Prospective and adaptive management of small Combined Heat and Power systems in buildings

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SUMMARY

In the context of current promotion of Distributed Generation (DG), micro Combined Heat and Power (CHP) systems for single or small ensembles of (residential) buildings are seen advantageous to combine both decentralized generation and rather high overall efficiency. The latter presupposes intelligent management strategies which have to mediate between energy cost minimization and user comfort aspects. A flexible and auto-adaptive approach of such kind of energy and load management was developed and first results are shown with several operational examples gained from simulation based verification.

INTRODUCTION

Micro Combined Heat and Power (CHP) systems powering up to approximately 10 kW_{el} are considered as a future key technology for energy supply of buildings and settlements from the viewpoints of both heating systems manufacturers and energy suppliers; such CHP plants can be based on conventional Diesel, gas or biomass motors, gas or steam turbines, as well as Stirling engines or fuel cells [1]. In combination with existing public gas and electricity supply these technologies are well suited for cardinal provision of electric and thermal energy in single or multi-family residences and buildings with mixed occupancy of habitation and business establishments. It is evident that reasonable economic operation of CHP systems can only be achieved if power peaks are being moderated; for electrical peaks the public grid connection provides a sound basis, whereas thermal peaks can be smoothed out by both thermal storage and an auxiliary boiler. Efficient operation of such plants pivotally depends on their sound layout for the particular building under regard as well as powerful strategies for energy and load management. Energy management in this context means cost-efficient supply of all (electrical and thermal) loads by intelligent operation of all interacting system components, in particular the CHP unit. Load management means the controlled arresting and releasing of the operation of certain devices, especially larger electro-thermal loads with a significant power demand – for instance a washing machine.

So far, commercial CHP plants do not include sophisticated control structures for flexible and automatic adaptation of their operation to the individual customer behavior, given tariffs and local infrastructure. The existing conventional energy management systems usually control the power of the CHP unit with respect to the actual electricity and heat consumption, but do not apply past or forecasted quantities; user specific consumption behavior as well as dynamic weather influences (such as outside temperature, wind, insolation) are not adequately considered. The potential of installed CHP plants therefore cannot completely be exploited.

In the frame of a current research project – accompanied by manufacturers of CHP plants, network operators and natural gas service providers – efficient strategies for a powerful energy and load management of a micro CHP based energy supply for buildings are being developed and verified on a sound simulation of the complete CHP system. Besides regarding the operational demands and boundaries of the plant components involved, the energy management is designed to fulfill comfort demands by flexible adaptation to user habits (evaluation of past and consequential prognosis of future consumption) as well as local tariffs and infrastructure, and therefore provides economic generation of electricity and heat under inclusion of environmental compatibility. The load management controls the operation time of certain (mainly larger electro-thermal) devices based on evaluation of past user behavior – considering both comfort demands and economic aspects. The management functionalities are elaborated and verified on a detailed operational simulation of the complete CHP system under regard; first results are presented in the following.

METHODS

Simulation model

A versatile Matlab/Simulink® based simulation tool containing a library of Distributed Generation (DG) component models was developed, allowing to arbitrarily compose typical residential micro CHP systems and to investigate the characteristics of the components as well as their operational interdependence within the complete supply system under high temporal resolution and simulation fidelity [2]. The minimum simulation step size is 1 s, while 60 s has proven as a good compromise between accuracy and computation time. This simulation tool was used for test and verification of the CHP energy management focused on here.

