A Mixed-Integer Linear Optimization Approach For Efficient Utilization Of Wind Power For District Heating

1. Introduction

In order to meet the goals of Austrian's climate and energy strategy #mission 2030 [1] it is necessary to include more and more renewable energy sources (RES) into the existing energy grids replacing conventional fossil fuels. Additionally, including more RES is required to transform the energy system towards a totally decarbonized and green system. One major share of RES is wind power, especially in the region of Burgenland, where currently more than 1,000 MW of wind power are available. The increasing number of wind parks is based on attractive subsidies for the produced electricity from OeMAG, the Austrian settlement agency for green electricity [2]. However, these subsidies are limited in time and thus electricity from an increasing number of wind parks has to be marketed on the liberalized free electricity market with lower revenues and considerable risks due to forecasting uncertainties.

Therefore, it is important to devise novel business models for wind power in order to sustain the rapid transformation of the energy system. One approach is to use sector coupling to integrate wind power into a district heating grid forming a hybrid energy system. Such hybrid systems enable the utilization of various energy carriers and storage solutions to optimize the use of all integrated energy types (e.g., electricity, heating, and mobility). These storage solutions allow offsetting the availability of RES, but they increase the complexity of the design and operation of a hybrid system. In order to derive optimal schedules, mixed integer linear programming (MILP) combined with forecast models has proven itself as a versatile tool [3] [4] [5].

This work focuses on a real-world application, i.e., the hybrid energy system of the city of Neusiedl am See, where regional wind parks are integrated into the existing district heating system using a power-to-heat approach. This approach is realized with heat pumps that are powered using energy stemming directly from a regional wind park. A MILP model is used to compute an optimized schedule of the involved components in the modeled district heating grid of Neusiedl am See, aiming to minimize the overall net costs.

2. MILP-based Model

The hybrid energy system implemented in Neusiedl am See couples the electricity (wind parks) and the district heating systems. It consists of a direct connection from the wind parks to an electricity storage (ES) and four heat pumps. The ES is used to safely shut down the heat pumps when the energy from the wind parks cannot provide enough power to operate them. Two of these heat pumps are air-to-water devices (H_1 and H_2) and transfer energy into a low temperature thermal storage (LS), whereas the remaining two heat pumps (H_3 and H_4) are water-to-water heat pumps and transfer the energy from LS to a high temperature thermal storage (HS). HS is directly linked to a thermal buffer storage (Buffer) providing thermal energy for the district heating grid. Additionally, a biomass plant (BP) can directly provide energy for this thermal buffer storage. Furthermore, a gas boiler (GB) serves as backup if the demand cannot be met by the aforementioned systems.

a. Objective Function

The objective function of the MILP optimization problem is to minimize the total net cost.

$$\sum_{t=0}^{n} C(t) = \sum_{t=0}^{n} (C_{BP}(t) + C_{GB}(t)) \rightarrow min \tag{1}$$

$$C_{BP}(t) = \left(\frac{p_{f,BP}}{\eta_{th,BP}}\right) \cdot P_{th,BP}(t) + switch_{on_{BP}}(t) \cdot C_{BP}^{start} \tag{2}$$

$$C_{GB}(t) = p_g \cdot P_{th,GB} \tag{3}$$

Here n denotes the number of time steps (i.e., 8,760 as the optimization covers a full year in 60-minute time steps). $p_{f,BP}$ denotes the price of the biomass in ct/kWh, $\eta_{th,BP}$ the efficiency of the BP, $P_{th,BP}(t)$ the thermal power in kW provided by the BP, $switch_{on_{BP}}(t)$ is a Boolean denoting if the BP is powered on in time step t, and C_{BP}^{start} the costs for powering on the BP. Furthermore, the BP obeys the following constraints, ensuring minimal and maximal power output:

$$P_{th,BP}(t) \leq on\_off_{BP}(t) \cdot P_{max,BP}, \tag{4}$$

$$P_{th,BP}(t) \geq on\_off_{BP}(t) \cdot P_{min,BP}, \tag{5}$$

where $on\_off_{BP}(t)$ describes whether the BP is running or not at time step t and $P_{max,BP}$ and $P_{min,BP}$ denote the maximum and minimum power output, respectively.

