A simulation study on the integration of wind in a district heating system

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ABSTRACT: Wind energy plays a major role besides photovoltaics or hydropower as a key energy source for a successful transformation of the energy system into a sustainable system relying on renewable energy sources. Wind generation operates with levelized costs of electricity (LCOE) of around 39.9 to 82.3 €/MWh (Kost et al. 2018) which can be significantly above the average market price of 2019 of around 40.39 (EXAA Base) to 43.39 €/MWh (EXAA Peak) (EXAA 2020). Thus, the economic viability of operating wind power plants is currently strongly dependent on subsidies by OeMAG (the Austrian settlement agency for green electricity), which are limited in Austria for a period of 13 years (OeMAG 2020). While the funding will ensure that the most investment costs are met, it is preferable that the wind park stay in service after that as well. Hence, it is of utmost importance to evaluate new business models in order to sustain an economically justifiable operation of wind turbines which don't receive subsidies anymore and further foster the incentive to build new plants even without the existence of tariff subsidies. This is the case for several wind turbines located near the city of Neusiedl am See, Austria, where subsidies have run out, which has sparked the search for new business models for said wind turbines. Fortunately, the city of Neusiedl am See operates a local district heating network providing a perfect test bed for the investigation of new cross-sectoral approaches to directly use wind energy utilizing power-to-heat or power-to-gas applications. These sector coupling approaches are combined in a mathematical optimization model which will provide the necessary information to create a so-called "energy hub" (Gabrielli 2017). The energy hub enables the investigation of different business models and novel use cases based on the existing infrastructure. The target function of said optimization model is the minimization of the total net costs alike, considering different combinations of components. As hydrogen presents an interesting energy source for future energy systems also business models including an electrolyser are evaluated, e.g., with a focus on heat or hydrogen production. The presented simulation study shows that already available ready-to-use technologies, e.g., heat pumps and electrolysers, are efficient enough to extend an existing district heating network and aid in transforming it into a more sustainable and future-fit energy network. In addition, this work investigates how the excess wind energy can be used in an economically efficient way utilizing an electrolyser based on an estimated demand of hydrogen in the near future (e.g., hydrogen powered busses).

1. INTRODUCTION

Electricity from wind power plays a major role in transforming our current power grid into a more sustainable system. The economic viability of wind power plants in Austria is heavily dependent on subsidies from OeMAG, which are limited by law to 13 years (OeMAG 2020). To ensure the continued operation of these plants after the end of the subsidy period, new business models must be developed for these wind farms. This also incentivizes the construction of new wind farms even without subsidies. In the immediate vicinity of the city Neusiedl am See, in the federal state of Burgenland, Austria, there are several wind turbines for which the funding has already expired or will soon expire. In addition, wind power plants must be switched off in critical grid situations. In these situations, flexibilities such as heat storages can be used to increase the grid stability. Additionally, Neusiedl am See operates a district heating system creating an ideal test bed for evaluating innovative sector coupling concepts and strategies as well as novel business models. Therefore, a new system is built which connects the electric grid and the district heating system. This system forms a so-called energy hub (Favre et al. 2005) consists of two air-to-water heat pumps, three thermal storages, two water-to-water heat pumps to supply the district heating network with heat. A biomass power plant (BMP), a gas burner (GB), and a flue gas condenser act as backup systems. In this paper, it is shown how existing technologies can be combined with heat pumps and BMPs to form an efficient energy hub based on a mixed integer linear program (MILP) (Gabrielli et al. 2017). Despite the production of district heating from the wind park's electrical energy, there is still excess energy, which has to be sold on the electricity market. The available surplus energy results from the fact that the wind farm has a peak power of **30** MW whereas the heat pumps reach only a peak consumption of **415** kW. Hence, there is an enormous potential of electricity for various use cases with more economic value as the wholesale market would provide. In this article we investigate one potential use case, i.e., the production of hydrogen, and evaluate if its potential is sufficient for operating a potential future hydrogen powered public transport system (e.g. with busses).

