# Advanced Control Strategy for Solar Combisystems

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**Abstract**

Solar combisystems are solar heating installations providing space heating as well as domestic hot water for the inhabitants of the building. The energy sources are solar energy as well as an auxiliary source, gas or oil typically.

This paper describes the advanced control strategy that realizes the energetic optimization of the building and the combisystem as a unique system. This strategy also aims at maximizing the degree of comfort to the users. It has been implemented on a solar combisystem manufactured in Switzerland.

The strategy chosen is a predictive control strategy. It computes one-day optimal profiles for the flow-rate in the collector loop and for the power to be dissipated in the building. To do so, dynamical models of the combisystem and the building have been developed. Weather forecasts are also required to implement this predictive control strategy. The weather forecasts are provided on-line by the Swiss Meteorological Institute (SMI).

## 1 Introduction

The current control strategies in solar heating systems are mainly based on manufacturers' know-how. These strategies don't take into account the evolution of the operational conditions, typically the weather conditions or the users' behavior. They have been designed to work in the worst case scenario, often leading to very conservative behavior.

The goal of this contribution is the development of an advanced control strategy for all the manipulated variables. The developed strategy is an extension of our work on solar domestic hot water systems [1][2].

The combisystem, the building considered and their models are described in section 2. The principle of the advanced control strategy is presented in section 3.

Section 4 presents a closed loop implementation of the optimal profiles computed. Simulation results are given in section 5.

## 2 Description and modeling

A schematic view of the system under consideration is given in figure 1.

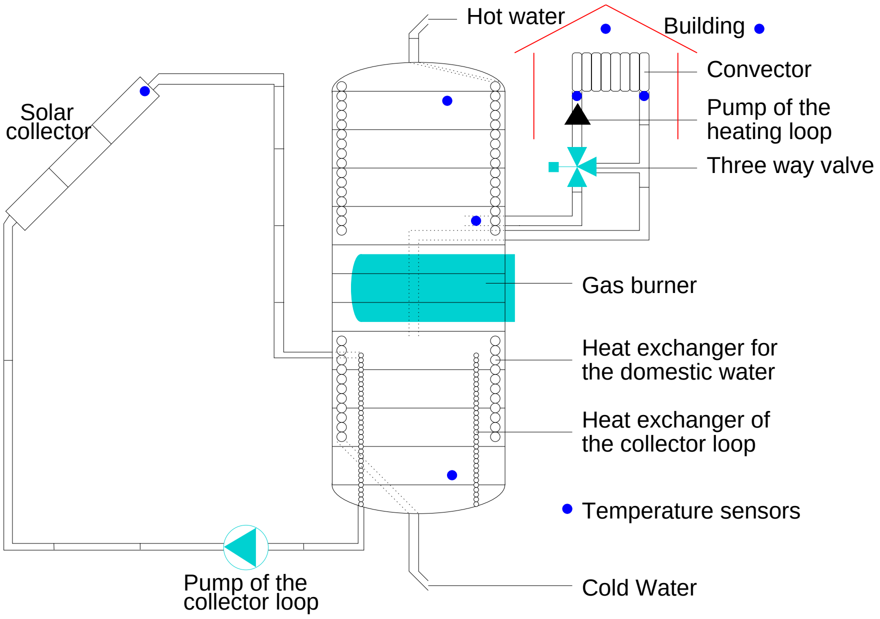

Figure 1: The combisystem and the building nodes for modeling.

A pump drives the fluid through the collector. This fluid gathers solar energy and heats the liquid inside the storage tank owing to an immerged heat exchanger. This is a closed loop called the collector loop. The pump can be controlled to change the flow-rate.

The domestic water is heated instantaneously by passing through another immerged heat exchanger. Another pump drives the fluid inside the storage tank through a loop called the heating loop. The building is heated owing to convectors installed in this heating loop. This pump is either switched on or off. The power dissipated in the building is controlled by a three-way valve which re-injects a varying part of the liquid going out of the convector. The auxiliary energy source is provided by a 20 kW gas burner which is also either switched on or off.

