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Model based optimization of a combined biomass-solar thermal system

Florian Stift[a] *, Michael Hartl[a], Tarik Ferhatbegović[a], Stefan Aigenbauer[b], Andreas Simetzberger[c]

[a] *AIT Austrian Institute of Technology GmbH, Energy Department, Donau-City-Straße 1, 1220 Wien, Austria*
[b] *BIOENERGY 2020+ GmbH, Gewerbepark Haag 3, 3250 Wieselburg-Land, Austria*
[c] *SOLARFOCUS GmbH, Werkstraße 1, 4451 St. Ulrich / Steyr, Austria*

Abstract

This paper presents the model based optimization of the control parameters of a combined biomass-solar thermal system for heating and domestic hot water supply, designed for small residential applications. The system consists of a thermal storage with an integrated pellet burner and a heat exchanger to feed solar energy from a small collector field into the storage. By using a physical model of the existing system, the time for optimizing the control system can be reduced significantly. To optimize the given system, it was desired not to vary the system specific parameters such as the collector or the storage size. However, the control parameters (i.e.: set-points of local control loops of the combined system) of the system are supposed to be optimized.
The system was simulated with the dynamic thermal simulation environment TRNSYS using validated models. Monitored data was used to estimate several model parameters. The control strategy of the off-the-shelf product was implemented using MATLAB. In this study it was clearly shown that the performance of the described system can be improved by optimizing the control parameters upon a model based approach. A complete system model was set up and the control strategy was reproduced within the simulation environment.

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Keywords: Solar collector; combined solar thermal system; control strategy; dynamic simulation and optimization;

* Corresponding author. Tel.: +43 (0) 50550-6277; fax: +43 (0) 50550-6613.
E-mail address: florian.stift@ait.ac.at

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1. Introduction

Half of the European Union's final energy consumption accounts for the heating and cooling sector. Herewith, renewable energy sources like biomass and solar energy have a huge potential for heating and cooling. Since renewable energy sources account for only 12% of the overall energy demand for heating and cooling, there is still a huge need for efficient and economical heating systems [1].

The given system produced by the company SOLARFOCUS GmbH combines both energy sources within one technology focusing on allocating heating energy for single and multiple family houses. Two tasks, crucial to further develop the market attractiveness of the given system are to reduce investment costs and to improve the system performance. This paper shows results of the optimization set point values of a feedback controlled biomass-solar thermal system for heating and domestic hot water preparations. In a first step of the project, comprehensive laboratory measurements and field tests were carried out to find realistic model parameters for following simulation of the system [2]. Within the ongoing project a simulation model of the system and its control strategy was created and an optimal set of parameters found to maximize the solar gains. Additionally a variation study was performed to utilize the effect of system parameter variations with regards to the system performance.

Nomenclature

$\dot{Q}_{solar}$	Heat transfer rate from the solar collector
$\dot{Q}_{biomass}$	Heat transfer rate from the biomass fuel, i.e. wood pellets
$\dot{Q}_{losses}$	Heat transfer of the energy from the boiler to the ambient
$\dot{Q}_{DHW}$	Heat transfer rate for domestic hot water preparation
$\dot{Q}_{heating}$	Heat transfer rate for space heating

2. Mathematical model of the controlled bio-mass and solar thermal system

The optimization of an existing system configuration on-site is complex and time consuming. By using a mathematical model of the existing system, the time spent optimizing the control system can be reduced significantly. For the given project it was desired not to vary any physical parameters of the system, such as the solar collector area, or the hot water tank volume. However, the control parameters of the system are supposed to be optimized, giving the possibility to also update already installed and operating systems and optimize their system performance.

2.1. System description

The system consists of a hot water store tank, a pellet burner and a solar thermal collector loop. To minimize heat transfer losses from the biomass combustion to the hot water storage, the burner is integrated within the storage. A solar thermal loop is delivering heat to the same storage. Fig. 1 shows a visualization of the storage tank and a rough outline of the heat flows in an out of the system. The visualization clearly shows how the pellet burner is integrated within the steel tank and also shows the solar heat exchanger at the bottom of the storage.

