. The non-convexity of the problem also suggests the use of stochastic optimization methods since deterministic methods (e.g. gradient-based methods) easily get stuck at a local minimum. For the present problem, a stochastic method closely related to evolutionary algorithms has been used.

Potential for improvement by the low-level control

The results of the simulation studies are the improvements achievable for the different categories. The specific improvements have been used with the energy quantities of the different categories to calculate the improved solar yield. The sum of the improved solar yields of the single categories gives the total potential for improvement by an optimized low-level control. Table 3 shows the improvements per category as well as the total improvement achievable.

Discussion

The smallest relative improvement is achieved for high, slightly varying global radiation (*S-sunny*, *T-sunny*). This has two reasons: On the one hand, these days are those in which the solar thermal plant is almost operated at the design point. This means that for the real plant the pump is operated at maximum speed, which corresponds to a maximum flow velocity through the collectors in the simulation. This reduces the possibilities of the control since the plant is mainly operated at maximal flow after the initial heating of the collectors.

The other investigated model days show the greatest relative improvements. Global radiation which is only moderate to average but exhibits very dynamic behaviour reveals the weaknesses of the standard control. This effect has its origin in the fact that a state-of-the-art controller can only react when a deviation between actual value and set point value occurs; thus it is necessarily always behind. This effect is further intensified by the throughput time the fluid requires from the inlet of the collector to the outlet. This inevitably causes the outlet temperature to oscillate, because for a rapid collapse of the global radiation followed by an abrupt increase the controller will initially reduce the velocity of the fluid and then rapidly increase it. An integrated static energy balance used as a feed-forward control to improve the performance, which is sometimes the case in modern control implementations, could lower this effect. However, even very modern control strategies neither consider the coupled characteristics of the different components, nor do they take into account information on future conditions, and can therefore not utilize the full potential of such plants.

Based on the results it can be concluded that the potential for improvement of the low-level control of about 8% is possible. The greatest potential is to be found for operating conditions which significantly deviate from the design point, especially on days with dynamic external conditions as they can occur all year round.

3.3. Evaluation of the high-level control

The high-level control defines the general mode of operation of a plant (e.g. feeding the heat into a district heating network vs. storing it in a local buffer storage). For the evaluation of the control, first the most promising possibilities for improvement of the actual buffer management are described for the main categories (*T*, *W* and *S*). Then the improvements are monetarily evaluated because there are different prices for the various heat flows (see Table 4). Finally, this yields to the total potential for improvement through an optimized high-level control.

T- Buffer management in the transition period

Analysis of plant data reveals that the buffer is often suboptimally operated. The largest savings can be achieved in the transition period *T*, in which a lot of energy is fed into the DHN over the day and during the night the needed heat has to be retrieved from the DHN – at a higher prize – again. In this case, the high-level control should be able to estimate the future heat demand of the local consumers and load the buffer appropriately in order to prevent the more expensive recharging from the DHN.

For evaluation, of these days the buffer charging was increased to its maximum, since the heat demand during night was even higher. Except for the (small) storage losses, the latter DHN recharge can be reduced by the same amount as the buffer charge had been increased. Since there are different prices for the heat for feeding into the DHN as for recharging the buffer by the DHN, the improvement achievable is exactly the correlated monetary profit.

W - Buffer management in the winter period

Especially in the winter when the thermal solar plant cannot meet the needs of the local consumers, the buffer gets often charged by the DHN. During the charging the buffer is not operated like a pure hydraulic switch. The actual high-level control loads the buffer to nearly two-thirds if it detects that the temperature sensor at the top of the buffer gets cold. A modern high-level control should be able to estimate the heat demand of the consumers and then adapt the heat flow from the DHN to it, without loading the buffer storage. The current charging strategy leads to avoidable ambient and exergy losses.

To calculate this potential, the daily buffer charges from all heat sources were summed up for all days relevant to this issue. The difference of this overall buffer charge compared to the total heat demand of the connected consumers was classified as unnecessary charging which occurred since the buffer was not operated as a hydraulic switch. This amount, reduced by losses still occurring when operated as hydraulic switch, represents the surplus of heat which can be subtracted from the amount of heat fed into the buffer by the DHN, finally leading to a potential financial gain.

S - Buffer management in the summer period

Considering the fact that a modern, predictive high-level control can estimate the future heat demand, the buffer storage could be loaded less in the summer because there is less heat consumption by the consumers. This means that more heat would be available to be fed into the DHN, since buffer losses would be reduced.

To calculate the potential, a procedure similar to the *W* period was used. The buffer charge from all heat sources was summed up. The difference of this overall buffer charge compared to the total heat demand of the connected consumers had thus been unnecessarily

Table 4: Heat prices for the investigated plant, which are the actual prices from the latest valid contracts between the solar thermal plant operator and the utility

€/kWh	heat source/sink	period
0,0630	local consumer	-
0,0630	buffer charge from DHN	-
0,0345	feed into DHN	winter and transition
0,0293		summer

Table 5: Percentage improvements of the high-level control for the main categories

Main category	Improvement as percentage of total profit
T	1.14%
W	0.76%
S	0.62%
total improvement	**2.52%**

stored into the buffer, since the high-level control did not take into account predictions for the heat demand of local consumers. In this case, the difference was reduced by change of energy stored in the storage. The resulting amount could have been fed into the DHN and would have generated an additional profit.

Potential for improvement by the high-level control

For each strategy, the difference between the improved and the initial profit is related to the total annual profit achieved by the plant. The percentage improvements of the high-level control for the main categories are given in the Table 5.

Discussion

The potential for improvement shown here is smaller than for the low-level control but involves only improvements which are easy to quantify. The further potential for efficiency increase, e.g. an improved heat pump management, has not yet been quantified. For this reason the total potential for this plant can be expected to be significantly higher. Similar to the case of low-level control, the highest potential can be achieved in situations with high variations in the transition period.

4. Conclusions

This paper reveals that there is a significant potential for efficiency increase by the application of model-based control strategies for the low-level and the high-level control. The potential for increasing the efficiency by a model-based low-level control has been estimated to be at least 8.63%. The potential for increasing the economic efficiency by a model-based high-level control has been estimated to be around 2.52%. Since these results have been obtained on different bases (energy vs. money) they cannot be directly summed up. However, in a rough estimate the additional solar yield can be translated to a proportional additional profit of the plant. Thus one obtains an overall potential for increase of economic performance of at least 11%. These potentials can never be fully exploited by a real control implementation (since perfect forecasts would be necessary), but one should keep in mind that the evaluation of the low-level control has been performed in comparison with a standard control which had been individually optimized for each test case. This is not a realistic scenario either. Thus the potential compared to a realistic state-of-the-art control implementation could be even higher; and it could also be in a similar range in comparison to a control strategy additionally enhanced by integrating static energy balance calculations. For both low- and high-level control, an improved heat pump management has not been considered. The improved integration of a heat pump would result in an additional improvement of system efficiency and economic gains.

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