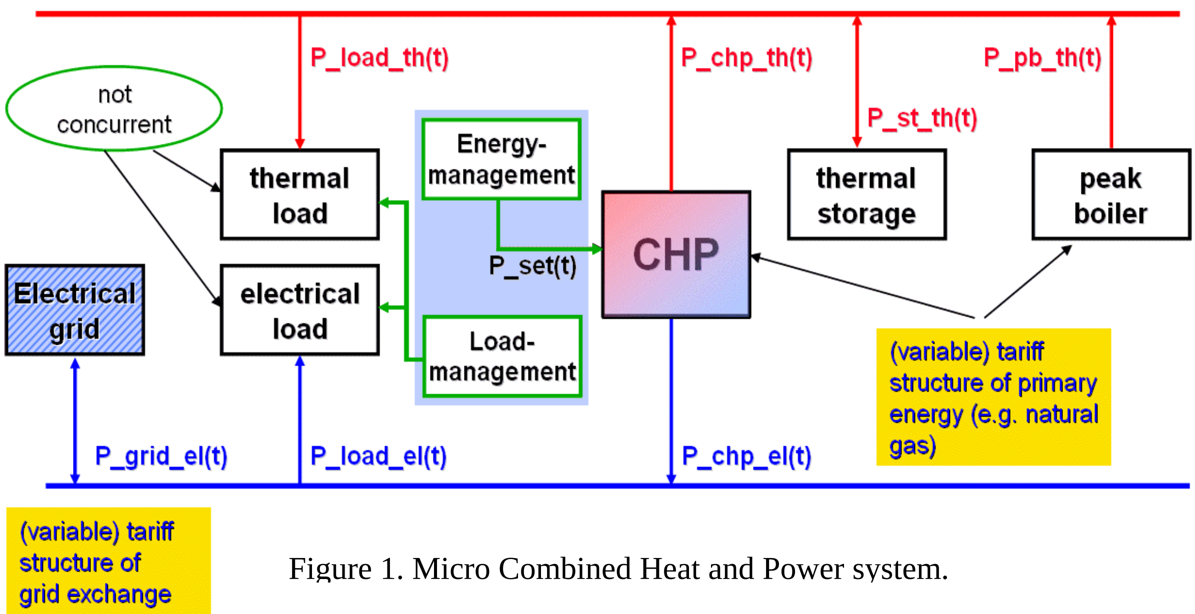

Figure 1. Micro Combined Heat and Power system.

A typical residential CHP system is shown in Figure 1. The system consists of the following main components which were modeled by use of the simulation tool for validating the management functionalities focused on here under largely realistic operational conditions:

Electrical and *thermal loads* are considered as a time series of power samples; these can either be taken from measurements or they can be synthesized by superposition of individual load curves – if required. Innovative energy supply systems are usually installed in connection with modernization of old or construction of new buildings. Therefore, modern building standards and corresponding demand curves were used to develop and verify the CHP plant management. In particular, for the investigations made here, load curves of 140 m^2 low-energy single occupancy houses (4 person's households) over one year in 15 minutes temporal resolution had been available from a German measurement program [3]. As an example, a detailed electrical and thermal (both heating and warm water) demand curve for a cold week in January is shown in Fig.2.

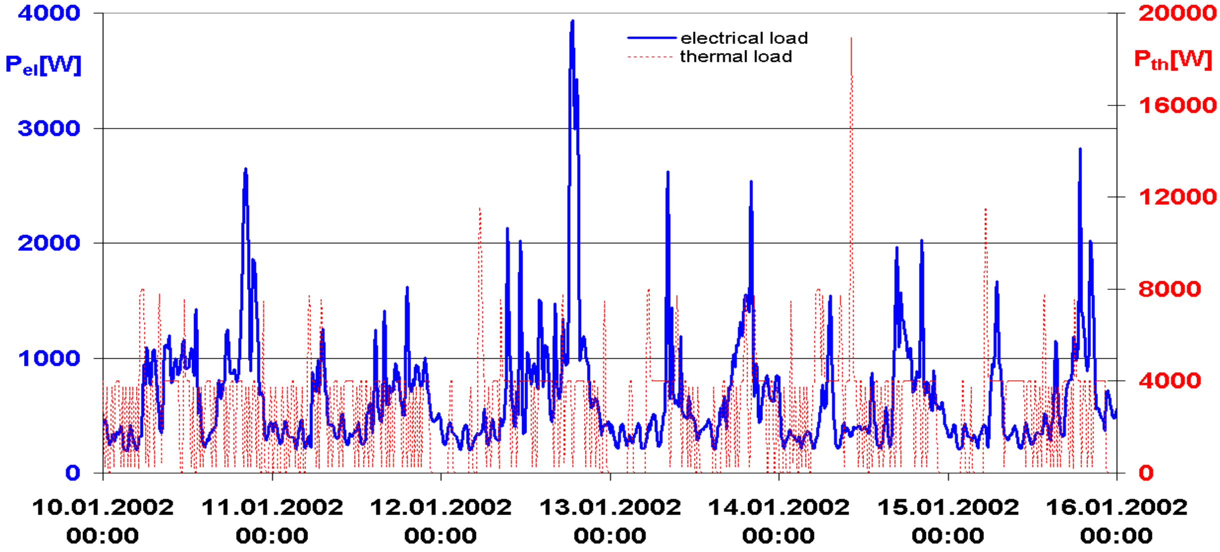

Figure 2. Electrical and thermal load curves in 15 minute resolution (excerpt).