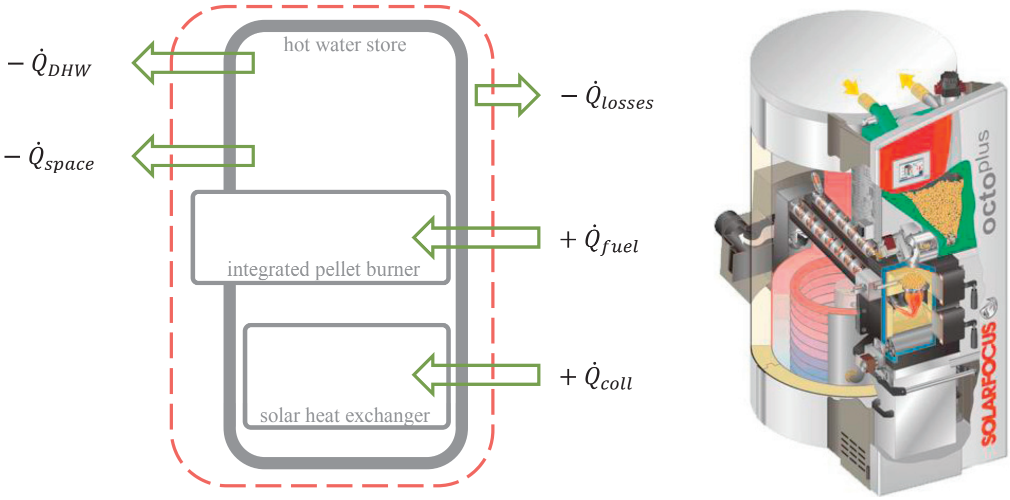

Fig. 1: Investigated system with integrated pellets burner and solar loop heat exchanger (source: SOLARFOCUS GmbH)

For the shown physical system a thermal dynamic system simulation model was created within the dynamic simulation environment TRNSYS. Validated models from Haller [3], Drück [4] und Perers [5] have been used to represent the hot water storage tank, the pellets burner and the solar collectors respectively. It is vital for the operational optimization of a system model that the reference case matches the actual performance of the system as closely as possible. Therefore, the used models were parameterized using data collected from extensive laboratory measurements during a first step of the project. [1]

2.2. System Control Strategy

The control strategy of the system operates upon several set-point (difference) temperatures to run the system. The aim was to select a set of parameters which are installed by default in the off-the shelf product to be able to implement the optimized parameters within all existing systems. A majority of the sensors are installed for security reasons though. . Within the frame of control parameter optimization, an extensive survey with respect to possible control parameter variations has resulted in a set of few admissible variations. Most of these variations are determined on the basis of control system constraints, which are provided by the biomass-solar-boiler manufacturer. Those parameters, which are listed in Table 1, are temperature set-points and temperature differences mainly. The table shows also the constraints for the chosen parameters.

The given control strategy was implemented within MATLAB and coupled to the thermal model within TRNSYS. To perform realistic controller operation during the simulation runs a short time-step had to be chosen. On the other hand this tends to be very time consuming with respect to the overall simulation time. An optimized set of (admissible) parameters should be valid for an annual operation of the system and should not be changed for winter or summer time after all. Therefore it was intended to find an optimal set of parameters for the annual operation. To keep the simulation runtime within a reasonable length, it was decided to run the optimization for half a year only. Therefore, the simulation accounts for winter, summer and the transition time period, but needs half of the simulation time only.

Table 1: Parameters used for the optimization, their possible variation span and the optimal set of values

An example of a column heading	Reference value (°C)	Possible variation span (°C)	Optimal parameter (°C)
Temperature difference at which the solar pump is switched ON	7.0	4.0 – 12.0	7.0
Set-point of the storage temperature at the top of the tank	85.0	60.0 – 85.0	63.0
Storage temperature hysteresis	20.0	1.0 – 20.0	10.0
Set-point of the storage temperature in the middle of the tank	80.0	60.0 – 80.0	62.0
Minimum temperature of the storage	40.0	35.0 – 60.0	35.0

3. Control Optimization

As described above, the control strategy was programmed in MATLAB and an interface used to couple it to the mathematical model of the system within TRNSYS. Before starting the optimization process it is essential that the model represents the actual system performance as good as possible. Three boilers were installed in the field and extensive measurements were carried out. The collected data was analyzed, focusing on the control parameters and set-point values used to run the system. The quality of the model was compared to the actual behavior of the monitored systems, therefore showing promising results.

