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Combined Optimization for Retrofitting of Heat Recovery and Thermal Energy Supply in Industrial Systems

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Abstract—The outcome of possible changes in interlinked industrial energy systems is hard to predict, especially in retrofit scenarios. This results in investment decisions under uncertainties. In this paper, a new combined optimization approach is presented, that aims to support decision-making in these cases. The approach links models for optimal design of supply systems and heat exchanger networks with operational constraints and is specifically designed for retrofit applications. It is formulated as one combined mixed integer linear programming (MILP) problem. The results of the presented approach are demonstrated using a case study representing a typical industrial process. The optimal solution shows a cost-effective way for a transition to more efficient use of energy and an increased share of renewable sources.

Keywords—industrial energy systems, optimization, heat exchanger network synthesis, unit commitment

I. Introduction

To achieve current climate and energy policy goals, efficient energy use and the transition towards renewable energy sources needs to be enforced also in industrial processes. Especially for retrofit scenarios, it is typically hard to estimate economic and technical effects of changes to the system, as components are often linked in multiple ways.

Currently available methods for optimal investment planning are limited as most of them only consider one aspect of the industrial energy system (e.g., optimal heat exchanger networks, optimal supply system, technical restrictions, retrofit scenarios). This creates uncertainties and investment risks or yields high payback times, hindering the transition to a renewable and energy-efficient system. A promising approach is to formulate a combined optimization problem that considers both energy supply and heat recovery measures within an industrial energy system. Reference [1] presented such a combined approach for the optimization of internal heat recovery through cost-optimal heat exchanger network synthesis and integration of thermal energy storage. This approach also considers operational constraints of the existing supply infrastructure such as ramping constraints and varying efficiency of supply units. The combined approach was compared to sequential implementation and proved to yield both economic improvements and more efficient usage of energy. The present paper extends this approach to allow retrofitting of the existing heat exchanger network in combination with optimal investment decisions for a renewable on-site supply system.

II. Method

A. Modeling the System

In order to limit the model complexity, we implemented the combined system as mixed integer linear programming (MILP) problem and built upon recently published methods for modeling the supply system [2, 3], linearization for heat exchanger network synthesis and storage integration [4], and for combined optimization of these aspects [1].

For the case study in this paper, we additionally considered selection and optimal sizing of new renewable supply units – such as biomass fired steam generators, biogas based combined heat and power (CHP) units, heat pumps, solar thermal collectors, and photovoltaics. This is further extended by a new linearized retrofit approach for the existing heat exchanger network.

B. Supply System

The supply system was modeled power based, as described in [5], with defined states at the start and end of each timestep. The units in the supply system were modeled using a combination of continuous and binary decision variables. Generating units were described in terms of current load, whereas energy storage units are modeled by means of their current state of charge.

There are possible operating constraints, such as minimum partial load, minimum up- and down-time, maximum load ramp rates, and limits on the possible load states before start-up and shut-down. These operating constraints are only applied for units where corresponding technical/physical restrictions apply (e.g., for steam generators). As the minimum and maximum load (or state of charge) for a unit is dependent on the design size, the tight formulations described in [6] and [5] could not be applied directly and were replaced with a more generic variant.

For units with a minimum part load, binary decision variables indicate their online state. Additional auxiliary variables that indicate start-up and shut-down were used for units with a minimum part load. For units that are capable of changing their load quickly with respect to the temporal resolution within the model (e.g., electrode boilers), load steps on timestep boundaries were permitted, whereas for all other units, the state at the beginning of one time interval was constrained to the value at the end of the previous time interval.

The optimal sizing of units is implemented through binary (existence of a unit) and continuous variables (maximum capacity/load) and constraints, that limit the load (or state of charge for storages) in each time step with the unit's design size. The design size itself is limited within a fixed range. For retrofit scenarios, already existing units are constrained with a fixed design size.

A new formulation of constraints was introduced to describe the link between the supply system and the heat exchanger network, using a finite and fixed set of temperature levels.

