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Profitability of power-to-heat-to-power storages in scenarios with high shares of renewable energy

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ABSTRACT

Intermittent electricity generation from variable renewable energies will lead to an increased demand for flexibility options in the future. Power-to-heat-to-power storage technologies present high potentials for large-scale application. However, investments in such technologies are still hampered by technical and economic challenges. To address the latter the possible revenues in electricity markets need to be analyzed. For this, we simulate the German electricity market in ambitious defossilization scenarios. We use different operational strategies for the storage (minimizing system costs versus maximizing storage profits) that show a wide range of storage profitability. The operator benefits from its attributed market power (i.e. assuming perfect foresight in a rolling horizon window) to generate positive net profits. Further research may focus on market situations with increased market competition.

Keywords: agent-based modelling, flexibility options, energy systems, electricity markets

NOMENCLATURE

Abbreviations	
AMIRIS	Agent-based electricity market model
P2H2P	Power-to-Heat-to-Power (storage)
REMix	Framework for optimizing energy system models

1. INTRODUCTION

Energy storages are an integral element of energy systems, especially in those with high shares of wind and solar power [1,2]. The intermittent nature of renewable energy sources can be balanced by the operation of flexibility options such as storages or demand side management. There are different storage types with various advantages and use cases [3–5]. Power-to-Heat-to-Power (P2H2P) storages such as Carnot battery concepts [6] promise to provide large-scale electrical energy storage capacities by operating at medium to high temperature ranges. Surplus electricity is transformed to heat and stored in a storage medium, i.e. molten salt, and finally converted back to electricity when needed. For this, Brayton or Rankine processes can be used.

Apart from solving technical challenges, such as increasing efficiencies, or unit upscaling, it is also important to investigate the economic perspective. Investments in P2H2P technologies require a detailed view on future profitability potentials. Hence, we simulate future electricity systems with high shares of renewable energies and evaluate the profitability of such grid-scale storage systems.

In Section 2, we describe our model setup and the important aspects of our scenarios. Section 3 describes the operational strategies of the P2H2P storage which is active on the day-ahead market. Results are presented in Section 4. Limitations of the presented study are discussed in Section 5 while we conclude and present an outlook on future works in Section 6.

2. METHOD

We apply the open agent-based electricity market model AMIRIS [7] in order to simulate the German day-ahead market. AMIRIS investigates market dynamics caused by the interactions of market actors, taking into account political frameworks [8,9] and actors' behavior under uncertainty [10,11]. For this purpose, agent-based modeling, which has its origins in artificial intelligence research, offers a powerful approach, since the actors with their perceptions and action patterns are at the center of modeling. AMIRIS has been calibrated and back-tested for the German [9] and Austrian [12] day-ahead market and shows a good fit in simulating historical electricity prices. Agents in AMIRIS represent different players at the electricity market ranging from power plant operators to traders and policy agents. Flexibility is provided by a dedicated storage agent class. We parameterize this agent with technical and economical parameters such as capacity, power, charging and discharging efficiencies, availabilities, costs. The two modelled operational strategies are described in Section 3. A detailed description of all agent types in AMIRIS can be found in [7] and [13].

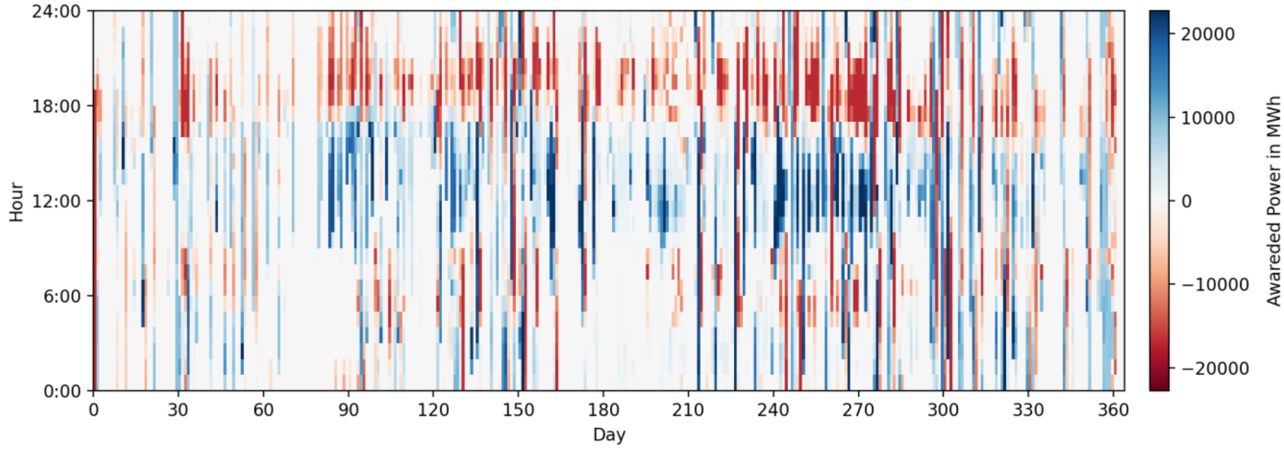

Figure 1: Storage dispatch in the simulated scenario year 2050 applying the Minimize system costs strategy

Regarding the scenario and infrastructure assumptions, we use the REMix framework for optimizing energy system models [14] with a previously published dataset for the electrical energy system which employs technologies for sector-integration between the power, heat and gas sectors [15]. A cost-optimal expansion planning for power plants, pipeline, grids, and storages is conducted while considering the preexisting capacities such as pumped-hydro storage plants. Preliminary findings indicate P2H2P storage systems can provide an additional building block for a low-cost energy transition especially when either network expansion is limited or high shares of variable energy sources are deployed. One of the main deciding factors on the technology share P2H2P in a future low emission scenario is the feasibility of a low-cost medium for the heat storage [16]. This can enable technology competitiveness against other storage technologies such as pumped hydro or lithium-ion batteries.

