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Integration of Cogeneration Systems into Smart Grids

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***Abstract*-- Much of the energy generated today is produced by centralized power plants using fossil fuels, hydropower or nuclear power, with energy being transmitted and distributed over long distances to the consumers. The electricity networks of the future will have to accommodate large scale distributed generation including renewable energy sources and residential micro-generation. Therefore solutions must be developed to allow efficient and secure system operation of future grids with significant intermittent generation. Moreover an active demand side management must be realized enabling all consumers, with or without their own generation, to play an active role in the operation of the system. In the context of these demands, three pilot plants will be tested within an experimental virtual plant depictured in figure 1. These decentralized CHP plants can be integrated into the electricity market and into the energy management of a future power supply system. [1]**

***Index Terms*-- smart grid, virtual power plant, combined heat and power (CHP), optimization, energy management**

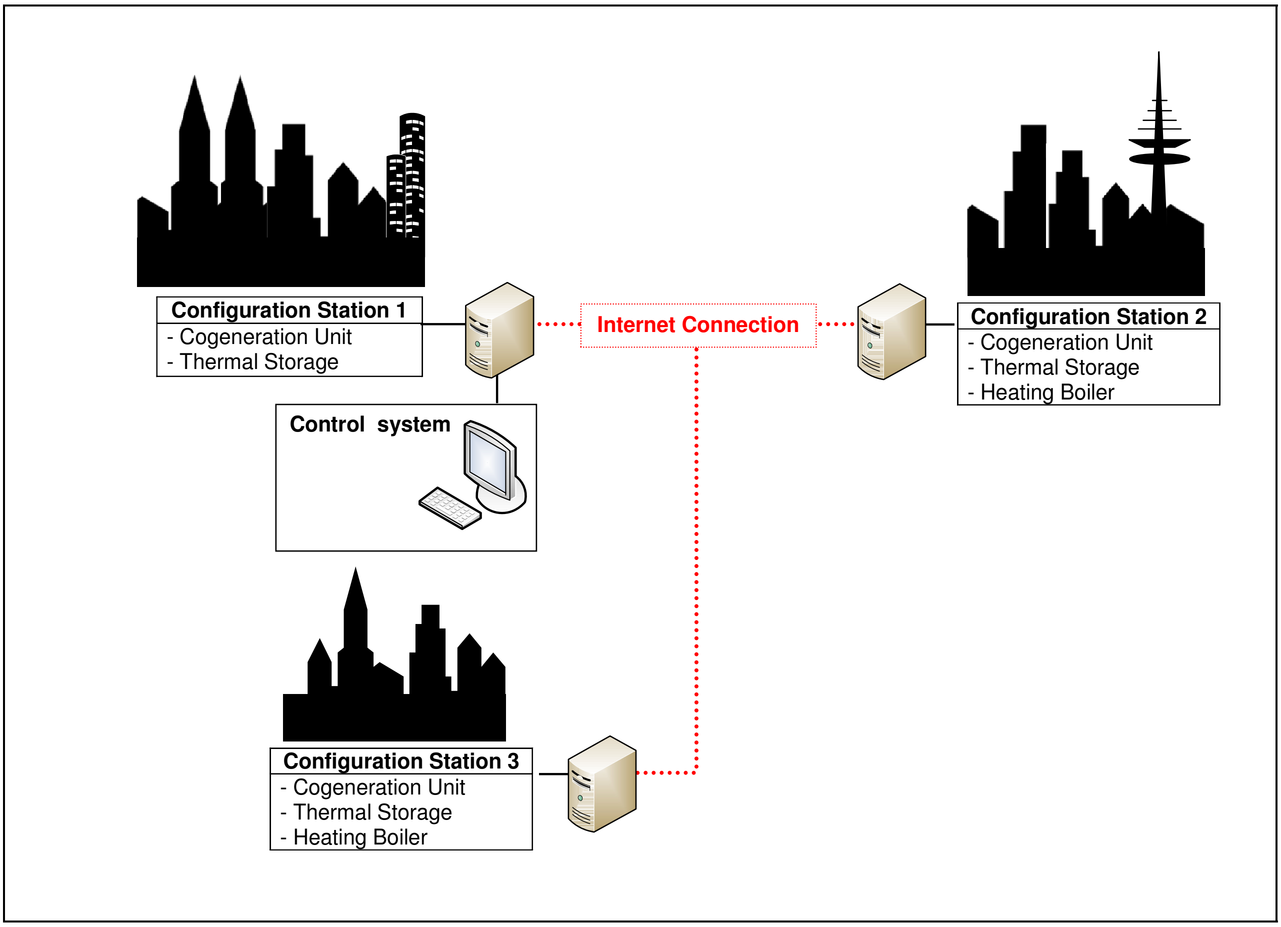

Fig. 1: Overview system configuration

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I. Introduction

The vision of the future energy supply is called "Smart Grid" as an electricity network that can intelligently integrate the actions of all users connected to it - generators, consumers and those that do both – in order to efficiently deliver sustainable, economic and secure electricity supplies [2][3]. Some of the key challenges for Smart Grids are:

- Developing decentralized architectures enabling smaller scale electricity supply systems to operate harmoniously with the total system;
- Finding the best ways of integrating intermittent generation including residential micro-generation;
- Allow consumers to play a part in optimizing the operation of the system;
- Effective integration of storage and demand response capacity by distributed control.

This paper describes the integration of cogeneration systems into Smart Grids. The efficiency of conventional centralized power systems is generally low in comparison with combined heat and power (CHP) technologies which produce electricity or mechanical power and recover waste heat for process use (cogeneration). CHP systems can deliver energy with efficiencies exceeding 90%, while significantly reducing the emissions of greenhouse gases and other pollutants. Generally residential CHP systems or cogeneration power plants connected to a district heating network are heat operated [4]. That means the operation control of the CHP system mainly follows the heat demand of the consumer. In order to integrate residential CHP systems into Smart Grids a mixed control strategy is needed combining both heat and power operated solutions. Based on a forecast of the power and heat demand the operation schedule of the distributed system will be calculated by an energy management tool [5]. In the next sections we will describe a procedure to find the optimal combination of the different generation units within the Smart Grid. Because of the large number of operation variables and restrictions the related mathematical optimization model has a very complex structure. We will demonstrate the control strategy for a real distributed cogeneration system including different types of CHP units and storage systems.