The *CHP unit* is characterized by its stationary power curve including upper and lower operating limits, maximal thermal and electrical power gradients δP/δt, minimal operating and down times, maximal numbers of start-ups and set-point changes per day, performance during the start-up procedure – including auxiliary power demand – and the associated start-up costs. In principle, the simulation system can be set up for various kinds of CHP units as enumerated in the introduction. The examples given in the following are specifically related to a *gas engine based generator set* because such units are presently the most common (and economic) ones used for micro CHP generation. The reference unit has 5 kW_{el}/8 kW_{therm} nominal power and 1 kW_{el}/1.6 kW_{therm} minimal power respectively; the electro-thermal generation interdependency, steady state operating points as well as the start up performance are shown in Figure 3a/b.

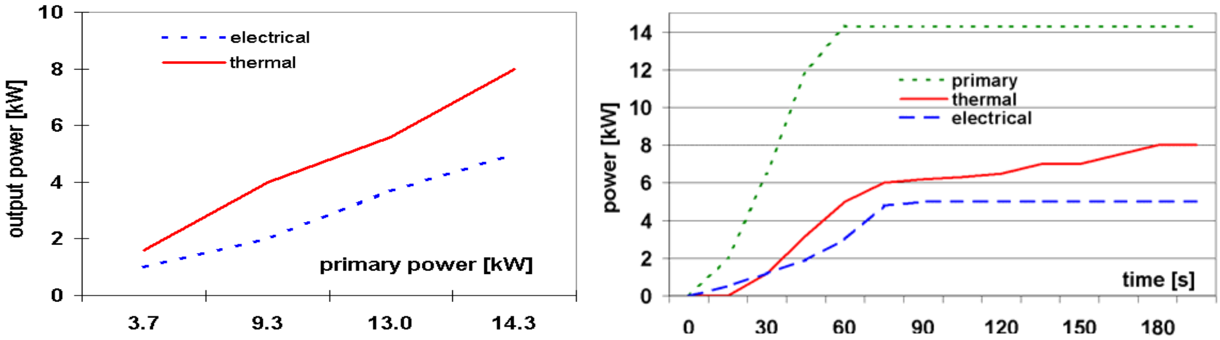

Figure 3. a) Stationary CHP operation points. b) Start-up behaviour of CHP

The *thermal storage* as a crucial component to moderate the thermal power peaks is modeled considering the capacity, maximum charging and discharging powers, maximal power gradients, efficiency of charging and discharging processes, and a fill level dependent loss factor. The storage actually considered here has a capacity of 600 l (≡ 35 kWh at operating temperature); the efficiency of a charge/discharge cycle was set to 95% and a discharging loss factor of 0.1 kWh/h was assumed. The maximal charge and discharge power is 22.9 kW. A dead band control keeps the thermal storage filling level within adjustable threshold values. In case the maximal admissible storage filling level is exceeded the CHP plant is shut down immediately.
The *peak boiler* is operated at nominal power if the thermal storage filling level falls below 20%. Boiler operation is stopped if the storage fill level exceeds 25 %. The simulation model accounts for a characteristic stationary power curve including upper and lower operating limits, and has no gradient limitations.
Coupling to the *electrical grid* – which is considered as unlimited but expensive electricity storage – is constricted by the connection power contracted with the provider.
The *tariff structures* of grid exchange power (feed-in and delivery) as well as primary power (natural gas) consist of both monthly connection rates and time variable kilowatt-hour rates. Even if nowadays electricity and gas rates for private customers are mostly constant (sometimes electricity rates may include special night tariffs for fixed time intervals) new electricity meter information technologies already do exist [4], allowing highly flexible and dynamic tariffs for future Distributed Generation applications; for instance, selective regional price signals can give the system operator an indirect control of a huge number of DG units. In order to prove the flexibility of the system, a tariff structure as shown in Fig. 4 was applied for the examples described in the following. Furthermore, a monthly connection rate of 7.50 € for electricity (each delivery and feed in) and 4.20 € for gas supply were assumed, reflecting actual tariffs in Germany.

