Optimal Control of Cogeneration Building Energy Systems

Conrad Gähler[1], Markus Gwerder[1], Raphaël Lamon[2], Jürg Tödtli[1]

[1] Siemens Switzerland Ltd, Building Technologies Group (SBT), Zug, Switzerland
[2] University of Ulm, Germany; formerly with SBT, Zug, Switzerland

Corresponding email: conrad.gaehler@siemens.com

SUMMARY

We investigate optimal supervisory control of a building energy system with cogeneration of heat and power (CHP). The system consists of a Stirling engine and a supplementary burner, space heating and a domestic hot water (DHW) storage tank. Cost and primary energy (PE)-optimal operation are considered.

The best theoretically possible operating strategy is found using the following assumptions:

- An ideal dynamic model of the system and an ideal prediction of all future disturbance variables (weather, hot-water draws, etc.) are available to the controller ("ideal" here means that model and predictions used by the controller perfectly match "reality", which is used for simulation after applying the control signals)
- The room temperature is allowed to vary within a time-dependent tolerance band (e.g. 21...24°C during the day and 19...24°C at night). Progression of the room temperature is then an output of optimization. A dynamic building model is used, rather than heat demand profiles. A similar tolerance band is used for the DHW storage tank

This strategy defines the so-called *performance bound*, since no real controller can yield a better performance. It is found using model-predictive control (MPC) with moving horizon. In this general setting, the following results are discussed:

- *Control strategy:* How does the system have to be operated to cover thermal and electrical energy demand with minimal costs, or with minimal PE?
- *Performance assessment:* What annual amount of primary energy and money can be saved by a CHP unit compared to conventional heating?
- *Influence of specific parameters (sizing of Stirling engine)*

The results, although obtained with a Stirling engine, can be used for other CHP units as well.

KEYWORDS: Model-based predictive control, CHP, Stirling engine, performance assessment

INTRODUCTION

Residential cogeneration is an emerging technology with a high potential to deliver energy efficiency and environmental benefits [1]. The concurrent production of electrical and thermal energy can reduce PE consumption and associated greenhouse gas emissions. The distributed generation nature of the technology also has the potential to reduce electrical transmission and distribution inefficiencies and alleviate utility peak demand problems. Leading contenders for residential building cogeneration include fuel cells, Stirling cycles and internal combustion engines.

However, the effective exploitation of the thermal output for space and DHW heating is critical to realizing high levels of overall energy efficiency and the associated environmental (CO_2 and other) benefits. It is believed that building-integrated cogeneration will not deliver the potential benefits outlined above without appropriate control strategies.

This research work has partially been carried out in the framework of the IEA ECBCS Annex42 project called "The Simulation of Building-Integrated Fuel Cell and other

Cogeneration Systems", where also CHP units based on Stirling engines are studied. This paper is based on [2]. Other research projects from Siemens in the field of building automation using the same optimal control approach involve heating applications [3] and integrated room automation [4]. A similar approach has been used in [5].