II. Scope and Objectives

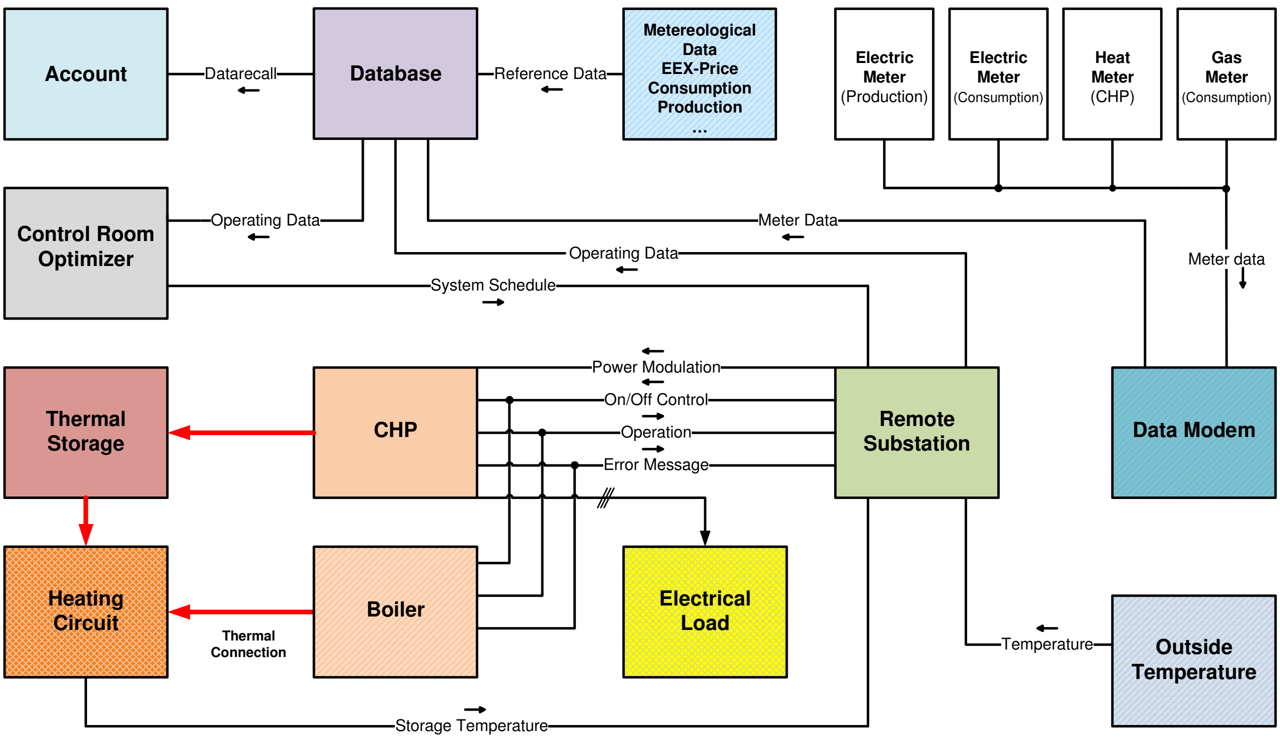

Fig. 2: Communication link of sub-systems

As shown in figure 2 the communication link as well as the controlling and monitoring of the decentralized generation systems are implemented within an experimental virtual power plant. The communication of the control system with the decentralized generation systems is realized by a wired Ethernet connection. In a first step the decentralized basic operation conditions and system information of the individual plant sections like CHP, boiler and thermal storage are collected by a micro remote control station and transmitted to a central database. The required meter data of each location are also collected and concentrated by a data modem and sent to the database in a second step. The use of smart meters enables additional service functions, e.g. remote shutdown of electrical loads, and allows a better manipulation monitoring. The primary goal of the bidirectional communication is to advance the account management and to improve the overview of the consumer behavior by remote reading. The reconstruction of the consumption and of the decentralized generation shows the saving potentials and makes shifting and production strategies possible.

The system is supervised by the process control system, which receives the measured values, messages and reference data of the individual components, and stores them into the database. The data are available during a long period for other applications like the optimizer. The main task of the optimizer is to calculate operation schedules for all plant sections on the basis of the different system information and forecast. The optimization includes economic as well as ecological aspects, e.g. emission limits. The plants can be directly controlled by the micro remote control stations. The process control and remote system offers additionally a visualization of the virtual plant, which gives an overview of the current plant conditions and makes a direct manual control and configuration possible. The calculated operation schedules finally cover the individual heat load profiles of each plant sub-section as well as the overall electric load profile in an optimal way shown in figure 3. The optimization structure based on a linear algorithm and is implemented into a mathematic solver named CPLEX via an open programming language.