It can be seen that four actuators can be manipulated: the two pumps, the three-way valve and the gas burner. The role of the control strategy is to manipulate these four actuators so as to optimize the behavior of the system in terms of energetic performance and comfort. Four manipulated inputs correspond to these four actuators, the collector flow-rate for the pump of the collector loop, the heating flow-rate for the pump of the heating loop, the auxiliary power for the gas burner and the aperture angle for the three-way valve. These four inputs are grouped together in a single vector $u(t)$ which obviously varies with time.

It can also be noticed that some other inputs have an influence on the behavior of the system. These inputs are called disturbances because they cannot be manipulated. Among them, there are the meteorological data, typically the solar radiation and the ambient temperature. These disturbances are grouped together in a single vector $w(t)$ also obviously varying with time.

The storage tank, the heat exchanger, the pipes of the two loops and the collector are modeled using a fixed number of nodes. Actually, the temperature of the liquid inside these elements vary gradually. This simple model, although detailed enough, is in fact well suited to develop and analyze control strategies without cumbersome computational limitations.

The dynamic behavior of the combisystem is defined by computing the energy balance of each node. It leads to one differential equation per node. For conciseness, the 49 differential equations resulting are not given in detail.

As for the building, a similar method has been used to elaborate the dynamical model. Indeed, the wall, the roof and the ceiling have been dividing into nodes, each leading to an energy balance and a differential equation. The total number of nodes for the building is 38.

The 87 (49+38) temperatures of the corresponding nodes are grouped together in a single vector $x$ called the state vector. The corresponding 87 differential equations can be represented in a compact form by the following equation:

$$\dot{x}(t) = f\left(x(t), u(t), w(t)\right) \tag{1}$$

# 3 Optimal control strategy

To achieve better overall performance, the controller has to take advantage of the dynamic model of the system as well as the *a priori* knowledge of the most significant disturbances. In that way, the variables manipulated can be adjusted according to a predicted behavior of the system until satisfactory performance is obtained. The resulting optimal inputs are then applied to the real plant. The performance level is characterized by an objective function that has to be minimized using a suitable optimization algorithm. A scheme illustrating this principle is given in figure 2.

The control strategy chosen is referred as *predictive* because changes in the operational conditions are anticipated. An excellent review of such a control strategy appears in [3]. Related works have been carried out for passive and active solar systems [4][5][6].

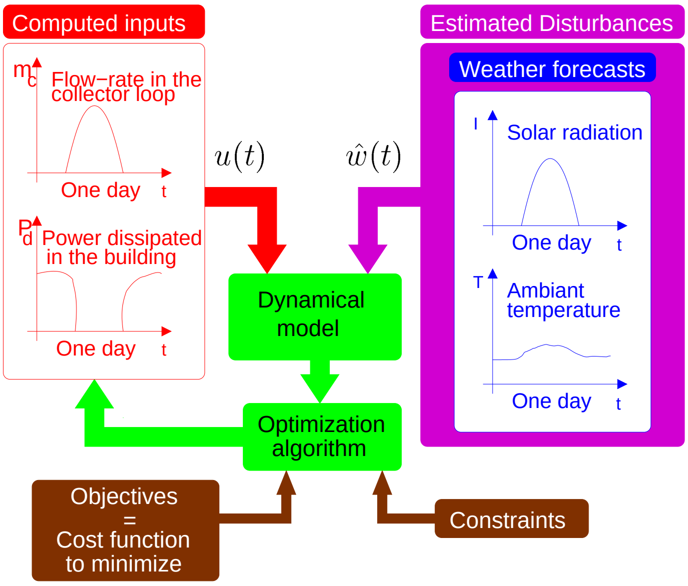

Figure 2: Optimal control strategy

As it can be seen in figure 2, only two profiles are computed by the optimization algorithm. The optimization horizon chosen is a one-day horizon. It means that these profiles are computed for the whole coming day and that the objective function is also minimized over this period. The two profiles computed are the flow-rate in the collector and the power to be dissipated in the building. Among the four manipulated variables mentioned earlier, there are the flow-rate in the heating loop and the three-way valve. The pump of the heating loop is either switched on or off, which means that the flow-rate can take only two values 0 and a maximum value which depends on the size of the pump. It justifies the presence of the three-way valve to control the power dissipated in the building. Thus, it also justifies the fact that the profile of the power to be dissipated is computed. The pump of the heating loop and the three way valve are controlled by conventional PID controllers such that the power dissipated in the building at a given time is as close as possible to the one computed by the optimization algorithm.