DESCRIPTION OF THE SYSTEM

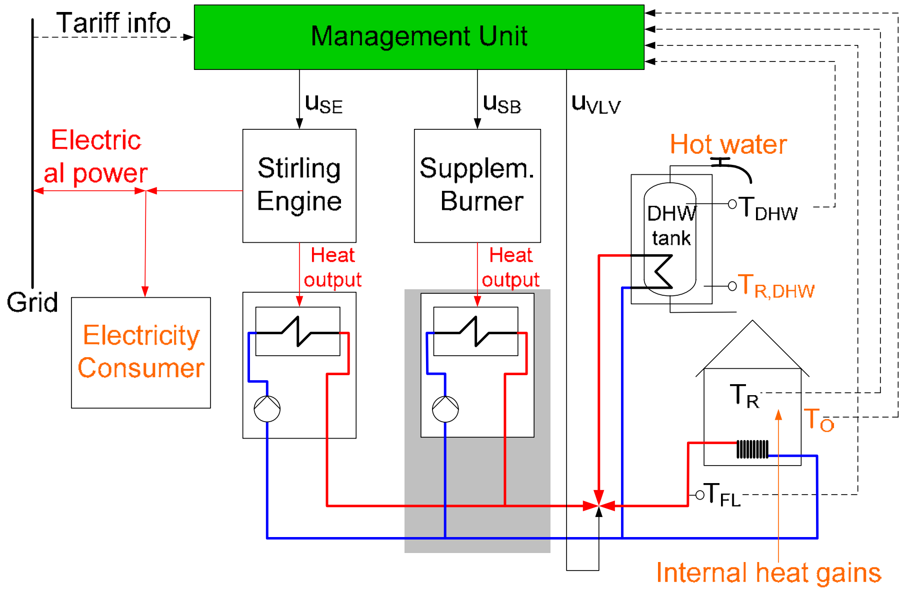


Figure 1: Overview of the system.

An overview on the system is given in Figure 1: A CHP unit heats the building by means of an underfloor heating system, supplies the domestic hot water and may partly or wholly satisfy the electrical demand. The CHP unit is made up of a Stirling engine and a supplementary burner that covers the thermal peak loads. Control signals u_{SE} and u_{SB} represent the gas input of Stirling engine and supplementary burner, and u_{VLV} is the fraction of heat that flows into the heating circuit.

ASSESSED OPTIMAL CONTROL STRATEGIES

Both optimal control strategies must satisfy the following constraints:

Room temperature	$T_R(t) \in [T_{R,min}(t), T_{R,max}]$
DHW storage tank temperature requirements	$T_{DHW}(t) \in [T_{DHW,min}, T_{DHW,max}]$
Maximal flow temperature limitation	$T_{FL}(t) \le T_{FL,max}$
No discharging of DHW tank for heating	$\dot{Q}_{th,DHW}(t) \ge 0$
Minimal and maximal limitation of the control signals (normalized)	$u_{SE}(t), u_{SE}(t), u_{VLV}(t) \in [0,1]$

(1)

Cost optimization

Cost-optimal control minimizes the sum of gas and electricity costs. The cost function is:

$$J_C = \min \sum_{\text{time } t} \left[C_{\text{PE,SE}}(t) + C_{\text{PE,SB}}(t) + C_{\text{el}}(t) \right] \tag{2}$$

where $C_{PE,SE}(t)$ and $C_{PE,SB}(t)$ is the cost of PE, i.e. the gas for the Stirling engine and supplementary burner, and $C_{el}(t)$ is the cost of electricity bought (from the grid) minus the gain from electricity sold (to the grid).

Primary energy (PE) optimization: Electricity credit method

For both PE optimization and performance assessment we compare the CHP system with a system with conventional generation (heat generated in a gas boiler; electricity generated in a gas-driven electrical power plant without exploitation of waste heat). In Figure 2 we first consider the situation *without supplementary burner* (same efficiencies used as later on).

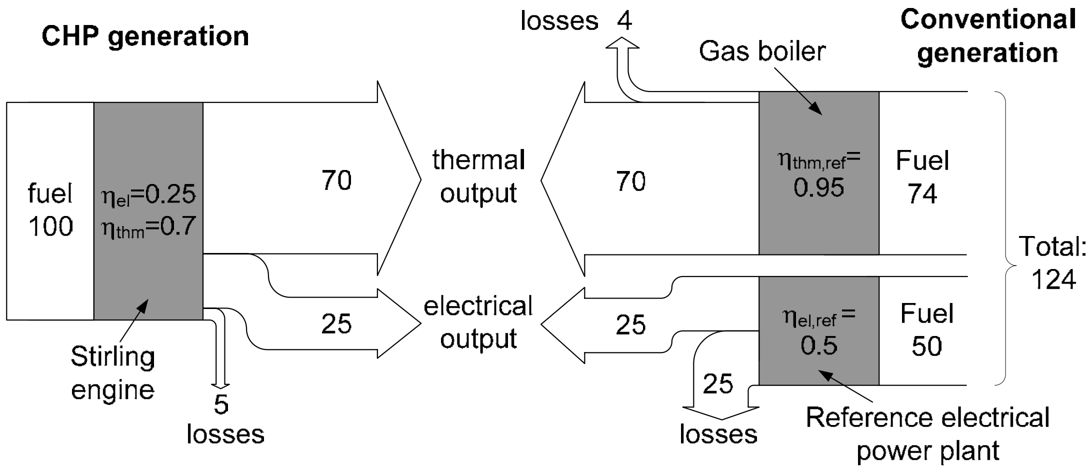


Figure 2: Comparison of energy flows of Stirling engine and conventional generation (situation without supplementary burner) .