3. STORAGE DISPATCH STRATEGIES

The bidding strategy for a flexibility provider, i.e. P2H2P storage, is essential for its profitable operation. The definition and analysis of bidding strategies on electricity markets has a long record in literature [17]. Different approaches ranging from stochastic programming [18], game theory [19], to machine-learning [20] can be used to find robust and profitable strategies. In the present work, we have applied two distinct strategies based on dynamic programming [21]. Both strategies require (forecasted) information about the market situation in a defined window. The algorithm evaluates discrete states-of-charge of the P2H2P storage. The optimal strategy is calculated by finding the best charging and discharging opportunities. The bids and asks which are submitted to the electricity market are then formulated accordingly. In detail, we perform a system-optimal solution (*Minimize system costs* strategy) and compare it with a best-case scenario for the P2H2P storage operator (*Maximize profits* strategy). For both strategies, the storage operator optimizes its schedule based on a window of 168 hours using perfect foresight.

3.1 MINIMIZING SYSTEM COSTS

The strategy to *minimize system costs* represents a “system-friendly” operation of the storage. It aims at reducing overall operational system costs stemming from dispatching the power plant park. Specifically, the sum of the marginal costs of asks is minimized over the forecast horizon interval. Typically, this strategy results in less profits than the *maximize profits* strategy as it represents the market-ideal behavior assuming strong competition among flexibility providers. Therefore, it is still worth considering this strategy, even though it does not provide a reasonable business case in this assessment.

3.2 MAXIMIZING PROFITS

The strategy to *maximize profits* takes full advantage of the storage operator’s market power in the electricity market, which is particularly relevant for large-scale storages. This strategy can be seen as the upper limit of storage operator profits in any given scenario. In general, the storage operator aims at charging when forecasted prices are low and discharging when forecasted prices are high. However, the algorithm utilizes its perfect foresight and also considers the impact of its own asks and bids on the final electricity price.

4. RESULTS

The simulation results derived from AMIRIS allow various insights into the market situations in the defined scenario. The dispatch of the P2H2P storage applying the *Minimize system costs* strategy is shown in Figure 1. Charge operations (blue areas) are mainly carried out around noon. This correlates with high output from photovoltaics. In contrast, discharge operations (red areas) typically commence when demand is high (i.e. morning and evening hours). The dispatch shows no strong seasonal pattern. Instead, we observe only short periods without significant storage activity. This can be explained by the optimization windows applied in the storage dispatch strategies.

Electricity prices are characterized by a large number of hours (> 8,000 hours) in which renewable energies are price-setting. Due to their assumed strategy of bidding at marginal costs, prices are 0 EUR/MWh in these cases. The remaining hours are dominated by conventional power plants resulting in prices between 37 EUR/MWh and 453 EUR/MWh. In contrast to the recent market situation, where rising gas prices can be identified as the primary driver for high prices, the simulation results can be explained by – compared to today's levels – high CO_2 emission prices of 216 EUR/MWh.

The profitability analysis for the two applied storage strategies is listed in Table 1. Yearly gross profits (revenues from selling electricity minus costs from purchasing electricity at the day-ahead market) are 561 million EUR/a (or 28 EUR/$kW_{installed}$) when *minimizing system costs* and 1,400 million EUR/a (or 71 EUR/$kW_{installed}$) when *maximizing profits*. Assuming a total lifetime of 20 years and an interest rate of 5%, the annual depreciation costs are 743 million EUR/a. This results in annual net profits of -243 million EUR/a when applying the *minimizing system costs* strategy. In contrast, *maximizing profits* is awarded with annual net profits of 611 million EUR/a. This significant improvement compared to the *minimizing system costs* strategy can be explained by the exploitation of market power. This result, however, comes with almost twofold costs for system's dispatch (excluding fixed and investment costs).

Table 1: Profitability of different storage dispatch strategies

Strategy	Day-ahead gross profit in million EUR/a	Depreciation in million EUR/a	Net profit in million EUR/a
Minimize system costs	561	743	-248
Maximize profits	1,400	743	611

5. DISCUSSION

When interpreting the presented results the following limitations have to be considered. First, the technical assumptions and cost basis of the presented P2H2P storage follow very optimistic learning rates, in particular storage power and energy cost assumptions of 90 EUR/$kW_{installed}$ and 20 EUR/$kWh_{installed}$ combined with a round-trip efficiency of 75%. Second, the scope is limited to the German day-ahead market only. This neglects additional revenue potentials, but also possible competition from neighboring market zones and other flexibility providers. Third, the profitability of the *maximize profits* strategy marks the upper limit of possible revenues since the storage trader benefits from its total market power and makes full use of it.

6. CONCLUSION

We present a profitability analysis for P2H2P storages in scenarios with large shares of renewable energies and high emissions reductions. For this, we applied the agent-based electricity market model AMIRIS which simulates the German day-ahead market. The P2H2P storages are represented by a dedicated agent actively bidding following two distinct strategies; the strategy of *minimizing system costs* leads to a negative net profit whereas the strategy of *maximizing profits* is resulting in a positive outcome when taking depreciation costs into account. The total system costs for dispatch, however, almost double in the latter case. This may contrast analyses from optimization models aiming at finding a global optimum in regard of system costs.

Further research may focus on more robust strategies for the storage operator since the *maximizing profits* strategy is only possible due to the storage operators substantial market power.

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