The other manipulated variable which is not directly computed by the optimization algorithm is the auxiliary power produced by the gas burner. The main reason for this choice is that, when switched on, the gas burner is able to provide approximately 20 kW to the liquid inside the storage tank. It is sufficient to fulfill instantaneously the energy needs for the heating of the building. It can be seen in figure 3 how the three-way valve and the gas burner are controlled.

As already stated, the profile of the power to be dissipated in the building is computed by the optimization algorithm. It is introduced as the reference of a

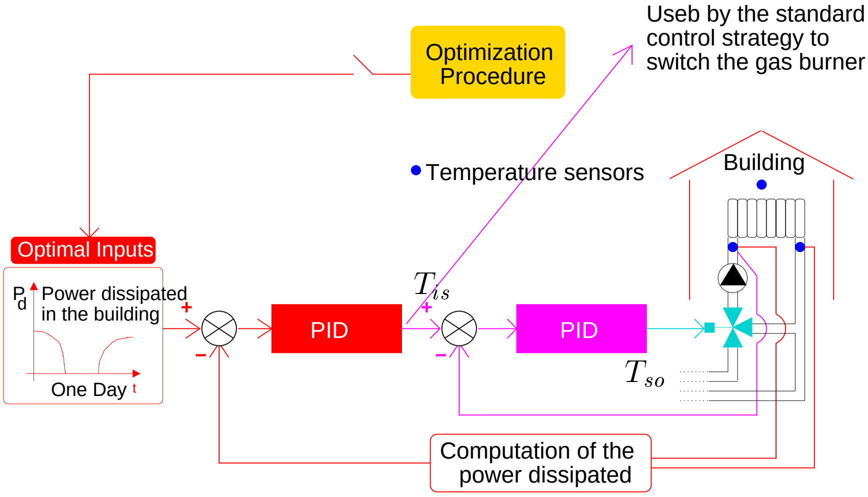

Figure 3: Cascade controller.

cascade controller. The first loop computes the desired temperature at the entry of the convector called $T_{is}$. This desired temperature is the input of a second PID loop which computes the aperture angle of the three-way valve. There could have been only one PID loop, if it was just about following the profile of the power to be dissipated in the building. However, owing to this cascade scheme, $T_{is}$ is computed, and it is used to decide when the gas burner is switched on and off. $T_{so}$ is the temperature of the water coming out from the storage tank and going to the heating loop. The gas burner is switched on when $T_{so} < T_{is} + 3.0°$, and stays on until $T_{so} > T_{is} + 8.0°$. The gas burner is also switched on when the temperature in the upper part of the storage tank called $T_{su}$ is lower than 60° and stays on until $T_{su} > 65.0°$. It should be kept in mind that the water which enters the convector comes partly from the storage tank and partly from itself. Thus, to be able to reach the computed $T_{is}$, $T_{so}$ has to be equal or higher than $T_{is}$.

As mentioned above, the performance desired is represented by an objective function. In this special case, the objective is twofold: the gas consumption is minimized whereas the comfort of the users is maximized. The objective function chosen $J$, as used to carry out this optimization, is the following :

$$\begin{aligned} J &= \int_{\text{one day}} [P_{burner} - (P_{sol} - P_{pump})]dt \\ &\quad + \int_{\text{one day}} \alpha (T_b - T_{set})^2 dt \end{aligned} \tag{2}$$

where $P_{burner}$ is the power consumed by the gas burner, $P_{sol}$ is the solar power collected, $P_{pump}$ the power required by the pump to drive the fluid in the collector loop and $T_b$ is the temperature inside the building. The parameter $\alpha$ is a trade-off factor and $T_{set}$ is the average temperature selected by the users. $T_{set}$ has been chosen equal to 19.5 °C. To summarize, this control strategy aims at minimizing the energy consumption of the gas burner while keeping the temperature in the building as close as possible to the chosen $T_{set}$. This objective function is minimized over a one-day horizon. This justifies the fact that $P_{sol}$ is introduced in this objective function. Indeed, the variation of the internal energy is not negligible in a one-day energy balance.