Additionally, the BP has two constraints regarding its minimal up- and down-time due to process reasons. These constraints are modeled using the Big-M method [6], where initially helper variables need to be modeled. Subsequently, these helper variables are used to formulate the up- and down-time constraints.

$$switch_{BP}(t) = on\_off_{BP}(t) \mid t = 0, \tag{6}$$
$$switch_{BP}(t) = on\_off_{BP}(t) - on\_off_{BP}(t-1), \tag{7}$$
$$0 \leq -switch_{BP}(t) + M \cdot switch_{on_{BP}}(t), \tag{8}$$
$$M \geq -switch_{BP}(t) + M \cdot switch_{on_{BP}}(t) \tag{9}$$
$$0 \leq switch_{BP}(t) + M \cdot switch_{off_{BP}}(t), \tag{10}$$
$$M \geq switch_{BP}(t) + M \cdot switch_{off_{BP}}(t), \tag{11}$$

with $M = 10$, $switch_{BP}(t)$ denoting if a switching operation for the BP occurred at time step t (1 for switching on, -1 for switching of, 0 for no switching operation). $switch_{on_{BP}}(t)$ and $switch_{off_{BP}}(t)$ are Booleans stating if BP is switched on or off at time step t, respectively.

The inequation for the minimum run time (*MRT*) is modeled as

$$\sum_{s=0}^{MRT-1} on\_off_{BP}(t+s) \geq MRT \cdot switch_{on_{BP}}(t) \quad \forall\, t = 1,2, \dots n - MRT, \tag{12}$$

and for the minimum down-time (*MDT*) as

$$\sum_{s=0}^{MDT-1} on\_off_{BP}(t+s) \leq MDT\left(1 - switch_{off_{BP}}(t)\right) \quad \forall\, t = 1,2, \dots n - MDT, \tag{13}$$

where in both equations n is the number of time steps of the time series, i.e., 8,760. The GB is assumed to be able to start and shut down without any additional costs and during a single time step. Hence, no constraints except minimum and maximum power have to be formulated.

b. Components

The heat pumps are modeled obeying the commonly used Coefficient of Performance (COP):

$$Q_{H_i}(t) = COP_{H_i} \cdot N_{H_i}(t), \tag{14}$$

where $i \in \{1,2,3,4\}$ denotes the heat pump's index, $N_i(t)$ the electric power (provided by the wind parks) consumed at time step t, and $Q_{H_i}(t)$ the amount of heat transferred at this time step. The specific COP values for the four different heat pumps follow the data provided by the manufacturer. Additionally, the heat pumps have an individual upper limit for $N_{H_i}(t)$, denoted as $N_{H_i}^{max}$.

As already indicated, two of the aforementioned heat pumps transfer energy from the air to LS, and the remaining two heat pumps deliver energy from LS to HS, which subsequently provides the thermal district heating buffer storage with heat. Furthermore, to guarantee a safe shut down of the heat pumps and avoid abrupt stoppages in cases where no wind power is available anymore, an electricity storage (ES) is applied and its state of charge (*SOC*) is modeled as

$$SOC_{ES}(t) = SOC_{ES}(t-1) + SOC_{ES}^{charge}(t). \tag{15}$$

Here, the charging (and discharging) of the electrical storage is described with $SOC_{ES}^{charge}(t)$. Again, minimum and maximum *SOC*s are guaranteed by upper (SOC_{ES}^{max}) and lower (SOC_{ES}^{min}) limits, whereas SOC_{ES}^{init} denotes the initial *SOC*. The three thermal storages are modeled using the following equations:

$$SOC_{LS}(t) = SOC_{LS}(t-1) + Q_{H_1}(t) + Q_{H_2}(t) - Q_{H_3}(t) - Q_{H_4}(t)), \tag{16}$$

$$SOC_{HS}(t) = SOC_{HS}(t-1) + Q_{H_3}(t) + Q_{H_4}(t) - \Delta SOC_{HS}(t), \tag{17}$$

$$SOC_{Buffer}(t) = SOC_{Buffer}(t-1) - Demand(t) + P_{th}^{BP}(t) + P_{th}^{GB}(t) + \Delta SOC_{WS}(t), \tag{18}$$

where $\Delta SOC_{HS}(t)$ describes the thermal energy directly transferred from WS to Buffer. Furthermore, constraints on the upper limits depending linearly on the medium storage temperature are applied as well as initial SOCs for both LS and HS are set (see Table 1).

3. Optimization

In order to evaluate the feasibility and complexity of the MILP model an exemplary optimization using real heat demand and wind data was conducted. To solve the optimization problem, the heat production and transfer conducted by the four heat pumps has to meet the district heat demand in every time step t of a time series denoted as $Demand(t)$. This time series covers a period of a year in 60-minute intervals resulting in 8,760 time steps. In the presented model the heat demand is a fixed floating point value time in inequation (18). Additionally, the energy provided by the wind park (maximum 32.4 MW) is modeled as fixed time series, obeying

$$P_{Wind}(t) \geq N_{H_1}(t) + N_{H_2}(t) + N_{H_3}(t) + N_{H_4}(t) + SOC_{ES}^{charge}(t). \tag{19}$$

The heat demand and available wind energy for an exemplary year in Neusiedl am See are depicted in Figure 1 and Figure 2, respectively. The data for the wind energy show high fluctuations in availability, thus requiring optimal use of storages and scheduling to ensure an efficient utilization of the wind energy. The specific values for the constraints and parameters introduced in Section 2 are shown in Table 1. To solve the optimization problem the commercially available solver *Gurobi* Version 8.1.1 was used [7].