Each supply unit is assigned to either one of these levels or has their generation split in a defined ratio between two or more levels (e.g., a CHP unit that generates both high and low temperature heat). In the heat exchanger network, the temperature levels are implemented as the hot utilities. Constraints for each temperature level ensure, that the demand of the heat exchanger network is met by the supply units.

C. *Heat Recovery System*

The heat exchanger network was modeled as described in [4], with the additional introduction of binary retrofit variables for existing heat exchangers that describe whether a heat exchanger is reused somewhere else in the network. This formulation is based on the classic superstructure formulation presented in [7].

D. *Objective Funcion*

The objective function is based on Eq. (35) of [1] but extended to accommodate for retrofit scenarios. Additional cost terms are added for each unit based on its binary existence variable (step fixed costs) and design size variable (variable costs).

For the heat exchanger network, additional reassignment costs are introduced if an existing heat exchanger is used between different streams after the retrofit.

III. Case Study

A. *General Description of the Test Case*

To apply the developed optimization model, we defined a test case that represents a typical industrial process. The hot and cold process streams, see Table 1, were chosen according to [8] and result in a maximum heating and cooling demand of 6,410 kW and 4,251.5 kW, respectively. The considered timeframe for the process were 24 hours. While only the six distinctive operating periods in the process where modeled for heat recovery, for the supply units a time step of 1 hour was chosen. In addition to the thermal demand, we prescribed electricity demand with reference load profile G1 [9], scaled to a daily consumption of 7.5 MWh. Electricity prices were assumed dynamic with hourly variation. All energy prices are shown together with the demand profile in Fig. 1.

B. *Before Retrofit*

The supply system before retrofit, as shown in Fig. 2 consists of a gas fired steam generator and a gas boiler, both with a maximum power of 2.5 MW, and a gas engine CHP plant with a maximum power of 0.75 MW. These provide heat on three temperature levels, 250 °C (steam), 150 °C (pressurized hot water), and 70 °C (hot water), and cooling

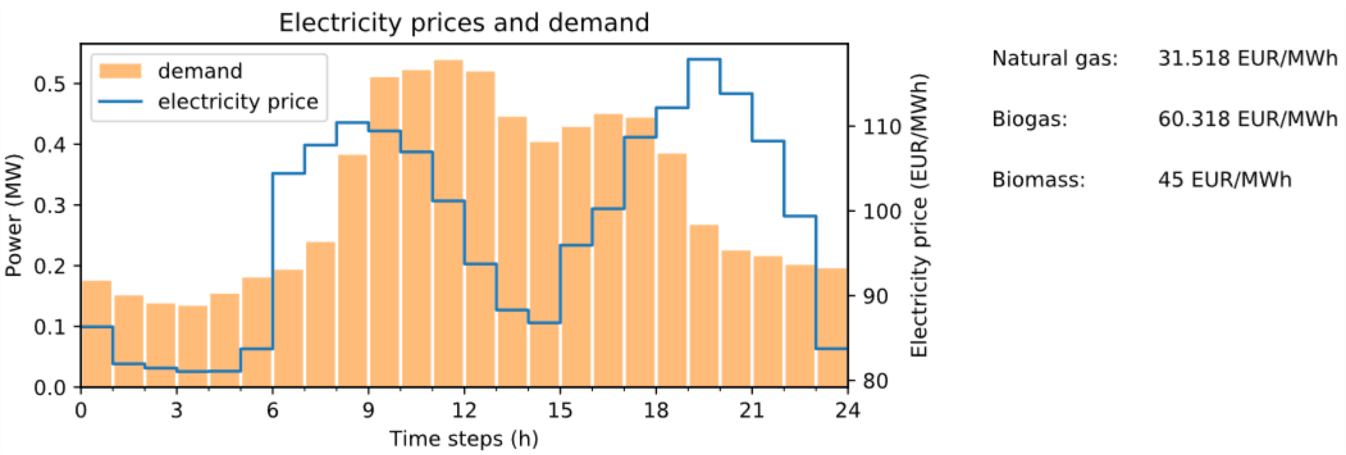

Fig. 1. Electricity demand and prices.

water is used as cold utility. The initial heat exchanger network is shown in Fig. 2 and consists of 13 utility heat exchangers and 5 direct heat exchangers between process streams for heat recovery.

