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Decentralized scheduling strategy of heating systems for balancing the residual load

Hassan Harb*, Jan-Niklas Paprott, Peter Matthes, Thomas Schütz, Rita Streblow, Dirk Müller

RWTH Aachen Universtity, E.ON Energy Research Center, Institute for Energy Efficient Buildings and Indoor Climate, Mathieustraße 10, Aachen, Germany

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A B S T R A C T

This paper introduces a decentralized scheduling scheme for electro-thermal heating systems i.e. heat pumps and combined heat and power units. The scheduling is modeled as a mixed integer linear optimization program (MILP) and reformulated based on the Dantzig–Wolfe decomposition method. The decomposed problem is solved by means of an iterative column generation algorithm that is modified to solve MILPs. The aim is thereby to enhance the integration of renewable energy sources by matching demand and supply. The architecture is based on a cooperative multi-agent system. A centralized scheduling approach is used as a reference to assess the performance of the decentralized concept. The analysis comprises a cluster of existing residential buildings. The results show that the centralized scheduling delivers the best coordination with a limited extendability. The decentralized scheduling presents a slightly lower coordination with a great potential for scalability. Moreover, the decentralized scheduling is based on an emphasized local intelligence which allows for reducing the communication of sensible data.

1. Introduction

The German electricity system is undergoing a significant reform in pursuit of the targets of energy and climate policies such as reducing greenhouse gas emissions and increasing the integration of Renewable Energy Sources (RESs). Furthermore, the installation of distributed energy resources i.e. micro combined heat and power (μCHP) units and photovoltaic (PV) systems has expanded over the past years. As a result, the shift of residential buildings from passive energy consumers to active prosumers is intensifying. This transition towards a decentralized electricity generation is foreseen to change the way electricity is produced and consumed. Mainly, the uncontrolled distributed generation and the increased penetration of volatile RESs are expected to cause challenges for the security of electricity supply and the stability of the electricity grid. Therefore, energy management concepts that take advantage of flexible load and generation capacities on the demand side, for balancing consumption and generation, are gaining importance. The implementation of such a concept depends on critical aspects such as the flexibility, extendability and scalability of the system as well as the protection of data privacy.

The scheduling of flexible loads in the residential sector has been investigated in several works such as Refs. [1,2]. These scheduling problems are formulated as mixed integer linear programs (MILP) and are NP-hard.[1] Consequently with increasing number of considered subsystems, conventional solvers are not able to solve this problem in a reasonable time. Therefore, several studies such as [3,4], apply the Lagrangian relaxation (LR) method to reformulate the large scale MILP and facilitate the solution process. However, the MILP in these studies is constrained to either consuming units i.e. heat pumps (HPs) or generating units i.e. CHPs.

The scheduling of a cluster of houses that comprises both CHPs and HPs induces a further challenge for a decentralized coordination concept as the interactions of these units result in oscillations of the solution. In Ref. [5], the authors propose a two-stage decentralized scheduling approach. Every building generates a set of feasible schedules that satisfy the local constraints which are then combined by a central coordinator to compute an optimal scheduling for the entire cluster. This approach displays large

* Corresponding author. Tel.: +49 241 80 49804; fax: +49 241 80 49609.
E-mail address: hharb@eonerc.rwth-aachen.de (H. Harb).

[1] Non-deterministic polynomial-time hard.

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fluctuations in the coordination of the considered cluster of residential buildings. The authors in Ref. [6] investigate a merit order pricing strategy for the decentralized coordination of electro-thermal heating systems which exhibits an emphasized CHP operation and results in significant electricity surplus.

In this paper, we propose a cooperative agent-based, decentralized day-ahead scheduling for the coordination of the heating supply systems in a residential neighborhood. Further, we reformulate the large scale MILP using a Dantzig–Wolfe decomposition and an adjusted column generation algorithm for MILP. The Dantzig–Wolfe column generation is an alternative decomposition approach to the LR which has been mainly applied to linear problems (LPs) [7]. The column generation algorithm is implemented based on a multi-agent system (MAS) framework which is a network of software agents that cooperate together to achieve both local and collective tasks [8]. MAS enables the decomposition of a complex problem into smaller subproblems which are handled by autonomous distributed agent entities on building level. This allows for enhancing the data security and to keep information locally when possible. Moreover, the combination of the Dantzig–Wolfe column generation and MAS enables a flexible, extendible and scalable energy management concept. This combination has been investigated in Ref. [9] and applied for an integrated production, inventory, and distribution routing optimization problem. The authors show that an agent-based Dantzig–Wolfe decomposition provides the potential to achieve performance improvements through distribution and parallelization.