2. METHODS

In this section the equations for the MILP model (Theo et al. 2016) are presented. Special attention is given to the cost function, which acts as the objective function in the optimization. Furthermore, the implementation of the summer and winter mode switching is presented. At the end of the chapter the modeling of the electrolyser is discussed.

$$C = \sum_t \Big[\frac{p_f}{\eta_{BMP}} P_{th,BMP}(t) + p_{v,bmk}\sigma_{BMP}(t) + c_{start,BMP}\delta_{BMP}(t) + p_g P_{th,GB}(t) - p_{el}\varepsilon(t) - p_{h2}\dot{m}_{pem}(t) + (p_{el} + p_{el,spread})\Big(P_{a1,el,grid}(t) + P_{a2,el,grid}(t) + P_{b1,el,grid}(t) + P_{b2,el,grid}(t)\Big)\Big]. \quad (1)$$

Here, p_f denotes the price for the biomass in ct/kWh, η_{BMP} denotes the efficiency of the BMP, $P_{th,BMP}$ the thermal power in kW produced by the BMP. The fixed costs of operating the BMP are modelled using $p_{v,bmk}$ in ct. $\sigma_{bmk}(t)$ denotes a binary variable which is one if the BMP is on and zero if the BMP is off. On startup of the BMP ramping costs for the BMP occur which are modelled by $c_{start,bmk}$ in ct. The cost of the GB consists of the gas price p_g in ct and the quantity of gas $P_{th,GP}$ in kW consumed. The excess energy $\varepsilon(t)$ in kW in the energy hub is sold on the electricity market at price p_{el} in ct. Variables $P_{a1,el,g}(t)$, $P_{a2,el,g}(t)$, $P_{b1,el,g}(t)$, $P_{b2,el,g}(t)$ in denote the electric energy from the power grid consumed by the four heat pumps.

The heat pumps are modelled using the so-called coefficient of performance (COP) value.

$$Q_{th}(t) = COP(T) \cdot P_{el}(t) \quad (2)$$

In (2) the variable $Q_{th}(t)$ in kW denotes the thermal power which is produced by the heat pump at time t and $P_{el}(t)$ in kW stands for the electric power consumed by the heat pump. The *COP* is the factor that indicates how many units of thermal energy the heat pump can produce from one unit of electrical energy. The *COP* of the air-to-water heat pumps is a function of the temperature T. In a MILP problem, however, only linear constraints are allowed. Hence, it is necessary to linearize Equation (2) by approximating it with a piecewise linear function (Hart et al. 2017). The two air-to-water heat pumps have two different operation modes, one for summer and one for winter. The system behavior is quite different in these two modes, so it is important to model the mode switching. In summer mode the COP of the heat pumps is higher as in winter mode. This effect occurs because the internal plumbing of the heat pump is different in these two modes (Grassi 2018). In winter mode the hot water produced by the air to water heat pumps is stored in a first thermal storage unit, in summer mode the produced hot water is stored in the second thermal storage unit because of the higher COP. These two modes are represented by the two binary variables $\sigma_{winter}(t)$, $\sigma_{summer}(t)$. Only one mode should be active at timestep *t* so for every time step the constraint,

$$\sigma_{winter}(t) + \sigma_{summer}(t) = 1, \tag{3}$$

is necessary. The binary variables $\sigma_{s,on}(t)$ and $\sigma_{s,off}(t)$ reflect the switching operations at time step *t* for switching on (1) and off (0), respectively. The helper variable $\sigma_{s,h}(t)$ approximates the derivative of $\sigma_{summer}(t)$, which is needed to calculate the switching points between the two modes. The variable $\sigma_{s,h}(t)$ can have three different states at time *t*: 1 when switching to summer mode in this time step, -1 when switching to winter mode in this time step, or 0 if there is no mode change. The constraints between these variables are modelled in equations (4-8).

$$\sigma_{s,h}(t) = \begin{cases} 0, \quad t = 1 \\ \sigma_{summer}(t) - \sigma(t-1)_{summer}, \quad t \neq 1 \end{cases} \tag{4}$$

$$0 \leq -\sigma_{s,h}(t) + 2 \cdot \sigma_{s,on}(t) \tag{5}$$

$$1 \geq -\sigma_{s,h}(t) + 2 \cdot \sigma_{s,on}(t) \tag{6}$$

$$0 \leq \sigma_{s,h}(t) + 2 \cdot \sigma_{s,off}(t) \tag{7}$$

$$1 \geq \sigma_{s,h}(t) + 2 \cdot \sigma_{s,off}(t) \tag{8}$$

The summer mode should only be active in summer in a continuous period. Therefore the switch-on and switch-off points are limited to one each (9-10).