TABLE I. LIST OF HOT AND COLD PROCESS STREAMS

#	Active times	Tin / °C	Tout / °C	CP / (kW/°C)
1	00–21	35	20	70.0
2	03–24	100	75	7.5
3	03–24	100	99	301.0
4	03–21	100	60	2.5
5	03–21	100	90	214.0
6	06–21, 22–23	110	20	2.0
7	06–21, 22–23	85	20	2.0
8	06–21, 22–23	45	20	2.0
9	06–21, 22–23	45	44	113.0
10	00–21	15	50	25.0
11	03–24	25	140	8.0
12	03–24	40	60	7.5
13	03–21	25	150	4.5
14	03–21	40	60	4.0
15	06–21, 22–23	60	95	9.0
16	00–24	15	220	4.5
17	00–24	15	125	23.5

C. Options for Retrofitting

For the retrofit case, we assume that the existing gas fired steam generator and the gas boiler have reached their end of service and must be replaced. The gas engine CHP plant, however, is still in operation. The superstructure of possible options for the new supply system, see Fig. 3, includes many options, but focuses on renewable energy sources: a biomass steam generator, a biogas powered CHP plant providing 250 °C and 70 °C, an electrode boiler, solar thermal collectors, a high temperature heat pump, a geothermal heat pump, and an ambient air heat pump. Photovoltaics to cover electricity demand are considered as well, but the combined area of solar thermal collectors and photovoltaics is limited to 5000 m². To decouple demand and generation, especially of renewable fluctuating sources, thermal energy storages on each temperature level and an electric energy storage are also implemented in the superstructure. We assume, that heat can be transferred from higher to lower utility temperature levels (e.g., by mixing with water).

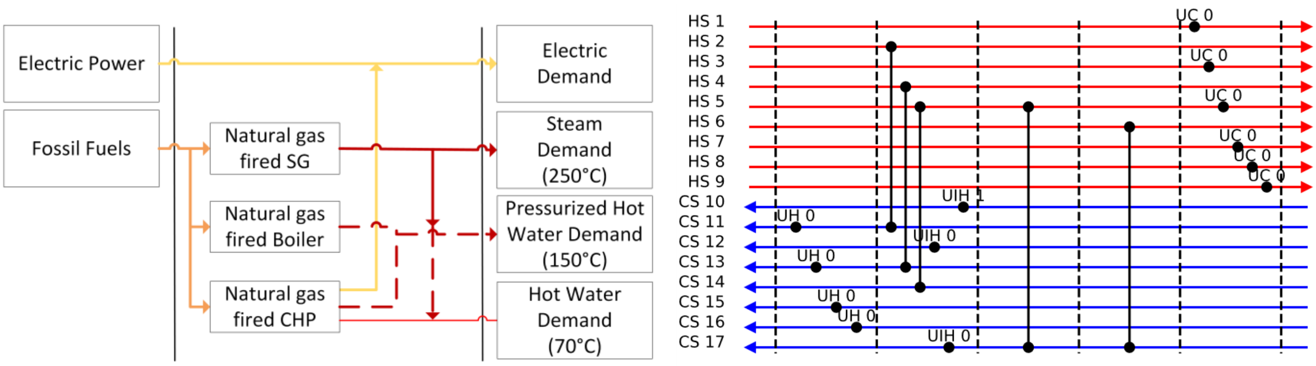

Fig. 2. Existing supply system and heat exchanger network.