In the presented case studies all considered households are supplied with a bivalent heating system i.e. air/water HPs with an additional electrical heater or a μCHP with an auxiliary gas boiler. All heating systems are coupled with a thermal storage tank to gain the flexibility that is needed to shift the load of the heating systems. The design of the heating systems is based on conventional criteria. CHPs are designed to run for a minimum of 4000 h/a to ensure the economic feasibility while the capacity of the heat pumps is determined at a bivalence temperature of −2 °C. The storage capacity is designed to cover a minimum of two to three full load hours of the respective primary heating system. All households are interconnected and exchange electricity with each other or with an external grid. The RES generation comprises PV systems and wind energy that is available within the residential area.

In Section 2, the modeling of the electro-thermal heating systems and their systematic relationship is described. Section 3 introduces a reference coordination scheme by providing a central coordinator, that holds access to all necessary information from the participating agents to achieve the high degree of energy coordination. Section 4 presents the cooperative, decentralized coordination approach. A cluster of 34 residential buildings is used as a test case to assess the performance of the two coordination strategies. The results are discussed in Section 5 and conclusions are drawn in Section 6.

2. Modeling of building energy systems

In this section, the modeling of the building energy systems mainly the thermal buffer storage and the electro-thermal heating units is introduced.

2.1. Thermal storage

The nonlinear energy balance of the thermal buffer tank can be expressed via its internal energy $U_S(t)$ as

$$\frac{dU_S}{dt} = \sum \dot{Q}_{in} - \sum \dot{Q}_{out} \tag{1}$$

by considering a discrete time resolution Δt, equation (1) can be discretized to

$$U_S(t) = U_S(t-\Delta t) + \left(\eta_S \cdot \dot{Q}_{gen}(t) - \frac{\dot{Q}_{dem}(t)}{\eta_S} - \dot{Q}_{loss}(t)\right)\Delta t \quad \forall t \tag{2}$$

$\dot{Q}_{gen}(t)$ comprises the heat production of both the primary heating device i.e. μCHP or HP and auxiliary heater i.e. gas boiler or electrical heater. $\dot{Q}_{dem}(t)$ is the heat demand of the particular building. The efficiency of the storage tank η_S takes into account the losses due to charging and discharging the storage tank. The efficiency of the storage tank is presumed to $\eta_S = 98\,\%$. According to [10] the losses of the storage tank $\dot{Q}_{loss}(t)$ are assumed to be 0.5%/h of the current internal energy $U_S(t)$. The capacity ΔU_{max} of the thermal storage tank is defined as

$$\Delta U_{max} = \rho_W c_W V_S \Delta T_S \tag{3}$$

where ρ_W is the density of water, c_W is the heat capacity of water, V_S is the volume of the storage tank and ΔT_S is the temperature spread of the heating system i.e. the difference between the flow temperature and the return temperature. The temperature spread for a CHP system is assumed to be 35 K and the temperature spread for a heat pump system is assumed to be 10 K. The volume V_S of the thermal storage tanks vary between 0.5 and 1.5 m^3 depending on the nominal heat output of the installed heating supply system.

2.2. Air/water heat pump

The heat output of a heat pump $\dot{Q}^{hp}(t)$ depends on its coefficient of performance COP(t) and the electricity consumption of the compressor $P_{el}^{hp}(t)$. The COP(t) of heat pump changes in accordance with variation of the sink and source temperatures. This can be approximated by a linear dependence of the ambient temperature while assuming a constant sink temperature and expressed as

$$\mathrm{COP}(t) = p_1 \cdot T_{amb}(t) + p_2 \tag{4}$$

$T_{amb}(t)$ is the current ambient temperature, p_1 is the slope and p_2 is the intersect of the linear curve. In this paper, non-modulating heat pumps are considered so the heat output $\dot{Q}^{hp}(t)$ is determined as follows

$$\dot{Q}^{hp}(t) = u^{hp}(t) \cdot \mathrm{COP}(t) \cdot P_{el,nom}^{hp} \tag{5}$$

with $P_{el,nom}^{hp}$ as the nominal electricity consumption of the compressor. $u^{hp}(t)$ is a binary variable that is 1, if the heat pump is operating in time step t and 0 otherwise.

2.3. Micro combined heat and power unit

The overall efficiency of CHP units takes into account the produced heat $\dot{Q}^{chp}$ and is defined as

$$\omega = \frac{P_{el,nom}^{chp} + \dot{Q}_{nom}^{chp}}{\dot{m}_F \cdot H_u}. \tag{6}$$

where $P_{el,nom}^{chp}$ is the nominal electrical output and $\dot{Q}_{nom}^{chp}$ is the nominal heat output. $\dot{m}_F$ is the fuel mass flow rate and H_u is the