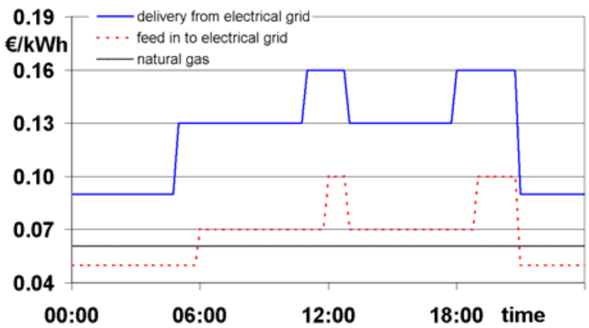

Figure 4. Electricity and gas tariffs applied.

CHP system management

Under regard of the current system states, the operating point dependent component characteristics, their dependencies, varying tariffs, forecasted electrical and thermal loads and potential commercial contracts, ad hoc online cost optimal CHP set-point setting is not a trivial task. The management structure was therefore designed to consist of the three modules *load management*, *load forecast*, and *energy management* (Figure 5), which provide decisions during online operation. The adaptation of the modules to user habits, local tariffs and infrastructure is regularly improved by off-line pre-processing of the archived measurement data, see

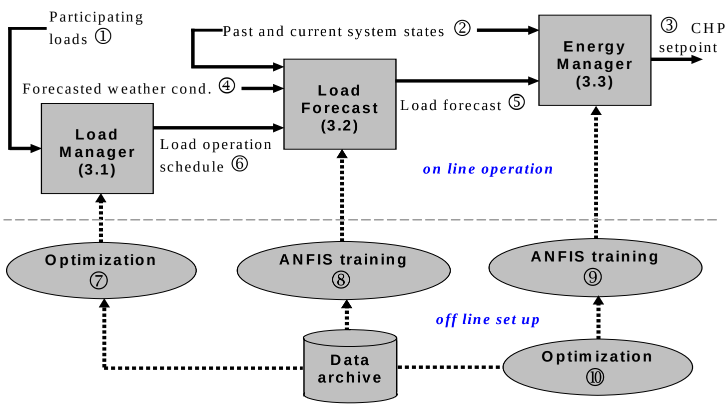

Figure 5. Structure of CHP set point decision making.

Figure 5, lower part. For the very first operation initial default values are implemented. In the following considerations, a weekly pre-processing cycle is applied.

The *load management* module provides a schedule (⑥ in Figure 5) of privileged operation times for each participating load ① one week in advance. These schedules are the result of a cost optimization process ⑦ and are based on the load specific maximal shifting intervals as well as on the measurement data recorded during the previous week. By overruling the proposed schedule, the user still can give emphasis on his comfort demands in which case higher associated costs have to be accepted. Even if controlling particular devices is not yet state of the art, there is current work in progress to establish such techniques, using for instance powerline or wireless communication [5,6]. In the scenarios presented in the forthcoming results section the total electrical load is composed from few controllable devices (e.g., washing machine) and the (uncontrollable) given rest.

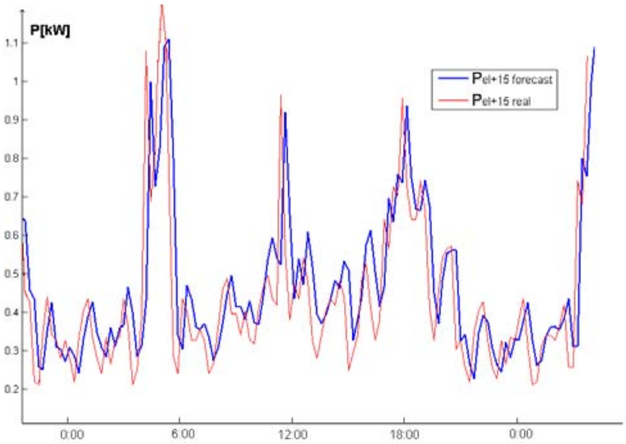

Figure 6. Example of 15 min. el. load forecast.