With 100 kWh of PE (gas), the example CHP unit produces 70kWh of thermal output and 25kWh of electrical output. To produce the same thermal and electrical output with conventional generation (i.e., a conventional gas boiler for heating and a conventional power plant for electricity production), 124kWh of PE would be needed, 50kWh of which for electricity production. For computing the relative savings, we can relate the difference of the PE used to the PE used for heating only with a conventional system, i.e.:

$$relative\, PE\, savings = (124-100)/74 \;=\; 32.4\%. \qquad (3)$$

This definition of relative savings is the same as for measures to reduce heating energy consumption, for example improving the building isolation.
There are different possible criteria for PE optimization [9]. Our approach is to minimize overall PE consumption (for heat and electricity, including the grid). Basic idea: The electricity produced by the CHP need not to be produced somewhere else in a conventional power plant (the reference electrical power plant), thus reducing the PE consumption of this reference power plant. These savings (50kWh in Figure 2) are accounted for with a corresponding “credit” in the optimization criterion for PE-optimal control, J_{PE}. We call this method “electricity credit method” [6]. For the system with Stirling engine *and supplementary burner*, J_{PE} is thus:

$$J_{\mathrm{PE}} = \min \sum_{\text{time } t} \left[E_{\mathrm{PE,SE}}(t) + E_{\mathrm{PE,SB}}(t) - E_{\mathrm{el,ref}}(t) \right] \qquad (4)$$

where $E_{PE,SE}(t)$ and $E_{PE,SB}(t)$ is the PE (gas) consumption of Stirling engine and supplementary burner, and $E_{el,ref}(t)$ is the credit for produced electricity.
Note that without the credit for electricity the Stirling engine is not used at all. PE optimization only favors the Stirling engine if it receives a payback from electricity production. Furthermore, the criterion for optimization should comply with the criterion for performance assessment (assessment of PE used, and of PE savings compared to a conventional system).

Optimization method

We use linear programming (LP) as optimization method. The optimization horizon is chosen to be 24h, with 15-min time steps. A moving horizon technique is then applied to run through the whole period under consideration (e.g. one year).
The optimization problem is formulated in terms of a cost function; see for example eq. (2), that has to be minimized under a set of inequality constraints given by eq. (1). The linearized plant model (in our studies, the plant model was of order 24) is used to express the temperatures $T_R(t)$, $T_{DHW}(t)$ and $T_{FL}(t)$ as a function of the control sequences $u_{SE}(t)$, $u_{SB}(t)$ and $u_{VLV}(t)$ for each time step within the time horizon. The cost function is then minimized by manipulating the optimization variables (i.e., the control sequences).

NUMERICAL VALUES AND PARAMETERS

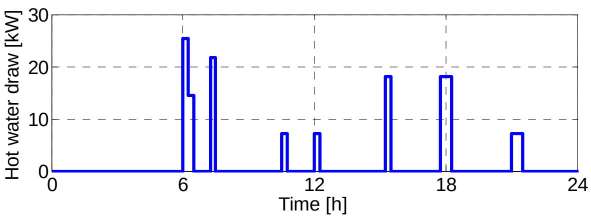
Building types

We studied three types of buildings with four apartments inhabited by three occupants each: An old one with thin walls and poorly insulated windows, an averagely insulated one corresponding to the German WSV95 building regulation and a well insulated one corresponding to the German EnEV2000 building regulation. More details on these building types can be found in [7]. The apartments all have a floor space of 150 m^2.
The nominal gas input of the Stirling engine has been chosen in such a way as to ensure the basic load, i.e. the engine should supply the average thermal energy needed during a whole year. On the other hand, the supplementary burner is sized so that the peak loads during winter (design temperature of -13.5°C) can be covered by both the engine and the supplementary burner.

