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Original article

Potential for residual load balancing of a frozen food manufacturing plant – A heuristic approach

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ABSTRACT

We simulated the potential of a frozen food manufacturing plant to contribute to the balancing of the residual load under the premise that the plant's production processes remain unaffected. The plant's technical balancing options comprise both demand side management (chillers for process cold, electric process heat generation) and dispatchable power generation (by a combined heat and power (CHP) plant). In the model, the decoupling of useful energy demand (heat and cold) from power consumption and power generation was enabled by the use of a high temperature thermal energy storage (HT-TES), a cold thermal energy storage (C-TES), and flexible cold storage warehouse temperatures. The analysis shows that the balancing potential basically depends on two factors: (1) plant operation (reflected by gross power demand and power generation) in the inflexible reference case, which defines to which extend power demand and generation can be increased or reduced when the plant is operated flexibly, and (2) the capacity of the thermal energy storages (TES) relative to the typical length of deficit and surplus periods. The model further shows that a heuristic algorithm controlling the operation of the plant's flexible units can exploit a large fraction of the technical balancing potential of the plant.

Introduction

With stricter global targets on reducing GHG emissions [1] strategies for the expansion of renewable energy (RE) supply gain importance [2]. Non-dispatchable sources of renewable power such as wind and photovoltaics (PV) lead the RE expansion in the power sector [3] and are expected to provide the backbone of RE power generation in the future [4–6]. As a consequence, balancing options for intermittent energy supply become increasingly relevant [7,8]. The balancing potential of technologies such as power storage, long-range load and generation balancing via the electric grid, flexibilisation of heat-driven combined heat and power (CHP) plants, or demand side management (DSM) are intensively discussed in the scientific literature [9,26,10–17]: For Germany balancing and storage demand is expected to sharply grow in the early 2020s, when a RE share in gross power generation of more than 40% is expected [18,19]. Up to now various studies have proven the potentials of demand side management for balancing intermittent energy supply [20,21], in particular also in the industry sector [22]. Due to the variety of industrial processes [23], DSM potentials largely depend on the specific local applications in companies. [24] demonstrated this high variability of load and supply on a regional disaggregation for Germany, suggesting that an analysis of industrial management potentials is required on local level.

Industrial demand side management often relies on preponing or postponing production processes in order to adapt power demand to power system requirements. However, as e.g. [25] points out, thermal energy storages (TES) can temporally decouple useful energy demand (in particular process heat or process cold) from power consumption. TES thus allow industrial demand side management without any change in production quantities or production schedules.

In frozen food manufacturing plants ("FFM plants") generally several thermal processes such as cooking and cooling take place which can principally be flexibilised through TES to allow demand side management. E.g. [26], [27], and [28] have identified a significant DSM potential in refrigeration systems, where the thermal inertia of the cooled goods acts as thermal energy storage. In contrast to this "passive" flexibilisation of process cold generation, TES at temperatures below 0 °C [34] can technically decouple cold demand for deep freezing from chiller operation. And finally, process heat demand and process heat generation (e.g. in a CHP unit or an electric heater) can be decoupled by a high temperature TES [31], allowing both DSM with the electric heater and a power driven operation of the CHP unit. These considerations illustrate that it is worth investigating the load balancing potential (potential for DSM and power driven operation of CHP units)

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of a FFM plant in detail in the following paper.

Research focus

Thus the paper addresses this research gap by presenting the first comprehensive simulation of technical load balancing potentials of a frozen food company, taking into account the complex interplay between heat and cold demand and generation at different temperature levels, thermal energy storage, as well the utilisation and upgrade of waste heat. The analysis is distinguished from previous studies in that it is based on realistic production process description and load time series for useful energy demand from an existing FFM plant in Rheine in Northwest Germany. Furthermore, it assesses not only technical load balancing potentials, but considers restrictions due to the plant's production schedules, which are assumed to remain unchanged by the load balancing. Finally, the study addresses for the first time the load balancing potential of a FFM plant in a local power supply system dominated by high shares of intermittent generation.

The focus of our research in this paper is manifold: First, what is the potential of the FFM plant for balancing local power generation deficits and surpluses in a hypothetical local energy system dominated by intermittent renewable energies? Second, how does the balancing potential of the FFM plant depend on the technical infrastructure of the plant, i.e. on electric loads, power production, and thermal energy storages (TES)? How does the necessary storage capacity depend on the length spectrum of deficit and surplus periods? How do the fixed production processes limit the balancing potential of the plant? And finally: Can the FFM plant's balancing potential be determined with a heuristic algorithm for the operation of the plant's flexible loads, flexible power generation and flexible operation of TES?

