Energy Management of Hybrid Power Plants in Balancing Market

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***Abstract*—This paper focuses on preliminary investigation of Hybrid Power Plants (HPPs) operation in balancing market in 2030. The opportunities of balancing market are firstly analyzed. Then the 2030 market information is simulated by balancing tool chain. Spot market optimization and balancing market optimization are introduced sequentially. For balancing market optimization, a scenario based stochastic optimization is applied to deal with the forecast errors of regulation price. By leveraging multi-price scenarios, the objective function is to maximize expectation of profits. In case study, market scenario of 2020 and 2030 are compared firstly. After that, we define two cases to simulate HPP operation in 2030. The case when HPP only participates in spot market is designed as a benchmark case to evaluate the value of balancing market. The investigation assumes an HPP located in West Denmark (DK1) and therefore applies the market rules for this area. Simulation results demonstrate that HPP can receive 11% increase of revenues in balancing market, but due to the high degradation costs of battery, the profit increase is 5.9%.**

I. Introduction

In recent years, the attention in both academia and industry has been directed toward to combine and integrate technologies that minimize the greenhouse gases emissions per delivered energy unit. In this respect hybrid power plants (HPPs), which co-locate wind power plants (WPPs) and battery energy storage systems (BESSs) behind same grid connection point, are becoming more popular nowadays [1], [2].

The emerging market opportunities facilitate the development of HPPs, because more revenue streams can be obtained for HPPs. For reserve market, HPPs can receive reserve payments by promising reserve capacities, which is less likely for individual renewable power plants. For energy market, in many cases, individual renewable power plants are paid by fixed price through power purchase agreements in U.S. or feed-in-tariffs in Europe [1]. However, HPPs can achieve energy arbitrage by capturing the fluctuation of market prices to charge or discharge their energy storage system. In addition, with the aid of storage, HPPs can provide ancillary services to guarantee reliability and stability of power system. e.g. balancing services in Nordic area.

To capture these profits in electricity markets, HPP operators use forecast of market prices and incorporate it into the energy management of HPPs. Currently, the accuracy of forecasts of market prices is not good enough for energy management of HPPs and this is the case especially for regulation prices, as the forecasting techniques are not yet well developed. Forecasting of regulation prices is especially difficult due to stochastic nature of power generations and loads going out of service due to faults. Therefore, a sound processing of forecast error is highly needed, as large forecast errors may cause aggressive or conservative operation strategies, which reduce the profits for the HPPs. For example, for balancing market, the profits may even be negative, if balancing reserves are expected for up regulation; however, in reality the required balancing is for down regulation and vice versa. In order to counteract such challenges, the development of an HPP energy management system (EMS), which incorporates prices forecast uncertainty in the optimization algorithm, is of high importance.

To solve these challenges, an energy management system is required to quantify the profitability of HPPs in markets. The study of operating HPPs in electricity markets has been discussed in literature. In [3], a day-ahead optimal offering model is proposed for wind-battery based HPPs to participate in spot market. In real-time operation, wind power forecasting errors are compensated by battery via a proposed balancing algorithm. [4] proposes a coordinated optimization model where the day-ahead, intra-day and balancing market are all optimized concurrently in the day-ahead stage. Although a novel machine learning method is used to generate day-ahead forecast of wind and price scenarios, the model does not consider to leverage updated forecasts to update decisions. This problem is investigated by [5], where four optimization models are proposed and work sequentially to utilize the updated forecasts. However, it does not consider any costs in the objectives, which leads to sub-optimal decisions. Although many works have been made, the study of HPPs is still in the preliminary stage. The profitability of HPPs in markets, especially balancing market, is still need to be investigated.

This paper aims to perform preliminary investigation on value of HPP in balancing market in 2030 with a case analysis of Western Denmark based on balancing tool chain [6] and two optimization models. The opportunities of balancing market are analyzed in this paper. Comparison of market prices in 2020 and 2030 are performed. The uncertainty of regulation price forecasts in balancing market optimization is handled by a scenario based stochastic optimization (SSO) model based on practical considerations. Section II analyzes the opportunities of balancing market and describes market information generation. Energy management models are introduced in Section III. Section IV discusses simulation results. Section V is the conclusion.

II. Electricity Markets

To study the energy management of HPPs in balancing market, the first thing is to obtain market information. The 2020 market information can be obtained via Nord Pool [7]. For 2030, the wind power and market information are modeled through Correlated Renewable Energy Source (CorRES) simulation tool [8] and balancing tool chain. The detailed explanation of generating market information is provided in the following subsections.

A. Opportunities in Balancing Market

Balancing market is an hour-ahead (HA) market. The goal of balancing market is to trade regulation power and settle power imbalances in order to ensure power system balance. We focus on the trade of regulation power in this paper. The following opportunities can be seen in balancing market.

1) excessive energy in up regulation hour: when excessive energy is seen in HA stage, the opportunity of offering up regulation power in balancing market comparing with injecting the energy into grid without trade can be expressed by:

$$(\lambda_t^{up} - \lambda_t^{sp}) \cdot P_t^{exc} > 0 \tag{1}$$

where λ_t^{up} and λ_t^{sp} are up regulation price and spot price at hour t. P_t^{exc} is the excessive power. In up regulation hours, the balancing up prices are always higher than the corresponding spot prices, therefore, it is obviously that the revenues are positive.