The optimization algorithm is very similar to the one described in [1].

# 4 Closed-loop implementation

It would be very risky to apply the computed optimal profiles for the flow rate in the collector loop and the power to be dissipated in the building without introducing a kind of closed-loop mechanism. Indeed, these profiles are computed owing to dynamical models for the combisystem and the building and owing to weather forecasts. And, what would happen if the weather forecasts have over-estimated the real meteorological conditions or if the expected behavior of the users in the building is significantly different from their real behavior ?

This closed-loop behavior can be introduced by repeating the optimization procedure each time new measurements are available. Indeed, owing to a suitable state estimator, new measurements can provide new initial conditions for the optimization procedure. These new initial conditions based on measurements could be combined with updated weather forecasts. These updated forecasts could be sent by the Swiss Meteorological Institute or previous forecasts could be improved using environmental sensors like low cost solar radiation sensors or temperature sensors.

However, there is another way to introduce this closed-loop mechanism. It should be clear that the optimization procedure not only gives the optimal one-day profiles for the manipulated inputs but it also gives the corresponding profiles for the eighty-seven state variables which are the temperatures of the eighty-seven nodes of the model, and among them the temperature inside the building. Instead of applying directly the computed optimal profiles, it would be wise to try to follow the corresponding optimal profiles for some of the eighty-seven nodes. And in case of perfect dynamical models and perfect weather forecasts, it would lead exactly to the computed optimal profiles for the manipulated inputs. However, in case of modeling errors or unforeseen disturbances, it would lead to something very different, but at least, the tracked temperatures would be those computed by the optimal procedure.

In our case, the tracked temperature is the temperature inside the building, and it is used to compute the power to be dissipated in the building called $P_d$. As for the flow rate in the collector loop, it turns out that the shape of the optimal

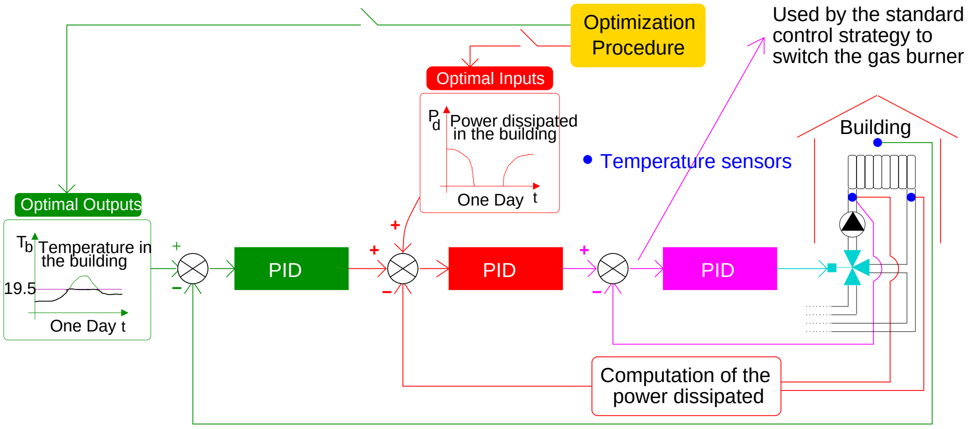

Figure 4: Scheme of the closed-loop.

profile is always very close to the shape of the solar radiation. Thus, the flow rate is chosen as a function of the solar radiation which is assumed to be measured by a low-cost sensor. This function is represented by a set of bases functions and a set of parameters which are computed by the optimization procedure. The closed-loop mechanism desired is thus implicitly included in the parameterization chosen for the computation of the optimal flow rate.