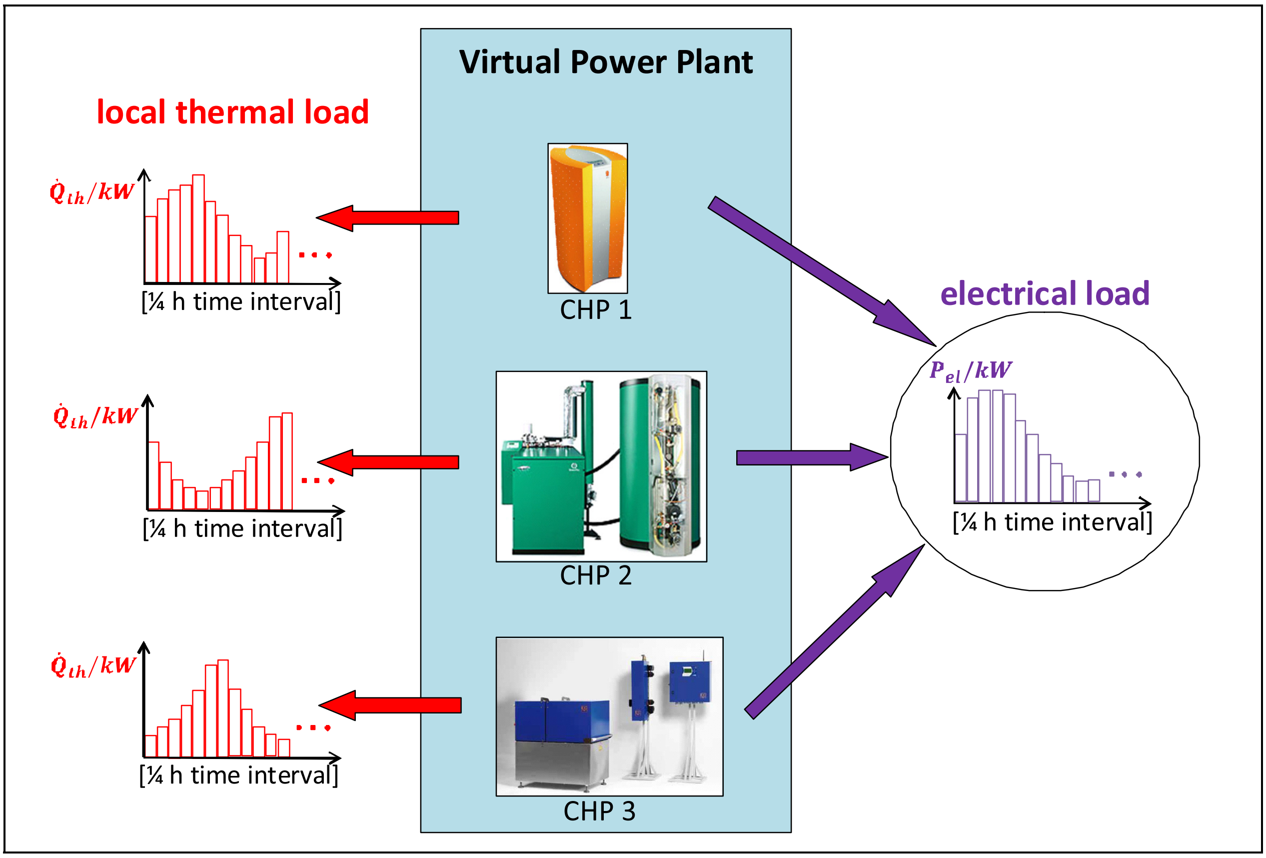

Fig. 3: Thermal and electrical load profiles

III. OPTIMIZATION MODEL

The basis of the designed optimization model is the assumption that the CHP plants are centrally controlled by an Energy-Contracting system. The produced thermal power is hereby used for covering the local heat load profile at the plant location. Additionally the schedule of the generated electrical power fulfills the restrictions of a superordinate electrical load profile. The system operation will be induced by EEX spot market prices, which behave proportionally to the given superordinate electrical load profile. All plants except CHP1 possess an additional boiler for covering heat demand and can be driven in a modulating operation process. A partly separation of the heat and power production using an enlarged thermal storage system permits a current operation mode, similar to the assumptions in [6]. In this example a planning horizon of the optimization model is limited by one day, which is subdivided into ¼ hours intervals, like it is usual in energy economics and regarding the given reference data,

In order to set up an objective function which describes the present problem, an optimization goal must be formulated. In this case the main goal should be the maximization of the contribution margin (CM). The contribution margin serves for covering the fixed costs. The CM is defined as the difference between the revenue (R) and the variable costs (C_V) [7], [8].

$$CM = R - C_V \tag{1}$$

The share of revenue and variable cost of the objective function are set up first relating to several plant locations depicted in equation 2-4. The main objective function (5) describes the time dependent CM of the operation schedule for the whole virtual plant. In this case the generated electrical power (P_{el}) determines the CHP revenue (R_{CHP}) from disposal at the spot market. The produced thermal energy of the CHP plant offers also a receipt ($R_{th,CHP}$), because of existing cost benefits comparing a covered heat demand by using a conventional boiler system. In addition the maintenance cost (C_M), fuel cost (C_F) and operating cost (C_{OP}) for CHP (C_{CHP}) and boiler (C_B) are considered [9].