Nominal values		Old	WSV95	EnEV2000
Stirling Engine heat output	[kW]	19.9	9.4	5
Stirling Engine electrical power	[kW]	7.1	3.35	1.8
Supp burner heat output	[kW]	41.2	18	8.2
Building heat losses	[W/K]	445.7	194.3	88.4
Building cooldown time constant	[h]	94	162	396

Table 1: Numerical values of the parameters for three building types

Loads and climate



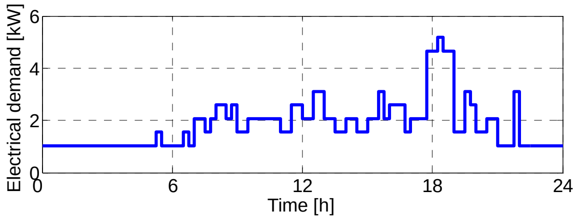


Figure 3: Profiles of hot water draws (left) and electricity demand (right), both in kW. Demand peaks are mapped to 15min-intervals (= sampling time of the control algorithm).

Five disturbance variables are included in our model and are shown in Figure 1 in orange.

- **Hot water**: An overview on typical electric and DHW load profiles is given in [8]. We assume an average daily hot-water consumption of 52 liter/person at a rise of 50K, which corresponds to 36.3kWh for a building with 12 inhabitants. We assume strong peaks in the morning and the evening (see Figure 3).
- **Electricity**: The daily electricity consumption is set to be 43.8kWh with a minimum

consumption of 1 kW and with peaks depending on the time of day (see Figure 3).

- **Outdoor temperature (T_O)**: For whole-year simulations, we use the temperatures measured at Zurich Airport during the year 2000
- **Internal heat gains (persons, electrical equipment etc.)**: Set constant to 0.6kW.
- **External heat gains**: Neglected. Reason: Incorporating solar gains correctly would involve the modeling of sunblinds, including an appropriate sunblind operation.
- **DHW tank**: The air temperature around the DHW tank ($T_{R,DHW}$) is set to be 10°C. The cooldown time constant of the DHW tank is set to be 2 days.

Prices

We use gas and electricity prices of Zurich, Switzerland (all in CHF-cents).

- **Natural gas**:
  - CHP devices: 5.1 cents/kWh
  - Conventional burners: 6.1 .. 7.1 cents / kWh (*lower* for large consumers)
- **Electricity**: Table 2 shows the electricity rates of Zurich.

period	Purchase from grid	Feed-in
Winter day-time	17 .. 19.5 cents / kWh (*higher* for large consumers)	15 cents / kWh
Winter night-time		11 cents / kWh
Summer day-time		7 cents / kWh
Summer night-time	5.0 cents / kWh	4 cents / kWh

Table 2: Electricity pricing, Zurich. Winter: 01.10 – 31.03. Day-time: 6am – 10pm.

Reference electrical efficiency

We adopt a marginal approach with a state-of-the-art gas reference power plant: From the viewpoint of achieving additional electricity capacity with a Stirling engine, the efficiency of an equivalent new central power generation installation should be considered, i.e. 56% for a combined cycle system at the power station, i.e. around 50% with losses resulting from electricity transport from the power plant to the apartment building. (Note that this is an ambitious benchmark. In many publications, the current electricity mix with η_{el} around 35% is used instead.) For more information see [9].
We assume that exported electric energy is consumed in-house or in the vicinity of the Stirling engine. Then the electricity produced by the Stirling engine is not subject to grid losses, in contrast to the electricity from the power plant. The grid losses are therefore included in $\eta_{el,ref}$ for both import and export.