$$1 = \Sigma_t^T \sigma_{s,on}(t) \tag{9}$$

$$1 = \Sigma_t^T \sigma_{s,off}(t) \tag{10}$$

A major part of this study is the electrolyser modelled with the linear equation,

$$\dot{m}_{pem}(t) = \eta_{pem} \cdot P_{el,pem}(t), \tag{11}$$

where $P_{el,pem}(t)$ in kW denotes electric power used for hydrogen production and $\dot{m}_{pem}(t)$ the mass of produced hydrogen per hour in kg/h. The degree of efficiency η_{pem} for this electrolyser is calculated based on the assumption that 72 % of the electric energy are converted into hydrogen, in the literature a total degree of efficiency of approximately 70 % is proposed (James et al., 2013).

$$\eta_{pem} = 19.19 \cdot 10^{-3} \frac{kg}{J} \tag{12}$$

The minimum and maximum power is modelled using equations (13-14).

$$P_{el,pem}(t) \geq \sigma_{pem}(t) \cdot P_{el,pem,min} \tag{13}$$

$$P_{el,pem}(t) \leq P_{el,pem,max} \cdot \sigma_{pem}(t) \tag{14}$$

In equation (13) and (14) $\sigma_{pem}(t)$ is a binary variable denoting if the electrolyser is on (1) or off (0). The minimum power of the electrolyser is modelled with the variable $P_{el,pem,min}$, which is 5 % of the maximum power, and the maximum power is modelled using the variable $P_{el,pem,max}$ which is in this case assumed with 17 MW.

3. EVALUATION

The presented mathematical model is implemented in the Python library Pyomo (Hart et al. 2017). The MILP model is solved using the Gurobi (2020) solver with following parameters. The MIP gap which is set to 0.03 describes the gap between lower and upper bound of the objective function. The solver terminates the optimization when this gap is lower the upper bound times the MIP gap (Gurobi, 2020). With MIP focus parameter the high level solution strategy of Gurobi is influenced (Gurobi, 2020). In this study the MIP focus is set to zero which is the default value. The energy produced by the wind park (Fig. 1), the district heating demand (Fig. 1) and the electricity price for the year 2018 (EXAA 2020) were used as input data for the optimization. The input data provides data for a whole year with a sampling period of one hour, which results in 8'760 data points.

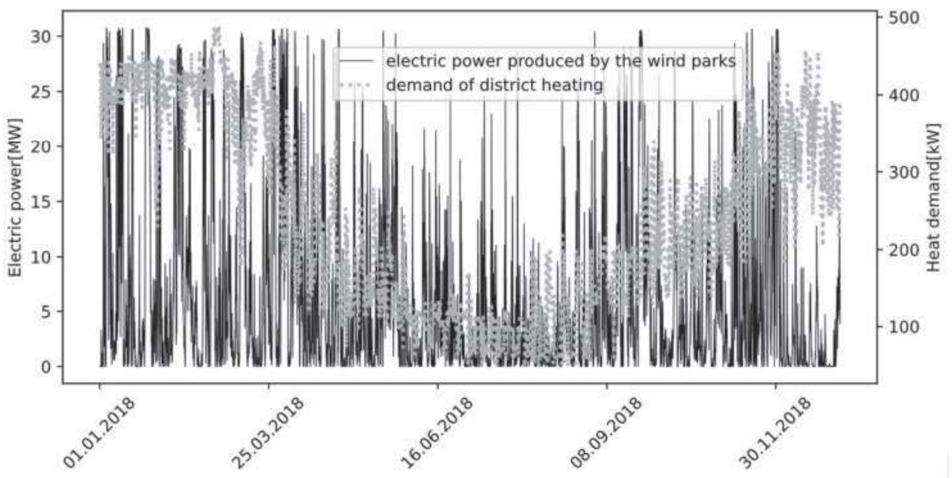

Fig. 1: Energy provided by the wind park and demand of district heating.

The values for the model parameters are chosen as presented in Tab 2. The values were chosen to reflect the cost structure of the real energy hub as good as possible in the model.