GenOPT was used to perform the optimization routine [6]. It was desired to increase the efficiency of the overall system by optimizing the control parameters. Better system efficiency is considered to be reached if the following optimization goals are accomplished:

- The overall losses of the system should be minimized. The losses include transmission losses through the storage envelope and losses from the pellet burner.
- The use of biomass energy should be minimized. A more efficient system performance is considered to use less biomass whereas the heat demands for space heating and domestic hot water preparation have to be fulfilled.
- The supply of solar thermal energy should be maximized. The more energy can be used from the collector loop, the more efficient the system performs.

The cost function, given in Equation (1), was defined to be maximized by the optimization algorithm.

$$\sum(\dot{Q}_{solar} - \dot{Q}_{losses} - \dot{Q}_{biomass}) \rightarrow max \qquad (1)$$

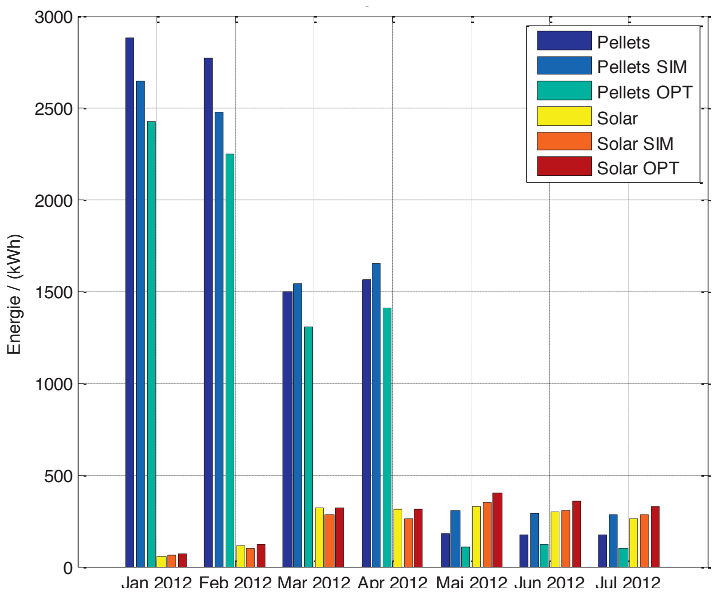

Fig. 2: Monthly biomass energy demand and solar energy supply - Comparison of Monitoring, Simulation and Optimization

Table 2: Monthly results of biomass energy demand and solar energy supply - relative changes in energy demand/supply

	(kWh)	Jänner	Februar	März	April	Mai	Juni	Juli	SUMME
PELLETS	Monitoring	2875.18	2767.19	1497.98	1561.37	179.58	173.08	169.86	9224.24
	Referenz	2641.42	2475.13	1543.09	1648.16	308.16	293.38	281.68	9191.03
		-9%	-12%	3%	5%	42%	41%	40%	0%
	Optimierung	2465.43	2270.67	1343.48	1443.73	135.25	127.33	118.91	7904.80
		-17%	**-22%**	**-11%**	**-8%**	**-33%**	**-36%**	**-43%**	**-17%**
SOLAR	Monitoring	56.00	116.00	318.00	313.00	324.00	297.00	258.00	1682.00
	Referenz	60.38	102.20	281.53	263.69	347.68	307.46	282.74	1645.68
		7%	-14%	-13%	-19%	7%	3%	9%	-2%
	Optimierung	69.87	122.85	316.35	302.17	393.90	356.59	324.71	1886.44
		20%	**6%**	**-1%**	**-4%**	**18%**	**17%**	**21%**	**11%**

Fig. 2 shows a comparison of measured data, results from the simulation of the actual system parameters and the results for the optimized control system. The energy supplied to the boiler from the collector loop and the energy used within the pellet burner are compared. The exact numbers of the simulation and optimization results are given in Table 2.

The optimization results show a decrease of all control parameters - see Table 1. The results show that the energy supplied by pellets could be reduced by 17% for the half year analysis. The solar energy supply could be increased by 11%.

4. Variation Study

As described above it was desired to optimize the given system without changing any physical parameters like collector area or storage volume. The goal was to increase the efficiency of the system by optimizing the control parameters. To assess the sensibility of the system to various physical changes, a parameter study was done. The parameter variations included:

- The overall heat loss coefficient of the storage tank (-23% / -33% / -50%)
- The collector area (+2m² / +4m²)
- The combination with reference or optimized parameters

Fig. 3 shows the results of the variation study. The monthly energy demand for biomass and the solar energy supply are compared. In addition to the simulated variants, the reference case and optimization case is given, as described in the last section. The results of the parameter study show that decreasing the overall heat loss coefficient of the storage by 50% has nearly the same effect on the pellets consumption as the optimization of the control parameters. Installing a larger collector area will increase the solar energy supplied to the storage during the summer months, but won't significantly reduce the pellets consumption during the winter months. The increased thermal insulation of the storage together with optimized control parameters showed the least pellet consumption.