The strategy chosen for the closed-loop implementation of the computation of $P_d$ in the building is summarized in figure 4. The computed optimal profile for $P_d$ acts like a feed forward to a third PID loop and the computed profile for the temperature inside the building $T_b$ is tracked. To summarize, the two first inner loops aim at controlling the power dissipated in the building and this third should be seen as a way of implementing the optimization results in a closed-loop way. A saturation is added to prevent the case where weather forecasts have over estimated the meteorological conditions. Indeed, in this case, the computed $T_b$ is likely to be very high because of passive gains in the building. Without the saturation, the proposed strategy would lead to a temperature in the building equal to the computed one. In other words, the power dissipated in the building would be far higher than the computed power based on the prediction that it would be sunny outside, and it is obviously not a desired feature. In this case, the strategy simply tries to maintain a temperature as close as possible to 19.5°C in the building.

# 5 Simulation results

This section presents simulation results that illustrate the performance of the control strategy proposed. Experimental validation is being carried out at the moment and will soon be available.

The following figures illustrate different configurations. Figure 5 represents the case where the weather is very good and the weather forecasts are perfect. It can be seen that the curves representing the real weather and the weather forecasted are the same. The high passive gains occurring when the sun shines are anticipated in the morning. Indeed, the advanced control strategy lets the temperature decrease to almost 18°C in the building so as to avoid a too high temperature later in the afternoon. This decrease is also due to the fact that the strategy tries to maximize the solar energy transfered. Forecasts indicate that the solar radiation is going to be significant. Thus, the strategy tries to keep the temperature in the upper part in the storage tank as low as possible by not switching on the gas burner. A lower temperature in the tank means obviously more solar energy transfered. As the forecasts exactly match the true weather, the power dissipated in the building computed by the optimization algorithm is very close to the power dissipated in the building in reality.

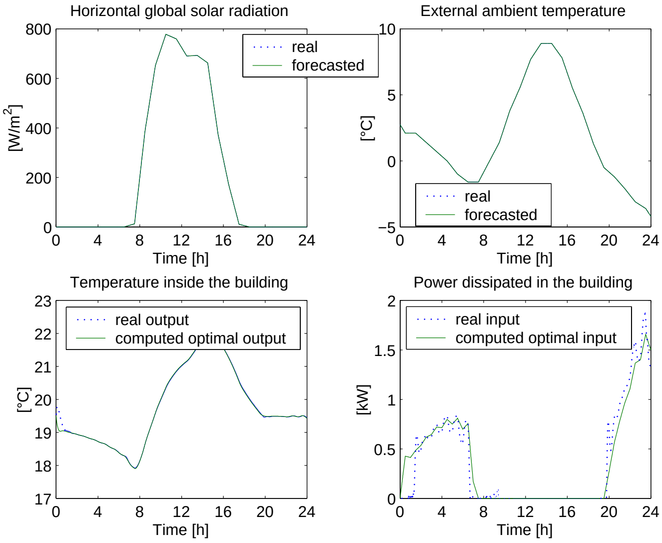

Figure 5: Good weather and perfect forecasts.

It can be seen on figure 6 what happens when the forecasts significantly over estimate the real solar radiation. The power dissipated in the building is far more important than the one computed by the optimization procedure.

It can easily be imagined what would have happened if the strategy had not followed the profile of the temperature inside the building but instead if the profile computed for the power dissipated in the building had been applied directly. It would have led to a very low temperature inside the building. It can be seen also that the computed profile of the temperature inside the building is tracked unless it is lower than 19.5°C for the obvious reasons already mentioned.