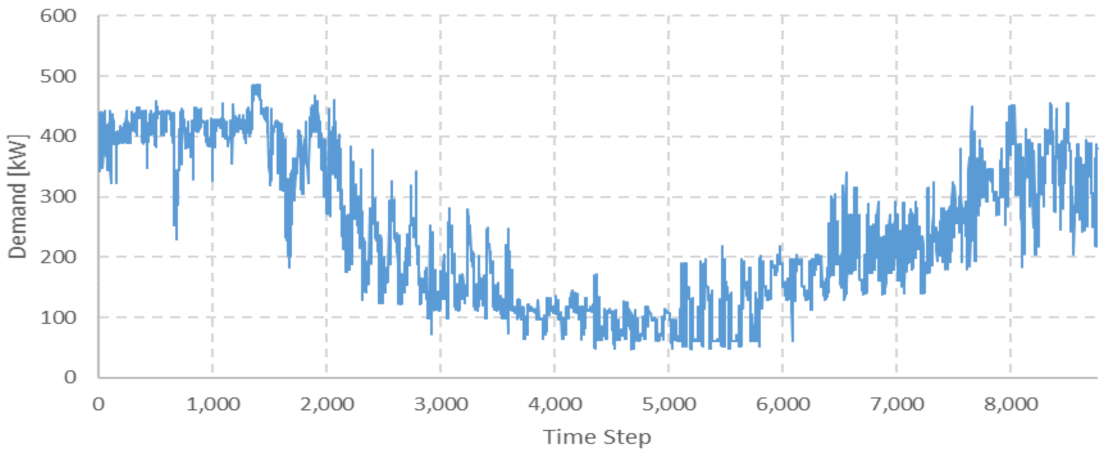

Figure 1: District heat demand for Neusiedl am See for a full year in 60-minutes time steps.

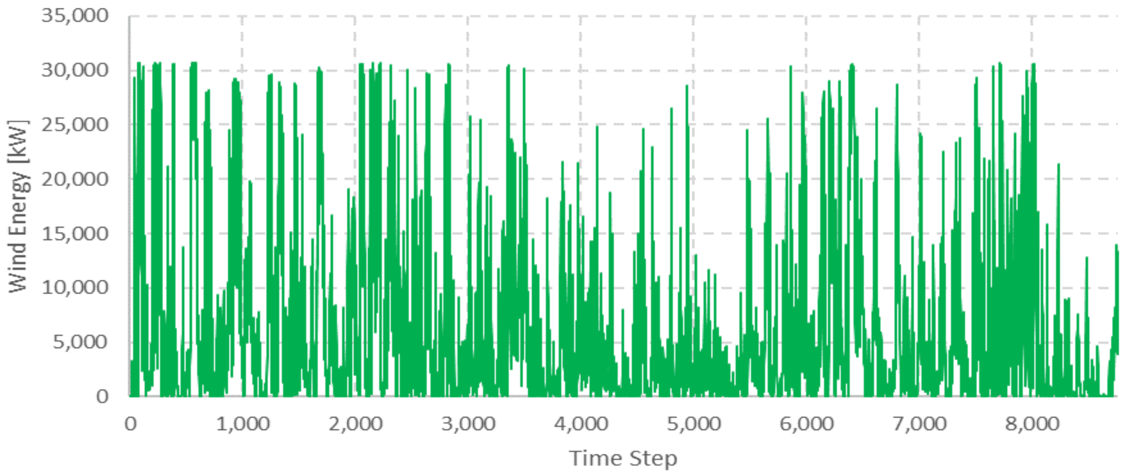

Figure 2: Available wind energy from the local wind parks in Neusiedl am See for a full year in 60-minutes time steps.

Table 1: Overview of the specific values for the parameters of the presented MILP model

$p_{f,BP}$	2.4 ct/kWh	COP_{H_1}	3.75
$\eta_{th,BP}$	0.85	COP_{H_2}	3.75
C_{BP}^{start}	2,000 ct	COP_{H_3}	3.266
p_g	4 ct/kWh	COP_{H_4}	4.34
$P_{max,BP}$	800 kW	$N_{H_1}^{max}$	160 kW
$P_{min,BP}$	5 kW	$N_{H_2}^{max}$	160 kW
MRT_{BP}	48 h	$N_{H_3}^{max}$	177 kW
MDT_{BP}	48 h	$N_{H_4}^{max}$	145 kW
SOC_{ES}^{max}	700 kWh	SOC_{ES}^{init}	100 kWh
SOC_{LS}^{init}	100 kWh	SOC_{ES}^{min}	0 kWh
SOC_{Buffer}^{init}	150 kWh	SOC_{HS}^{init}	150 kWh
SOC_{Buffer}^{max}	300 kWh	SOC_{Buffer}^{min}	0 kWh

