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Low-grade waste heat integration in distributed energy generation systems - An economic optimization approach

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A B S T R A C T

This paper proposes a Mixed-Integer Linear Programming (MILP) formulation for the economic optimization of the synthesis, design, and operation of an energy supply system of a manufacturing company. The multi-period approach incorporates both Heat Upgrading Technologies (HUTs) and conventional Distributed Energy Ressources (DER). Temperature requirements of heating and cooling demands are addressed explicitly and fluctuating ambient temperatures are considered, this gives rise to the possibility of temperature dependent modeling of technology efficiencies. The model enables the planner to consider waste heat recovery from hot process streams or from refrigeration cycles via direct heat integration or HUTs, such as mechanical heat pumps. Furthermore, it enables the planner to evaluate the complex interactions of HUTs with Combined Heat and Power (CHP) plants. To illustrate the practicability of the presented modeling approach, it is applied to a real-world case study. Furthermore, we exemplify how the optimal design is adjusted if HUTs and DER are investigated integrally in contrast to an isolated optimization.

1. Introduction

This work aims to include low-grade waste heat as an energy resource in the planning of Distributed Energy Ressources (DER) in industrial companies. Dependent on the temperature level, waste heat can be recycled using various Heat Upgrading Technologies (HUT). So far, temperature requirements have not been addressed explicitly in DER planning. However, the efficiency of HUTs is highly dependent on the temperatures of both heat sinks and sources. Thus, an assessment of these technologies requires an enhancement of the approach of DER planning.

We propose a Mixed-Integer Linear Programming (MILP) problem that considers the integration of HUTs and the planning of DER simultaneously. Thermal demands are modeled as hot and cold streams which are characterized by source and target temperatures and therefore temperature requirements are taken into account explicitly. The objective is to determine the synthesis, design, and operation of the system that minimizes the Total Annual Cost (TAC). It is shown that there are strong interactions between conventional DER and HUTs and that the integrated planning approach leads to significant cost and emission savings.

2. Literature and contribution

2.1. Literature

The literature review can be divided into two parts. First, a review of relevant literature on the planning of DER is presented. Secondly, literature that investigates the application of HUTs, in the field of heat integration, is reviewed.

2.1.1. Literature on distributed energy resource planning

For an overview of the extensive literature on the optimization of design and operation of energy systems, we refer to Pepermans [1], Karger [2] and Connolly [3]. In the field of DER planning a lot of MILP formulations have been proposed, that aim to identify the optimal configuration and operation strategy of DERs [4–9]. Typically a set of technologies is defined as the superstructure and

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within the optimization procedure the optimal synthesis, design and operation, minimizing the total annual cost is determined. The majority of studies focus on cogeneration and trigeneration technologies [10–14] and/or the integration of renewable energies (e.g. photovoltaic, solar thermal, wind) [15–18]. In the field of DER-Planning waste heat utilization is typically considered in terms of combinations of CHPs and Absorption Heat Pumps (AHPs) or ORCs, as e.g. in Ref. [19]. However, waste heat utilization from refrigeration cycles and hot process streams is not investigated.

Some recent contributions have been presented that include Ground-Source and Air-Source Heat Pumps (GSHP, ASHP) [20–22]. Within these articles, the efficiency of heat pumps is calculated in dependency of the ambient air temperature or is assumed to be constant. Note that within these contributions heat sources are not modeled explicitly, heat pumps have only one possible heat sink and source and thus, heat pumps have only one degree of freedom. Lately, Steen et al. [23] and Bischi et al. [24] presented models that include a low- and high-temperature heat sink to enable the application of heat pumps for low-temperature heat supply and to increase the accuracy of identified thermal storage losses.

All those contributions in the context of DER planning consider the cooling provision in terms of a conversion of heat or electrical energy into cooling energy, without consideration of the dissipated heat. In our framework, we model all energy flows explicitly, including the heat absorption and dissipation of cooling facilities and water/air-heat exchangers, which enables us to evaluate the recuperation of thermal energy from cooling water circuits and refrigeration cycles. Since temperature requirements are crucially responsible for the efficiency of technologies based on thermodynamic cycles, we capture temperature related constraints, which have not been considered in previously proposed DER models. Compared to those contributions, in our approach, the number of degrees of freedom is increased since the operating temperatures are determined endogenously by the model.