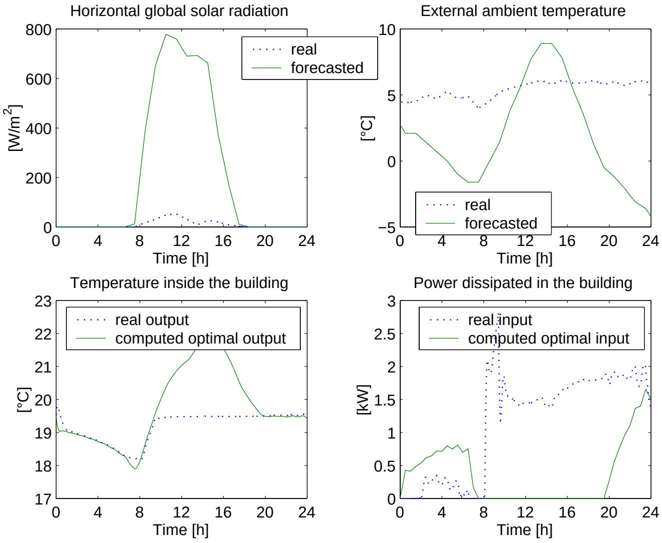

Figure 6: Bad weather and bad forecasts.

Figure 7 shows the opposite situation, weather forecasts significantly under estimating the real solar radiation. Of course, the anticipating effect of the passive gains in the building does not occur because of the bad forecasts. However, the power dissipated in the house is far less important than the one computed by the optimization algorithm. As for the energetic performance, initial experimental results have shown that the new advanced control strategy performs significantly better than the standard one. However, long term real-life experimentation should be carried out to evaluate precisely this improvement. By roughly extrapolating the preliminary results, we can expect a reduction of about 15 % of the gas consumption.

# 6 Concluding remarks

An advanced control strategy combined with a suitable implementation scheme has proven to be very efficient in terms of comfort and energetic performance. The strategy anticipates the coming evolution of the environmental conditions and the closed-loop scheme proposed gives robustness with regards to possible discrepancies between the forecasted and the real data.

# 7 Acknowledgment

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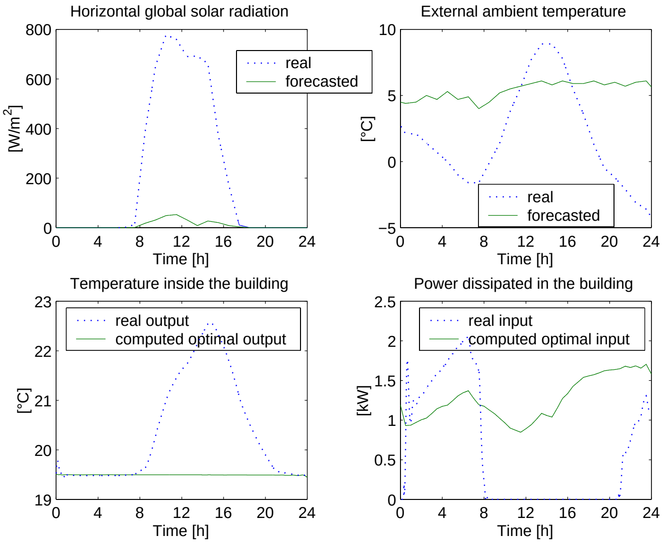

Figure 7: Good weather and bad forecasts.

# References

[1] T. Prud'homme and D. Gillet. Advanced control strategy for solar domestic hot water systems. *Energy and Building*, 33(5):463–475, 2001.

[2] T. Prud'homme and D. Gillet. Optimisation of solar domestic hot water systems. In *EuroSun'98*, volume 2, Portorož, Slovenia, 1998.

[3] S. J. Qin and T. A. Badgwell. An overview of industrial model predictive control technology. In J. C. Kantor, C. E. Garcia, and B. Carnahan, editors, *Fifth International Conference on Chemical Process Control*, CACHE, AIChe, pages 232–256, 1997.

[4] Y. Oestreicher, M. Bauer, and J.-L. Scartezzini. Accounting free gains in a non-residential building by means of an optimal stochastic controller. *Energy and Buildings*, 24(3):213–221, 1996.

[5] I. R. Williamson, S. Danaher, and C. Craggs. Optimisation of solar building control using predictive methodologies. In *6-th European Congress on Intelligent Techniques and Soft Computing, EUFIT'98*, volume 2, pages 878–879, Verlag Mainz, Aachen, Germany, 1998.

[6] E. F. Camacho, M. Berenguel, and F. R. Rubio. Application of a gain scheduling generalized predictive controller to a solar power plant. *Control Engineering Practice*, 2:227–238, 1994.