Figure 3 and Figure 4 depict exemplary computed load profiles for the BP and the thermal buffer storage (see Section 2). The results show that the wind park in combination with the BP is able to cover the required district heat demand over a full period of a year. However, the use of thermal storages is essential to cover periods of small to almost zero power from the wind park. Additionally, thermal storages provide flexibility to the system, such that optimal schedules of the different components with respect to the total net cost can be computed. Nevertheless, a GB remains necessary for situations where there is no wind and the district heat demand exceeds the capacity of the BP. Hence, the GB provides a flexible and economically viable backup solution.

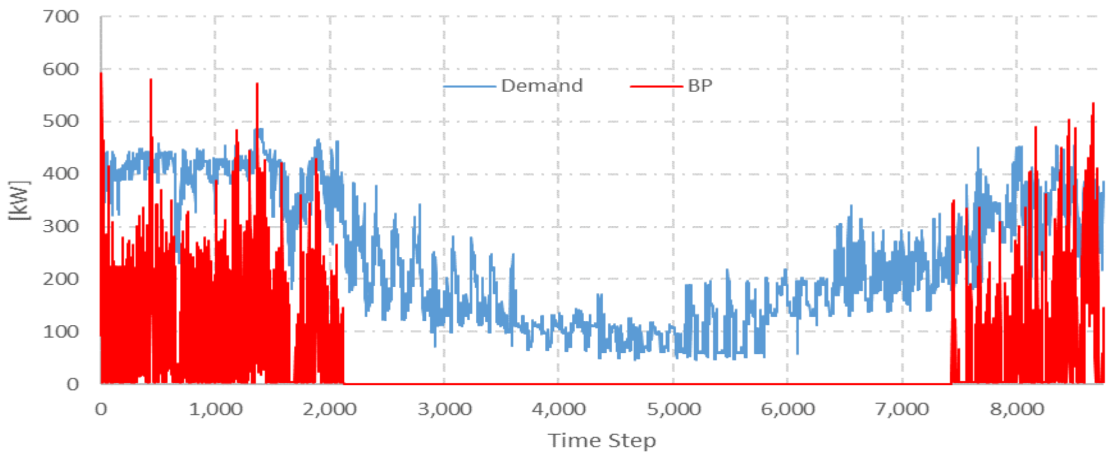

Figure 3: Demand and heat prodution from the BP.

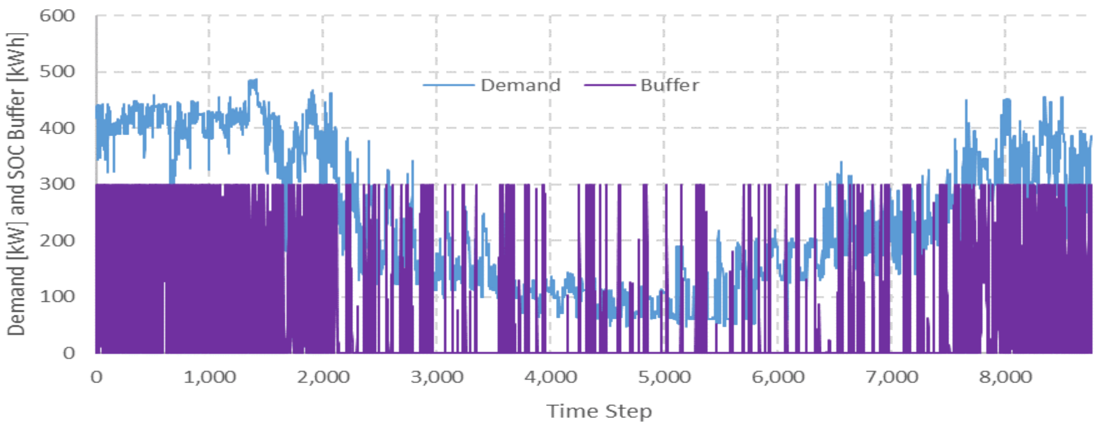

Figure 4: Demand and SOC of thermal buffer storage.

4. Summary and Outlook

The proposed MILP model is capable to capture the properties of a hybrid energy system for district heating consisting of local wind parks, a biomass plant, four heat pumps and a gas boiler as backup. Additionally, it is proved that this optimization problem can be solved with respect to the overall net costs yielding schedules for the components of the system based on district heating demand and wind forecasts. It is planned to improve the accuracy of the model by implementing finer tuned models for the COP values of the heat pumps as well as improving the heat demand and wind forecasts. Market prices for electricity from wind parks will also be implemented to take into account the opportunity costs of not selling electricity on the wholesales market.

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