$$\begin{aligned} max\,CM_{CHP1} = {} & R_{CHP1} + R_{th,CHP1} \\ & - C_{M,CHP1} - C_{F,CHP1} - C_{OP,CHP1} \end{aligned} \tag{2}$$

$$\begin{aligned} max\,CM_{CHP2} = {} & R_{CHP2} + R_{th,CHP2} \\ & - C_{M,CHP2} - C_{F,CHP2} - C_{OP,CHP2} \\ & - C_{M,B2} - C_{F,B2} - C_{OP,B2} \end{aligned} \tag{3}$$

$$\begin{aligned} max\,CM_{CHP3} = {} & R_{CHP3} + R_{th,CHP3} \\ & - C_{M,CHP3} - C_{F,CHP3} - C_{OP,CHP3} \\ & - C_{M,B3} - C_{F,B3} - C_{OP,B3} \end{aligned} \tag{4}$$

The index t is used for the indexation of the ¼ hours intervals. Due to a fault or a maintenance of plants, the operation could be temporary not possible. Therefore the integer coefficient f for fault [0, 1] was created and has been linked to contribution margin of every plant section.

$$\begin{aligned} max\,CM_{VP} = \sum_{t=1}^{96} (& f_{CHP1,t} * CM_{CHP1,t} \\ & + f_{CHP2,t} * CM_{CHP2,t} \\ & + f_{CHP3,t} * CM_{CHP3,t}) \end{aligned} \tag{5}$$

Inter alia within the constraints technical parameters of the system are described like electrical and thermal maximum rates. Modulation factors, CHP coefficients and storage capacities can be determined. For example beside the important restriction of covering thermal demand at every time equation 6 is depicted below. The "soft constraint" controls the restriction of the superordinate electrical load profile ($P_{el,LOAD}$).