Tab. 2: Parameter settings for the model.

p_f	2.4 ct/kWh	p_g	4.0
η_{BMP}	0.85	p_{h2}	300 ct
$c_{start,BMP}$	2000 ct	$p_{el,spread}$	1.5 ct

4. RESULTS

Based on the MILP model it can be shown that the district heating network can be supplied by heat pumps. The electric excess energy that is still generated can then be sold on the electricity exchange or used for hydrogen production as shown in this article. Fig. 2 proves that the amount of produced hydrogen highly depends on the hydrogen price. Above a hydrogen price of 500 ct/kg there is no more increase in production because of the maximum power consumption of the electrolyser. Consequently, the production costs decrease linearly when the hydrogen production is on maximum and the price of hydrogen increases. In order to evaluate the annual production of the electrolyser, the use of hydrogen as fuel for the public bus network in Burgenland is taken into account. For Example the fuel cell powered bus from SOLARIS (2020) can drive 11 km per kilogram hydrogen, so at the energy hub hydrogen for $8.8 \cdot 10^6$ km is produced. According to Postbus (2020) the yearly driven distance by all its busses in Burgenland is $3.4 \cdot 10^6$ km. Hence, in Neusiedl am See there is a potential to produce hydrogen for more than the complete road based public transport in Burgenland. The hydrogen production study presented in this article only shows that the wind farm provides enough excess energy to produce the specified amount of hydrogen. If one includes the investment costs and the running costs in such calculations, one finds that such plants cannot be operated economically at present. Hosseini and Wahid (2016) show that the price of electricity would have to drop by 75 % to make electrolysis competitive with hydrogen production from fossil fuels. This proves that without sufficient political support and suitable subsidies the goal of green hydrogen production is economically hardly to achieve. Especially, as pilot implementations are generally more cost intensive compared to fully developed off-the-shelf solutions.

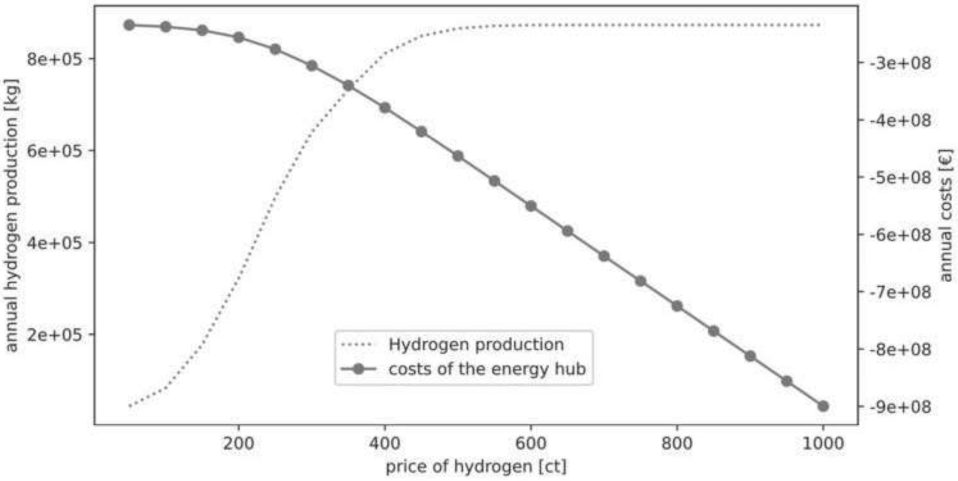

Fig. 2: Amount of hydrogen produced dependent on the selling price of hydrogen.

5. SUMMARY

In this article a MILP model for a hybrid district heating system was presented. This energy hub connects a wind farm with a district heating network. The result of the optimization shows that there is enough excess energy available for further business models in the energy hub, e.g., producing hydrogen as fuel for public transport. However, no investment costs and operational costs were considered in this study. At present, however, the generally accepted opinion is that the production of hydrogen from green electricity is not profitable due to these additional costs (El Emam 2020). This, however, proves the fact that there is an urgent need on the political side for funding and subsidizing green hydrogen solutions. To successfully transform the existing energy systems, it is of utmost importance to support the corresponding research efforts in order to establish these new technologies.

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