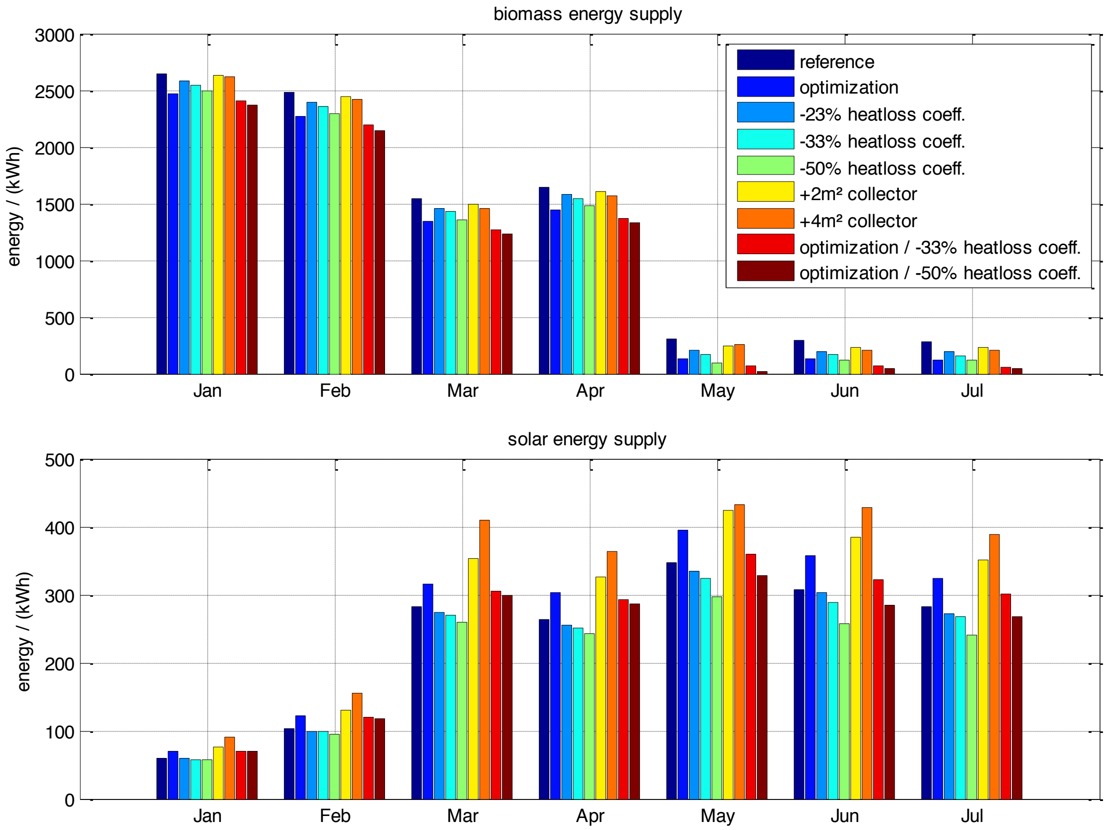

Fig. 3: Simulation Results of the Variation study for both pellet and solar energy supply

5. Conclusions and Outlook

In this study it was shown that the performance of the described system could be improved by optimizing the control parameters on the basis of a mathematical model of the controlled system. A model of the complete system was set up and the control strategy was programmed in a simulation environment. Extensive measurements were used to parameterize the mathematical models. By using an optimization algorithm, a set of five set-points could be optimized which led to a more efficient system operation. Savings of 17% in biomass energy demand and an increase of 11% in solar energy supply could be reached. A mismatch between simulated and measured performance was found. It is assumed that this is caused by an underestimated mixing of the water within the storage which cannot be modeled easily and therefore considered by the optimization routine. Nonetheless, the model could be used for the optimization as it showed realistic behavior. The quality of the model was confirmed with additional data sets from similar systems further. The parameters that resulted from the optimization routine are implemented in an existing system for future research activities.

The project team will be further looking at the development of a model predictive controller for the solar loop that continuously optimizes the energy supplied into the storage tank online. This measured is supposed to result in a minimized consumption of bio-mass eventually (cp. [7] and [8]).

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