$$P_{el,CHP1,t} + P_{el,CHP2,t} + P_{el,CHP3,t} \le P_{el,LOAD,t} \tag{6}$$

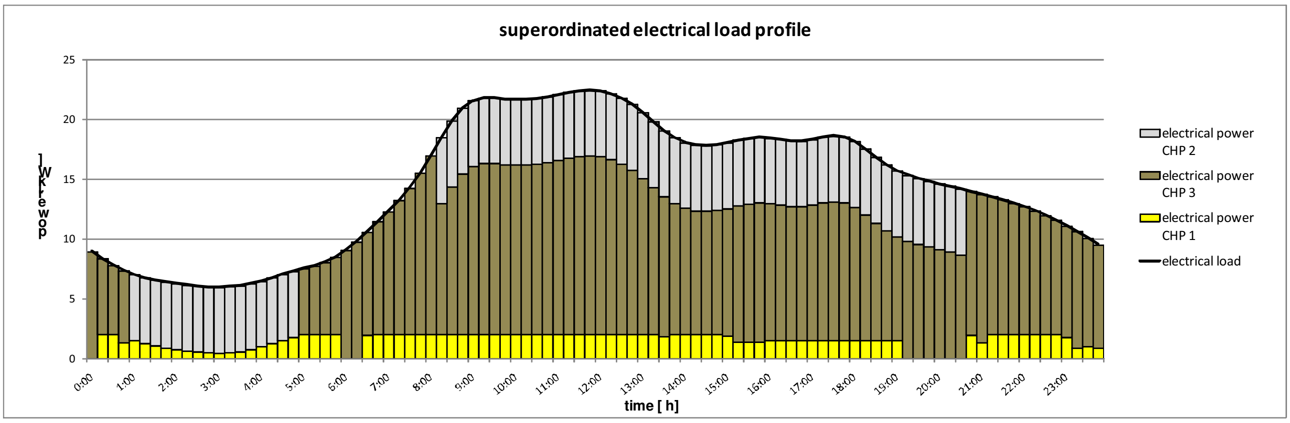

Fig. 4: Schedule of covering electrical demand

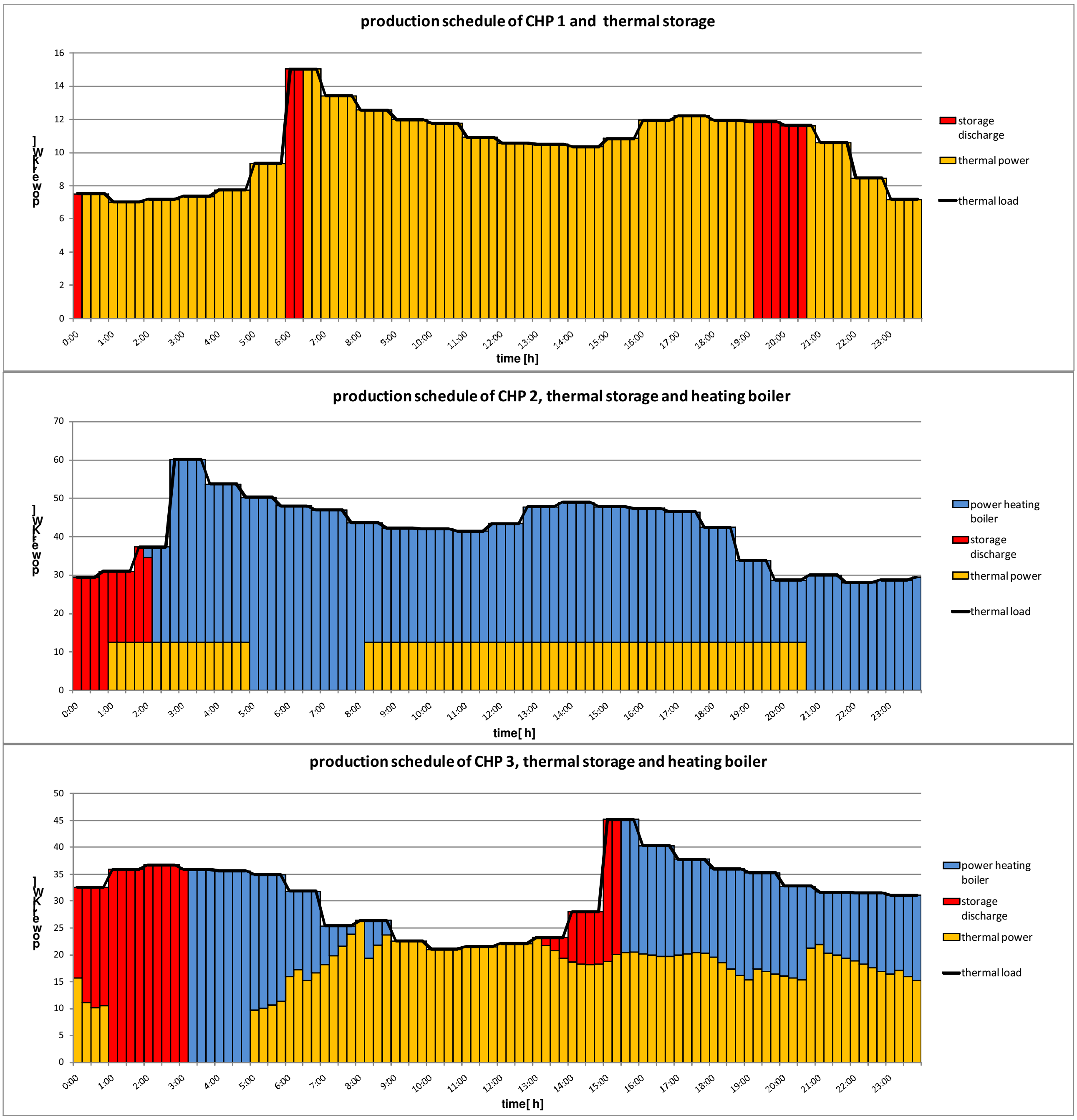

Fig. 5: Schedule of covering thermal demand

IV. Results

The represented diagrams in figure 4 and 5 reflect the result of a selected optimization scenario. Figure 4 shows the superordinate electrical load profile, which is covered by the electrical contributions of the three individual CHP plants and their peripheral devices. A modified electrical daily standard load profile was used for the scenario, whose maximum power demand corresponds to the sum of the electrical power output of the CHP plants. Figure 5 shows the selected thermal load profiles of the individual asset locations, which are based on standard load profiles with night setback.