The *load forecast* module pre-estimates the electrical load at specific, discrete times in the future (15, 30, 60, 120 minutes ahead). Instead of the usually considered influence factors such as temporal and meteorological information the metaheuristic approach applied here (ANFIS, [7]) is based on recognition of characteristic sequences from the data archive. As an example of the forecast quality Figure 6 shows both the 15 minutes forecast and the actual load measured. Owing to the chaotic and hardly predictable instantaneous values of the warm water demand, the expected thermal *energy demand* (warm water and heating) within the next 2 hours is forecasted. The instantaneous difference is balanced by the thermal storage.

The *energy management* finally generates the next power setpoint ③ ensuring cost optimal operation of the micro Combined Heat and Power system. This is achieved based on past, current and forecasted loads ⑤ and tariff information as well as on current and past operating states ②. The appropriate CHP-setpoints are determined by the objective function described below: archived electrical and thermal load curves of the previous week as well as tariff information are applied to the CHP model, and optimal CHP-setpoints are identified with hindsight minimizing the associated costs. The interdependencies between the corresponding inputs and the determined CHP-setpoint values (see above) are periodically identified by means of the metaheuristic approach (ANFIS ⑨) – thereby extending the internal fuzzy knowledge base.

The cost optimal CHP-setpoints and load schedules are regularly determined based on the last week's measurement data, and used to continuously improve the quality of the management system. Owing to the high number of system variables (168 hourly setpoints for one week operation plus additional schedule parameters for all participating loads), the optimization has to be applied *offline* by means of an efficient technique. Taking into account all relevant operating conditions and restrictions, the energy and load management can be formulated as a mixed integer optimization problem:

$$cost_{tot} = cost_{prim\text{-}en} + cost_{grid} - pay_{grid} + cost_{util} \quad (1)$$

$$\min_{P_{CHP,set},\, load_{lm}} cost_{tot} = f(P_{CHP,set}, tariff_{el,prim}, load_{lm}) \quad (2)$$

subject to:

energy management:

- 1.6 kW $\leq P_{CHP,th} \leq$ 8 kW
- maximal gradients $\Delta P_{CHP,th}$: +50 / -60 W/s
- start-up cost of CHP : 0.10 €
- maximal number of CHP starts per day: 10
- average time between CHP set point changes: 60 minutes
- minimal CHP run time: 4 minutes,
- minimal CHP stop time: 1 minute
- start-up cost of peak boiler: 0.00 €
- maximal number of peak boiler startups: no restrictions
- maximal no-supply time of loads: 0 s

load management:

- $load_{shift\text{-}min,i} \leq load_{lm,i} \leq load_{shift\text{-}max,i}$

with:

$cost_{tot}$: total costs for supplying all electrical and thermal loads
$cost_{prim\text{-}en}$: costs for primary energy, e.g. natural gas
$cost_{grid}$: costs for connection to and delivery from el. grid
pay_{grid}: refund for feed-in to el. grid
$cost_{util}$: costs for utilities (e.g. start-up, maintenance)
$P_{CHP,set}$: thermal CHP setpoint
$load_{lm,i}$: loads taking part in load management
$load_{shift\text{-}min\text{-}max,i}$: maximal shifting interval in load management

The optimization mode (pure energy- or combined energy/load management) is selected by incorporating one or both of the variables P_{CHPset}, $load_{lm}$ into the optimization process, see Eq. (2). Additional contracts such as minimal CHP overall efficiency for subsidies, or stipulated feed in power can be added if necessary.

In conclusion, the three modules load management, load forecast, and energy management are regularly adapted to user habits, local tariffs and infrastructure by incorporating means of *Computational Intelligence* into the developed control system. The identification of existing correlations between the last week's recorded measurement data (input) and corresponding output data – being results of the optimization or the prognosis – is extended weekly. This process of accumulation and generalisation results in a continuously improving online operation of the CHP system.