Efficiencies and setpoints

- Efficiencies of the Stirling engine: $\eta_{\mathrm{SE}} = 0.95, \quad \eta_{\mathrm{SE,\,th}} = 0.7, \quad \eta_{\mathrm{SE,\,el}} = 0.25$
- Efficiency of the supplementary burner: $\eta_{\mathrm{SB}} = 0.95$
- Reference electrical efficiency: $\eta_{\mathrm{el,\,ref}} = 0.5$ (after subtraction of grid losses)
- Reference thermal efficiency: $\eta_{\mathrm{th,\,ref}} = 0.95$
- Room temperature: $T_{R,\,\min} = 19°\mathrm{C}$ between 22:00 and 06:00, $T_{R,\,\min} = 21°\mathrm{C}$ between 06:00 and 22:00, $T_{R,\,\max} = 24°\mathrm{C}$
- Flow temperature: $T_{FL} \le 50°\mathrm{C}$
- DHW storage water temperature: $T_{\mathrm{DHW,\,min}} = 20°\mathrm{C}$ and $T_{\mathrm{DHW,\,max}} = 80°\mathrm{C}$.
  ⇨ Note that T_{DHW} is the *average* water temperature of the DHW storage tank, not the measured (sensor) temperature. For the minimal state of charge we assume that 20% of the water in the tank has a temperature of 60°C and 80% has a temperature of 10°C

so that the average temperature is 20°C.

SIMULATION RESULTS

Diurnal progression of the temperatures and control signals (base case)

Figure 4 shows progressions with PE-optimal control over 2 days for a sinusoidal outdoor temperature with a mean value of 7°C, an amplitude of 6°C, and a minimum temperature reached at 3am. The building type is chosen to be an older one for better contrast. Note that the Stirling engine works with full heat output throughout the night. The peaks of the supplementary burner are caused by hot water consumption. The progressions are quite the same for cost optimization with winter tariff as well, but not for cost optimization with summer tariff.

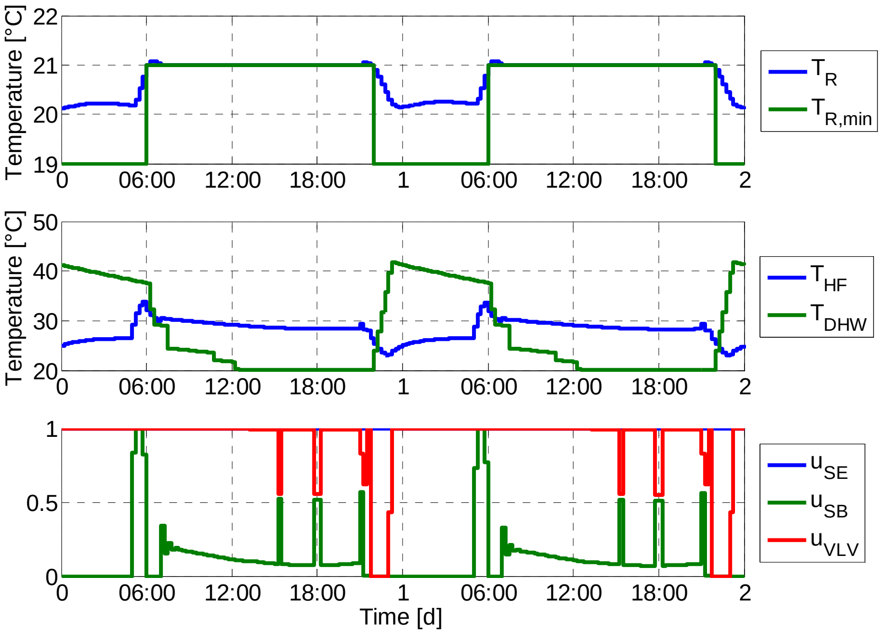


Figure 4: Results of PE-optimal control for an older building with a mean outdoor temperature of 7°C. Middle panel: Flow temperature TFL (blue) and hot water temperature (average over the whole tank, green).