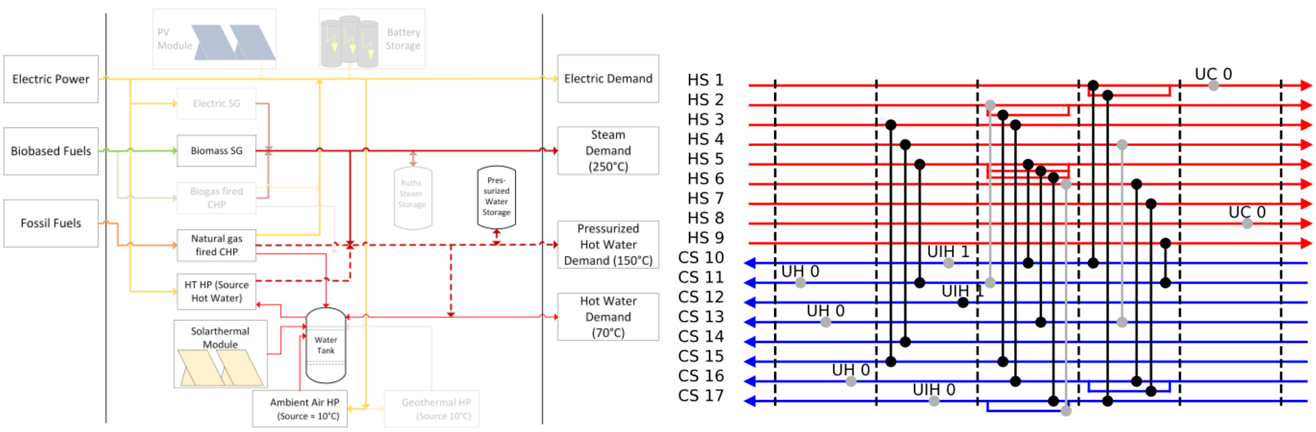

Fig. 3. Optimized supply system and heat exchanger network after retrofit.