RESULTS

In the following first results of the application of the three management modules on a simulated CHP system are presented. The results are based on the load shapes of the January week from Figure 2.

Figure 7 shows the cost optimal plant operation (CHP set points) as determined by the energy management module (load management still disabled). From a broad view it is visible that the energy management in compliance with all active constraints results in

- a shut down of the CHP unit during night hours
- and an individual operation during daytimes.

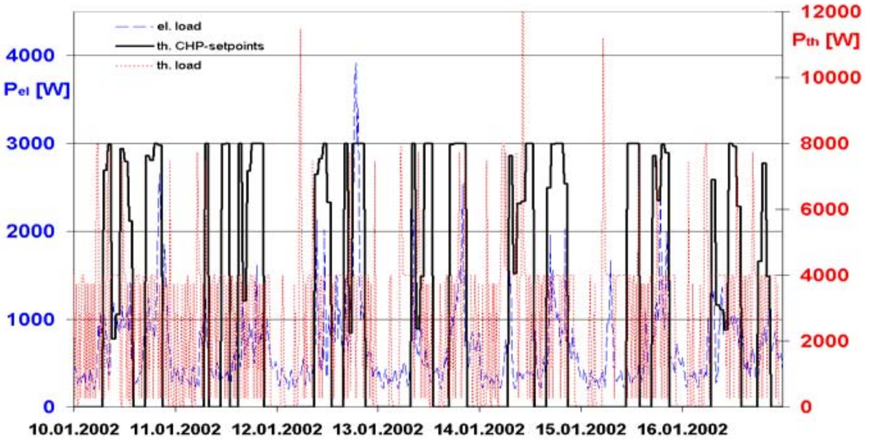

Figure 7. Results of energy management for a cold week in January.

From a more detailed view of the CHP set points, as exemplarily shown in Figure 8 for the Saturday, it can be realized that

- the mutual dependency of the system components,
- the varying electricity and gas tariffs during the course of the day (Figure 4),
- and the constraints as outlined above

do not allow for direct and easy derivation of the optimal system operation from the given electrical and thermal load shapes, thus demanding for intelligent techniques like the approach presented here.

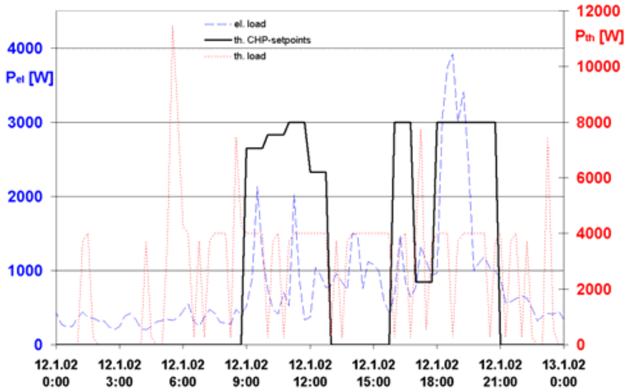

Figure 8. Setpoints determined for Saturday.

As an example of the *modeling detail grade*, the electrical grid exchange power resulting from the CHP operation and the filling level of the thermal storage are shown in Figure 9. It is obvious that the storage is generally charged at daytimes and discharged during the nights, but this is gradually influenced by the electrical grid exchange and the load profiles (Figure 2), thus leading to a rather individual daily operation of the plant.

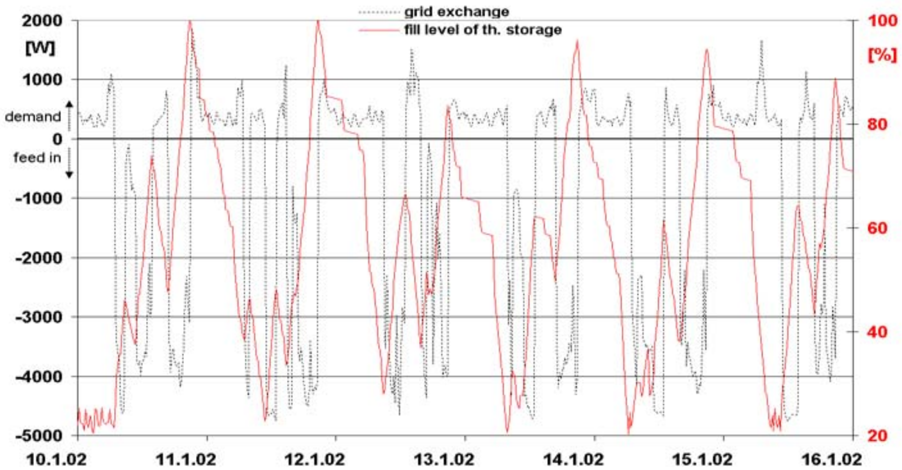

Figure 9. Filling level of thermal storage and el. grid exchange power.