Differences between cost-optimal and PE-optimal control

The characteristics of the control behavior depend in a complex way on many factors. We restrict ourselves to pointing out a few major differences between cost- and PE-optimal control:

- Generally, PE optimization (as well as cost optimization with winter tariff) tries to use the Stirling engine as much as possible and to use the supplementary burner as little as possible.
- As a consequence, the Stirling engine runs throughout the night unless the outdoor temperature is too high. This results in a moderate night setback. The DHW storage may preferably be charged at the beginning of the night.
- Cost optimization with summer tariff tends to shut down the engine, thus producing a more pronounced night setback and postponing the DHW charge to the early morning. As a consequence, more support from the supplementary burner is needed in the morning.

Performance assessment (PA) for whole-year simulations (base case)

The operation cost and PE consumption of the investigated system has been compared to the figures from a conventional generation (reference) system. In the reference system, there is no Stirling engine; however the supplementary burner (conventional gas boiler) is more powerful, such that the total rated thermal output is the same. All electricity is produced by the electrical reference plant ($\eta_{el} = 56\%$). For the computation of the relative PE savings, the PE consumption for heating only with the conventional system is taken as a reference (example without supplementary burner see equation (3)). Table 3 shows the main results:

			Building type		
			Old	WSV95	EnEV2000
Conventional heating (=gas burner alone)		Cost PE consumption for heating	CHF 15,169.-- 196.5 MWh	CHF 8,512.-- 87.4 MWh	CHF 5,650.-- 40.5 MWh
CHP system	Cost-optimal control	Cost saving PE saving	28.5% 20.6%	28.1% 21.9%	23.3% 23.7%
	PE-optimal control	Cost saving PE saving	27.5% 21.4%	25.5% 22.9%	20.6% 24.9%

Table 3: Main PA results for the base case. Reading example for old building: With conventional heating (a conventional gas burner alone), the yearly energy cost is CHF 15,169.- and the PE consumption for heating is 196.5MWh. With cost-optimal control, the one-year energy cost for the reference system with Stirling engine is 28.5% lower than with a gas burner alone, and saves 20.6% of PE. PE-optimal control saves 27.5% energy cost and 21.4% PE.

The differences in cost and PE consumption between both types of optimization (cost/PE) are only a few percent. This means the tariffs in Zurich reward a PE-optimal operation quite well. The equivalent full-load operating time of the Stirling engine is between 260 and 280 days, or about three quarters of the year for all cases. This indicates correct sizing of the SE.
The whole-system PE savings of 21 .. 25% can be related to the PE savings of the Stirling engine alone, which are 32.4% (equation (3)). The latter figure is the limitation for achievable PE-savings with a much more powerful SE. In other words, the base case design (SE for peak load only) achieves 65 .. 75% of the possible savings. This result is backed in the following section.

Variation of the sizing of the Stirling engine

Starting from the base case, the variation of many parameters has been investigated, including time shift of room temperature setpoint profile and electricity tariff profiles; electricity and gas prices; reference electrical efficiency; Stirling and supplementary burner efficiencies; and DHW tank size. In this section, we vary the nominal gas input of the Stirling engine and assess the effect on operation cost and PE consumption. The size of the supplementary burner is varied accordingly, such that the total nominal heat output remains constant. (Note that SE power multiplier = 0 results in the conventional reference system used for the performance assessment, see above).

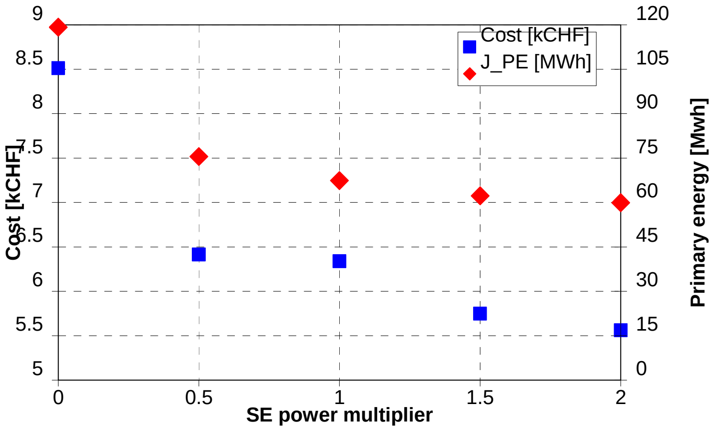


Figure 5: Cost and PE consumption as a function of the SE sizing (power multiplier)