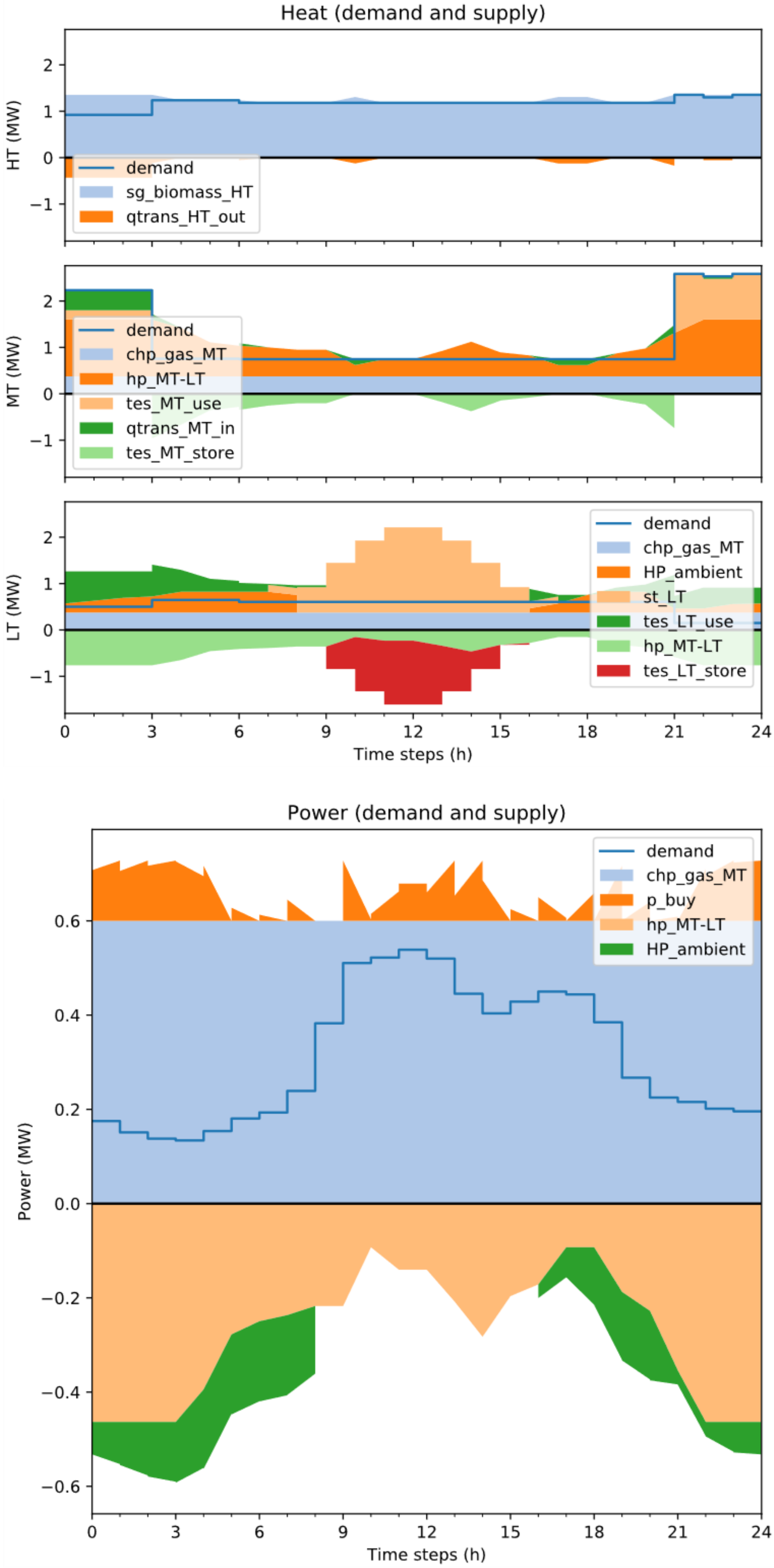

Fig. 4. Demand and supply of heat and power in optimal supply system.

D. Implementation

The combined optimization problem was modeled using Python 3.7 and Pyomo 5.6.7 [10, 11] and solved with Gurobi 9 on a 4 core Intel i7-3770K machine. The equation system consisted of 15,163 decision variables (10,745 continuous, 4,418 binary) and 28,830 constraints. The calculation was halted after 24 hours. While the global optimal solution was not found by then, the remaining duality gap was less than 6%.

IV. Results

Solving the combined problem for the test case resulted in an energy system, see Fig. 3, that shows a cost-effective way to utilize renewable energies in the described industrial process. On the supply side, shown in Fig. 4, the high temperature heat demand is provided by a new biomass boiler. Medium temperature heat is provided by a new high temperature heat pump and the previously existing gas motor CHP. A large area of solar thermal collectors and an ambient air heat pump supply the low temperature heat demand. This system is supported by large thermal energy storages at low and medium temperature levels (4.6 and 3.7 MWh). Most of the total power demand, including the prescribed load profile and the demand of the heat pumps, is satisfied by the existing CHP. The remainder is taken from the grid, especially during the cheaper nighttime hours.

The optimal heat recovery system (see Fig. 3) consists of 13 new direct heat exchangers between process streams and one additional utility heat exchangers. Eight of the previously existing heat exchangers (shown in grey) are reused. This increases total heat recovery from 40 % of maximum possible integration before the retrofit to 97 %, which means an overall reduction of heating demand in 24 hours by 42.7 MWh (38 %).

V. Conclusion

The newly presented method provides a flexible framework to cover various retrofit scenarios in industrial energy systems. In the demonstrated case study, we showed that the combined optimization approach can successfully be applied. Simultaneous optimization of the heat exchanger network and the supply system allows investment decisions with greatly reduced uncertainty. This enables the necessary transition to renewable energies and more efficient use of energy in a cost-effective way.

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