A result of the additional application of the *load management* is shown in Figure 10: for one particular day (January 12th) shifting of certain electrical loads within a 24 hour period has been released. Comparison of the original load curve with the one resulting from load management generally proves that power peaks are defused and high-load periods are shifted to low-tariff regions (according to tariffs from Figure 4).

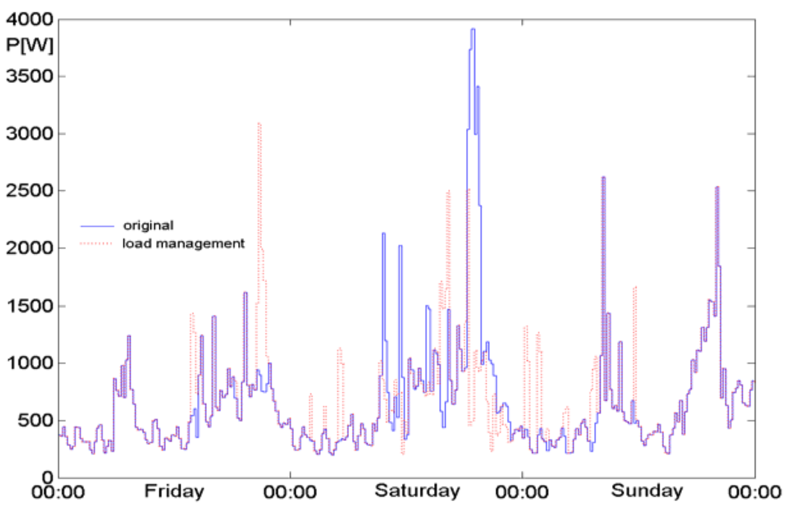

Figure 10. Effect of load management for certain el. devices.

A monetary comparison of different CHP operation modes is finally shown in Table 1 for the winter week under regard.

It is apparent that CHP operation with the energy management enabled (4) is saving approximately 17% of cost compared to no CHP operation - that is, complete electricity demand covered by external grid and thermal demand covered by peak boiler, (3). Having additionally the load management released for one day (see above) saves another 6%, (5). In contrast, blindfold CHP operation at either nominal (1) or minimal (2) constant power is even more expensive than no CHP operation at all.

Table 1: Comparison of energy costs.

CHP operation mode	**Weekly cost [€]**
1 Constant nominal power	139,16
2 Constant minimal power	54,14
3 No CHP operation	53,22
4 CHP with energy management only [1)]	44,00
5 CHP with energy and load management [2)]	41,07

1) see Fig. 7-9 2) see Fig. 10

DISCUSSION

Combined Heat and Power (CHP) systems for individual domestic appliances are a promising approach in the context of the recent developments in decentralized energy supply: they are based on an existing infrastructure (gas and electricity systems as well as house installation) and provide good efficiency. Owing to the extreme variation and non-simultaneity of electrical and thermal loads in single households, a flexible and adaptive system management is required. The proposed approach proved in first investigations performed on a detailed plant simulation that

- reasonable set points for the CHP unit are provided by having the energy management rely on historic (archive), actual and forecast data;
- the results are qualified by application of an adaptive load forecast module;
- power peaks are smoothed and heavy-load periods are shifted to opportune times by enabling the load management of certain (electro-thermal) devices;
- the overall energy cost can significantly be reduced.

Thus, by use of intelligent management functionality the benefits of decentralized Combined Heat and Power systems for buildings can fully be exploited.

ACKNOWLEDGEMENT

The authors highly appreciate the financial support by the German Working Committee for Industrial Research (AiF).

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