2.1.2. Literature on heat upgrading technologies

For general reviews on HUTs, their applications in the industry and economic comparison of different technologies the reader is referred to the articles of Chua et al. [25], Van de Bor et al. [26] and Oluleye et al. [27]. In the field of heat integration, the application of HPs has been investigated to maximize the recovery of low-grade heat. Many approaches based on pinch analyses have been presented (e.g. Refs. [28–32]). Within these publications, it is investigated how HUTs can be used to transfer heat over the pinch point and therefore reduce heating requirements. However, pinch analysis aims to minimize energy consumption and economic aspects are only taken into account on a second level. In contrary, our work takes investment, integration and operating cost directly into account. Pinch analysis typically investigates steady-state systems, whereas our model considers fluctuating demands.

Most recently, some studies on HUTs based on mathematical modeling have been proposed. Hipolito-Valencia et al. [33] proposed a Mixed Integer Nonlinear Programming (MINLP) formulation that aims to integrate Organic Rankine Cycles to recover useful waste heat from hot process streams. Kang and Liu [34] proposed an optimization model for the retrofit of an existing heat exchanger network with a heat pump. Both of these studies analyze steady-state systems with a focus on the design of the heat exchanger network. They do not consider the design of the energy supply system. We, on the other hand, focus on the energy system supplying heat, cold and electricity to time-varying demands on different temperature levels.

Oluleye et al. [35] presented a MILP approach for waste heat exploitation in process sites using different upgrading technologies. They consider multiple waste heat sources and sinks and calculate energy cost savings provided by the reduction of heat supplied by the conventional technologies. The system of interest is assumed to be steady-state and implications on the optimal design of energy supply facilities are not considered.

Existing studies on the application of HUTs focus on energy systems that are in steady-state, as they often occur under continuous production, e.g. in the process industry. We, on the other hand, focus on dynamic systems that are characterized by strongly fluctuating demands, as they often occur under batch production. This leads to the necessity of operational constraints that capture the system's functionality and performance (e.g. minimal part load) as well as the introduction of additional operational variables. To the best of our knowledge, the existing contributions to the literature do not aim for an integrated and optimal design of the energy supply system and HUTs. We address the design problem of the entire energy supply system, including combined heat and power plants as well as cooling facilities, in contrast to the existing publications that typically focus on the sole application of HUTs. The detailed modeling of cooling facilities enables an accurate evaluation of the opportunity cost of heat dissipation to the environment and a detailed evaluation of the recuperation of low-grade waste heat.

2.2. Contribution

Our work builds on the ongoing efforts in the fields of DER planning and HUTs. It is our purpose to develop a framework for the integrated evaluation of DER and HUTs and, therefore, to contribute to both strands of literature.

Compared to the existing publications in the field of DER planning we explicitly model the heat flow in energy conversion units based on thermodynamic cycles and capture temperature related constraints to evaluate the unit's efficiencies accurately. This enables us to investigate the application of HUTs to recover low-grade waste heat from cooling cycles.

As compared to previously proposed approaches found in the literature which evaluate the application of HUTs, in our approach we address questions related both to the optimal operation and the optimal design of the entire energy supply system and do not exclusively focus on the application of HUTs in an existing system. To capture the dynamics of fluctuating operating conditions, as they often occur under batch production, our model captures part-load behavior and operational constraints. Existing contributions, in contrast, focus on steady-state systems.

In sum, we (i) develop a framework to optimize both the design and the operation of DER and HUTs that captures seasonal, weekly and daily fluctuating demands and temperature requirements. The framework developed (ii) allows to endogenously determine changing operating temperatures of DER and HUTs as well as cooling facilities and therefore enables a realistic assessment of temperature-sensitive technologies. We (iii) finally present a real-world case study that demonstrates the capability of the proposed framework to identify interactions between DER and HUTs design.

The remainder of the paper is organized as follows. The problem definition and the mathematical formulation are given in Sections 3 and 4, respectively. In Section 5, the model is applied to an industrial case study. Section 6 provides the results of the case study along with the discussion. Section 7 concludes.

3. Problem specification

The system of interest is an energy supply center of a manufacturing company, which is represented by the superstructure shown in Fig. 1. We consider multiple technologies that supply the local demands with heat, cold and electricity. Candidate