Figure 5 shows the result of PE-optimal simulation over one year with temperatures measured in 2000 for the WSV95 building. We can see that the curves become rather flat when increasing the size of the Stirling engine above the reference case (i.e. SE power multiplier > 1): Doubling the size of the Stirling engine reduces operating cost of only by about 12%. Since on the other hand, investment and maintenance costs increase with the size of the Stirling engine, an SE seems to be correctly sized in the base case.

DISCUSSION

The method described in this paper allows determining the cost- or PE-optimal CHP operation for a given system, with known loads and climate. This optimal solution is the performance bound and can be used for a comparison with real or simpler (suboptimal) control strategies. It also gives us useful hints for developing such simpler strategies.
Numerical values for building model, load profiles etc. used in this paper may be debatable. Nevertheless we are convinced the general quantitative results are usable:

- We investigated a combination of a Stirling engine for the base load and a supplementary burner for the peak load. Using the assumptions on parameters, loads, and climate outlined in this paper, such a set-up can yield a whole-year PE and CO_2 savings are in the range of 20..25% comparing to conventional generation (modern reference electrical power plant with an ambitious $\eta_{\mathrm{el}} = 56\%$).
- Increasing the SE size at the expense of the supplementary burner increases the PE savings only moderately may increase investment costs significantly.

The use of CHP is encouraged by many governments in order to meet the goals of the Kyoto protocol. However in practice, CHP owners and operator will only operate their CHP device in a PE-optimal way if this is financially rewarded. Governments should therefore convince energy suppliers to offer attractive prices for feed-in electricity. (Technically this means that the two cost functions (2) and (4) should be similar, see [2].)

ACKNOWLEDGEMENT

The partial funding of this research by the Swiss Federal Office of Energy (SFOE) in the context of the IEA ECBCS Annex42 project is gratefully acknowledged.

REFERENCES

[1] I. Knight, I. Usurgal: Residential Cogeneration Systems: A Review of the Current Technologies, Annex 42 of the International Energy Agency (IEA) Energy Conservation in Buildings and Community Systems (ECBCS) Programme, April 2005, http://www.cogen-sim.net

[2] R. Lamon, C. Gähler, M. Gwerder (Siemens Building Technologies): Optimal Control of CHP Building Energy Systems. Report submitted to the IEA ECBCS Annex42 project, Sept 2006. Available from the authors (*conrad.gaehler@siemens.com)*

[3] P. Gruber, M. Gwerder, J. Tödtli: Predictive Control for Heating Applications, Clima 2000, 7th REHVA World Congress, Napoli, Italy, 2001

[4] M. Gwerder, J. Tödtli: Predictive Control for Integrated Room Automation, Clima 2005, 8th REHVA World Congress, Lausanne, Switzerland, 2005

[5] A. Collazos: Optimisation Based Control System for the Optimal Management of Micro-Cogeneration Systems. Master's thesis, EPF Lausanne, Switzerland, 2006

[6] W. Suttor, A. Müller: Das Mini-Blockheizkraftwerk. Eine Heizung, die kostenlos Strom erzeugt. C.F.Müller-Verlag, Heidelberg, 2000

[7] M. Schmidt, Veränderung der Anforderungen an Heizanlagen bei steigendem Wärmedämm-standard, Wärmetechnik-Versorgungstechnik, 11, 2000

[8] I. Knight et al: Residential Cogeneration Systems: European and Canadian Residential non-HVAC Electric and DHW Load Profiles, IEA / ECBCS Annex 42, The Simulation of Building-Integrated Fuel Cell and Other Cogeneration Systems

[9] V. Dorer, A. Weber: Performance Assessment of Residential Cogeneration Systems, Part A: Methodology. IEA / ECBCS Annex 42, July 2006