A complete covering of the thermal demand is reached here by the production of the individual CHP plants as well as the auxiliary heating boilers and thermal storages. The configuration of the system components is presented as follows:

CHP1: 3,5 – 16 (19) kW_{th} and 0,2 – 2 kW_{el}
Thermal storage: 800 l

CHP2: 12,5 kW_{th} und 5,5 kW_{el}
Heating boiler: 65 kW_{th}
Thermal storage: 2000 l

CHP3: 17 – 30 (19) kW_{th} and 6 – 15,2 kW_{el}
Heating boiler: 106 kW_{th}
Thermal storage: 8000 l

The initial charging level of the thermal storages was accepted with 50% in each case.
The main optimization problem contains about 19100 variables and approximately 8000 constraints. It was solved using CPLEX based on a branch and cut algorithm. Total CPU time required to figure out the optimal solution in this case study was about 20 seconds on an Intel Pentium Dual Core processor with a clock frequency of 3GHz and a working memory of 2 GB. The number of iterations needed was 6860 by a given time limit of 60 seconds. No faults or relaxations were detected, and a complete electrical and thermal covering of the demand could be reached within the scenario. Additionally to the main objectives used here also different optimization targets are conceivable like CO_2 emission reduction or minimization of provided fuel.

V. CONCLUSIONS

By the energy management system the decisions are made for an economic and ecologic operation schedule of the experimental virtual plant on the basis of the following information and restrictions:

- operation parameters of the decentralized CHPs and their related thermal energy storages and boilers (e.g. electric capacity, thermal capacity, heat demand, storage capacity, state of charge),
- the central power demand,
- energy prices at the energy exchange (EEX)
- the forecast concerning meteorological data and feed in behavior of renewable energies

As the current market information of the EEX is included, the concept makes an integration of the plant into the energy market possible and rentable. The most efficient operation mode is calculated using a linear algorithm structure for solving the existing optimization problem. The decentralized produced energy is used directly at the place of production. In that case a virtual plant can be used for the substitution of missing wind and solar energy. Thereby the heat demand of each building can be covered and guaranteed. [10]

References

[1] Demand Response, state doctorate, Prof. Dr.-Ing. habil. I. Stadler, Kassel, 2005

[2] Vision and Strategy for Europe’s Electricity Networks of the Future, European SmartGrids Technology Platform European Commission, Brussels, 2006

[3] The German Roadmap E-Energy/ Smart Grid, German Commission for Electrical, Electronic & Information Technologies of DIN and VDE, Published by VDE Association for Electrical, Electronic & Information Technologies, Frankfurt am Main, Germany, 2010

[4] Schellong, W.: Integrated energy management in distributed systems. Proc. of SPEEDAM 2006 Symposium, Taormina (Italy), May 2006, pp. 492-496.

[5] Schellong, W.: Energy demand analysis and forecast. In P. Giridhar Kini (ed.): Energy management, InTech Open Access Publisher, 2011

[6] G. Streckienė, V. Martinaitis, A. N. Andersen, J. Katz: Feasibility of CHP-plants with thermal stores in the German spot market, Lithuania, Denmark, Applied Energy 03.2009

[7] Energy Management in the Low-Voltage Supply by means of Decentralized Decision, D. Nestle; Renewable Energies and Energy Efficiency Vol. 7, Kassel, 2008

[8] Optimized Management of Low-Voltage-Grids with high Fraction of Decentralized Generation, M. C. Thoma; Diss. ETH Nr. 17063; Zürich, 2007

[9] Multiperiod Optimal Power Flow Using Benders Decomposition; N. Alguacil, A. J. Conejo; IEEE Transactions on Power Systems, Vol. 15, No. 1, February 2000

[10] Consequences for district heating and natural gas grids when aiming towards 100% electricity supply with renewables 6th Dubrovnik Conference on Sustainable Development of Energy, Water and Environment Systems, W. Kusch, T. Schmidla, I. Stadler, Dubrovnik, Croatia, 2011