We restricted this study to the analysis of technical aspects of the load balancing potential. Economic aspects – such as additional investment of the flexibilisation and additional operation and maintenance (O&M) costs for flexible operation – are only taken into account as restrictions due to space limitations (to install e.g. TES or heat exchangers) at the plant site etc.

Methodology

First we describe the principal system applications as well as limits of flexibility of the represented FFM plant. Section "*Principal structure within the INSEL simulation environment*" then describes the model representation within the simulation tool INSEL, including data input. Section "*Operation algorithms for the flexible units*" covers the operation algorithms of the simulations.

Main processes in the FFM plant and their flexibilisation

The FFM plant model represents the main processes of the plant according to Fig. 1. Many of these processes can be operated in a flexible manner, as thermal energy storages (TES) decouple useful energy demand (heat or cold) and power consumption (resp. power generation). This allows a flexible operation of the heat and cold generation units independent of useful energy demand. Consequently, production schedules are not affected by the flexible operation of these units.

The following processes are included in this integrated system:

Cooking

The major energy consumer of the model FFM plant is the cooking of convenience food. In the standard setup of the model a **cogeneration unit** (a high temperature gas fuel cell, see e.g. [29,30]) provides baseload process heat for the cooking processes; additionally, an **electric heater** provides peak load process heat. Alternative process heat technologies have been taken into account in sensitivity tests (see Section 2.4).

The cogeneration unit can be flexibly operated, if heat from cogeneration is stored in a **high-temperature thermal energy storage** (HT-TES) at times of a high power generation deficit in the municipality and low process heat demand in the FFM. In turn, the HT-TES can provide process heat at times of generation surpluses in the municipality when power cogeneration therefore is shut off.

The **electric heater** (in combination with the same high-temperature thermal energy storage) provides additional flexibility: In times of a municipal power surplus, the electric heater generates high temperature heat. If no process heat is required at these times, the high temperature heat can be used to charge the TES.

Deep freezing

The freshly cooked food is frozen immediately after leaving the kitchen. It is cooled down from approx. +70 °C to −24 °C within 60–90 min.

Electricity demand of the **deep freezer** unit can be decoupled from the production schedule by a **cold thermal energy storage** (C-TES). It is charged in times of municipal power generation surplus and provides process cold at times of a municipal generation deficit.

Cold warehouse

After freezing, the food is stored in a cold storage warehouse at a temperature of −22 °C until delivery. Process cold for deep freezing and the cold storage warehouse is provided by two compression chillers.

Temperature within the **cold storage warehouse** may vary between −20 °C and −24 °C. The **thermal capacity** of the cold storage warehouse (and its content) serves as a cold storage. During municipal power surplus situations, the cold storage warehouse can be cooled down below the default temperature (−22 °C). During power deficit situations, cold storage warehouse cooling is shut off until inside temperatures reach −20 °C.

Mechanical energy

The system includes a compressed air system, providing mechanical energy (for the band conveyors, automatic packing machines etc.) and producing waste heat, which can be tapped for heat supply (see below). The compressed air system is not a flexible in the model.

Air conditioning (AC) and space heating

Office and production buildings are air conditioned in summer and heated in winter in order to keep inside temperatures between +20 °C and +22 °C during working hours. Climate cold is provided by a third compression chiller, which is operated in a non-flexible way. Space heat is provided by waste heat (see below).

Hot water demand

Cleaning of kitchens and cooking equipment require large amounts of hot water (additional to the hot water demand for sanitary purposes). Hot water is provided by waste heat (see below).

Waste heat recovery and upgrading

In the model a large fraction of the low temperature heat demand (space heating, hot water) can be covered by waste heat recovery from the chillers (from desuperheaters, compressors and condensers) and from the compressed air unit (see Fig. 1). An **electric heat pump** can upgrade low-temperature waste heat from the chillers' compressors from ca. 30 °C to 70 °C (the minimum temperature required for space heat and hot water). A **low-temperature thermal energy storage** (LT-TES) can decouple **waste heat upgrading** from low-temperature heat demand, so that the electric heat pump can be operated in a flexible manner.

Electricity demand for information, illumination, and communication (IIC)

Finally, electricity demand for information, illumination and