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A solid thermal storage model for the optimization of buildings operation strategy

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ABSTRACT

With an increasing fluctuation of energy supply due to the integration of renewable energy utilities peak-shaving becomes more and more important. Storage systems are a considerable option for this purpose. For the heat supply in cities the buildings themselves can be employed as solid thermal energy storages utilizing their thermal inertia and applying an operation strategy which takes into account comfort, economic and ecologic considerations.

Therefore the present work proposes a MILP (Mixed Integer Linear Programing) model accounting for the system's dynamics to optimize this operation strategy and the according comfort temperature, by taking into account a dynamic effect of the building. The dynamic effect considers that the building can be charged/discharged to a certain degree, depends on the effective heat capacity of the building and the indoor comfort temperature. In order to properly account for the temperature, the model incorporates energy integration techniques.

By means of a test case it is shown that the primary energy consumption and the operating expenses can be decreased when operating the building within a given range for the comfort temperature.

1. Introduction

The configuration and the operation strategy of energy systems, in terms of the base load and the backup equipment, usually depend on the shape of the annual cumulative demand curve. The base load equipment should operate at maximum power for a large number of hours to reduce the payback time and to provide higher efficiency. The hourly and daily variations of consumers' demand may affect the system efficiency.

One way to overcome this issue is to integrate thermal storage systems between supply and demand sides. The thermal storage can be employed to increase the operating hours of base load technologies. It preserves thermal energy during off-peak hours that can be used at peak hours. The aim is to balance the energy demand fluctuation, increase the utilization of base load technologies and avoid oversizing of the backup equipment.

The state of the art on the modeling and optimization of storage systems is summarized in Table 1. Researchers have paid much attention in the literature on thermo-economic simulations and synthesis of a thermal storage unit in batch processes. Stoltze et al. [1] studied the integration of heat storage units for waste-heat recovery. They proposed the "combinatorial method" for an incorporation of heat storage tanks in batch processes. For a simple system it was shown that the maximum energy-saving targets as calculated by the pinch-point method can be achieved by integrating storage units with process streams. Sadr-Kazemi and Polley [2] discussed the optimal layout and the number of storage tanks in a batch process and proposed an iterative search method based on the composite curves to define the temperature levels of the storage tanks. They showed the possibility of heat recovery and decreasing the process costs through heat storage utilization.

Also using pinch analysis principles, Krummenacher and Favrat [3,4] proposed an evolutionary algorithm to identify the optimal number of heat storage units and operating temperatures. They evaluated the potential cost savings associated with the use of storage systems in batch processes. These works show the advantages of process integration techniques for discovering the heat recovery opportunities in batch processes and also for including the heat quality, in terms of the temperature, in the optimization.

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Table 1
The state of the art and the contribution of the present work.

References:	[1]	[2]	[3,4]	[5]	[7,8]	[9]	[10,11]	[16]
Thermal storage	×	×	×	–	–	×	×	×
Multi objective optimization	–	–	–	–	×	–	–	×
Design optimization (sizing)	×	×	×	×	×	×	×	×
Operation optimization (scheduling)	–	–	×	×	×	×	×	×
Temperature optimization (pinch analysis)	×	×	×	–	×	–	–	×
District energy system	–	–	–	–	×	×	×	×
Batch process	×	×	×	×	–	–	–	–

With respect to the operating strategy optimization (scheduling) of an energy system, Grossmann and Santibanez [5] presented a MILP (mixed-integer linear programming) formulation for optimizing the size and the operating schedule of an industrial process with limited number of time steps. However, the possibility of heat recovery and peak shaving through heat storage utilization was not included. Later on, thermodynamic optimization has been applied to show that there is a thermodynamically optimal operating strategy (charging and discharging periods) for a heat storage device in order to improve the energy system's efficiency [6]. Sadr-Kazemi and Polley [2] also pointed out that a good operating strategy can decrease the size of storage tanks and decrease the process costs.

In the literature, district energy systems are often optimized without taking into account the possibility of increasing the system efficiency and heat recovery through heat storage systems. Weber et al. [7] developed a multi-objective optimization model for designing a district energy system. They showed that process integration and pinch analysis techniques could be used to optimize the heat supply of consumers. However, storage units were not included in their model. Later on, the model is extended [8] for optimizing the system operation by considering the average values of energy demand, technologies' power and efficiency, without including the optimization of volume, temperatures and operation strategy of the storage system.

Soderman and Pettersson [9] proposed a multi period mixed integer linear model to integrate the storage tank with cogeneration units in the district system. They considered 8 time steps to optimize the size and operating schedule of the storage tank. Following the work of Weber et al. [7], Collazos et al. [10] developed a model based on MPC (Model Predictive Control) strategy for optimizing the operation strategy of poly-generation systems as well as the thermal storage tank. In a similar work, a MIP (mixed-integer programming problem) is formulated to optimize the storage capacity and the operation schedule of power plants [11]. They evaluate the potential cost savings and benefits through the integration of thermal storage as well as through the adjustment of the operation of power plants. They conclude that partially decoupling the production of heat in CHP units from the demand of a district heating network leads to lucrative pay back periods for storage devices in the considered energy system [11]. However, the optimization of the storage unit's operating temperature is not addressed in these ([9–11]) works.

The thermal energy storage material properties and modeling have been reviewed and classified by A. Gil et al. [12]. They consider three type of thermal storage systems namely sensible heat storage, latent heat storage and chemical heat storage. Different types of material and storage media are reviewed for each type of the storage system. Finally physical simulation models and cost analysis are performed to conclude on advantages and disadvantages of each of them. In the second paper of the same authors some case studies are presented [13], while no optimization approach is addressed. Moreover, it is referred to [14] for a review on sustainable thermal energy storage technologies in district energy system and [15] for a review on potential materials for thermal energy storage in building applications.

A multi-period, multi-objective optimization model including energy integration and pinch analysis techniques was developed by the authors [16] for optimizing the operation strategy of storage systems. The goal was to integrate thermal storage units with other conversion technologies for optimizing the design and the operation strategy of the overall system. However, only liquid storage was considered in the developed model.

The goal of the present work is to extend this proposed model [16] by developing a capacity model as a solid thermal storage system. The developed model is demonstrated by means of a test case in Sec. 3. In the test case, the capacity model is used to simulate a dynamic effect of a building. The dynamic effect considers that the thermal mass of the building can be charged/discharged to a certain degree, depending on the effective heat capacity of the building and also on the comfort indoor temperature. If the building mass temperature is higher than the room comfort temperature, then heat will be released and less energy is required. While if the building mass temperature is below the room comfort temperature, additional energy is needed to maintain the comfort temperature.

The results illustrate that the primary energy consumption and operating expenses are decreased by 10% and 12% respectively after integrating the dynamic effect of a building through the developed solid storage model. As the electricity price is lower early in the morning, the heat pump is used then to transform electricity to heat and store it in the building mass. Then the building will be discharged during the peak hours to supply the heat demand.

2. Methodology

In energy systems, conversion technologies are used to transform the primary energy into useful services. Several technologies may be used simultaneously or in competition. In the present work, multi-time energy integration optimization techniques are exploited to investigate effects of a solid storage system on sizing and operation strategy of poly-generation technologies.

2.1. Multi-time energy integration optimization

A multi-time optimization model for district energy systems including process design and energy integration techniques was previously developed [17]. The principal concepts of this model are explained in this section.

The objective function of the optimization is to minimize the total annual costs and cost of CO_2 emissions (Eq. (1) to Eq. (4)) under the energy balance and the heat cascade constraints. The principal purpose is to determine the best usage and operating schedule of conversion technologies in order to supply the