2) inadequate energy in down regulation hour: when inadequate energy is seen in HA stage, the opportunity of offering down regulation power in balancing market comparing with keeping the energy deficits can be expressed by

$$(\lambda_t^{sp} - \lambda_t^{dw}) \cdot P_t^{ina} > 0 \tag{2}$$

where λ_t^{dw} is down regulation price at hour t. P_t^{ina} is the inadequate power. In down regulation hours, the balancing down prices are always lower than the corresponding spot prices, therefore, HPP sells energy with spot prices in spot market but only pays the inadequate energy with lower prices in balancing market. The revenues are also positive.

The opportunities in balancing market are not restricted in these two situations. For example, even though there is no excessive or inadequate energy, HPP can also offer down regulation service. The saved energy can be trade in another hour in the formation of up regulation service to achieve arbitrage.

B. Electricity markets in 2020

Nord Pool is an important element in Nordic markets for electricity trade of Nordic countries. From the Nord Pool website, we can extract the spot price time series λ_t^{sp}, up/down balancing price time series $\lambda_t^{up}/\lambda_t^{dw}$, regulation volumes, etc.

C. Electricity markets in 2030

The 2030 markets are modeled by balancing tool chain, which is developed by Technical University of Denmark, Department of Wind and Energy Systems to simulation the operation of energy system with variable renewable energy (VRE) generation. The overall structure is shown in Fig. 1. CorRES is used to simulated day-ahead (DA) and HA wind power forecasts errors as well as available wind power in the areas, which are inputs of DA market model, balancing model and area frequency control model.

The DA market operation is simulated with the Balmorel open source energy system model [9] and the optimizations are carried out with a rolling seasonal horizon approach of one day. The outputs of DA market model are hourly power schedules and DA market prices. The balancing model is applied to simulate the HA balancing process. The updated HA 5-minute resolution wind power forecasts and hourly DA power schedules are used to calculate HA-DA system imbalances. Then adjustments are performed by activating regulation power offers. The output of balancing model is HA power schedules and continuously cleared regulation price in 5-minute resolution.

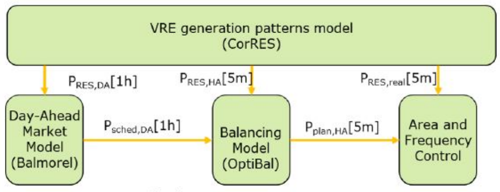

Fig. 1. The structure of balancing tool chain [6]

What energy management of HPPs requires from balancing tool chain are the cleared DA spot prices and HA regulation prices. However, currently in Denmark, the regulation price used in settlement is in hourly resolution [10]. We assume that this rule still holds in 2030. Therefore, we transfer the 5-minute resolution regulation prices from balancing tool chain into hourly prices and generate up and down balancing prices (λ_t^{up} and λ_t^{dw}) by Algorithm 1 according to rules in Regulation C2 provided by Energinet [10]. In Algorithm 1, $\lambda_{t,k}^{rp}$ represents the regulation price in k_{th} 5 minutes at hour t. λ_t^{sp} is the cleared spot price at hour t.

Algorithm 1

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k ∈ {0, 1, 2, ··· , 11}
For t = 0 : 23
    if min(λ^rp_{t,k}) ≥ λ^sp_t
        λ^up_t = max(λ^rp_{t,k})
        λ^dw_t = λ^sp_t
    elif max(λ^rp_{t,k}) ≤ λ^sp_t
        λ^dw_t = min(λ^rp_{t,k})
        λ^up_t = λ^sp_t
    else
        λ^up_t = max(λ^rp_{t,k})
        λ^dw_t = min(λ^rp_{t,k})
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III. Energy management model for HPP

A. Spot Market Optimization

Spot market optimization is an important part for energy management of HPPs, because most energy is traded in spot market. In spot market optimization, battery is used to charge when spot price is low and discharge when spot price is high to achieve energy arbitrage. The model in this paper is based on DA optimization model in our previous papers [3], [11]. Additionally, the battery degradation considered as costs is also included in the model in order to avoid over use of battery. Therefore, the objective function of spot market optimization is:

$$M^{SM} = \max \sum_{t} R_t^{SM} - C^{SM} \tag{3}$$

- M^{SM}: the profits of HPP estimated from selling energy in spot market of the whole day.
- R_t^{SM}: the revenues of HPP obtained from selling energy in spot market at hour t.
- C^{SM}: the degradation costs of battery in spot market.

The detailed constraints of spot market optimization can be found in [3]. The battery degradation cost is estimated based on life assessment model in [12].

B. Balancing Market Optimization

The goal of balancing market optimization is to offer regulation power and to manage imbalance power in balancing market, which creates requirements to have forecasts of regulation prices. The accuracy of regulation price forecasts plays important role in earning revenues in balancing market. We use a standard scenario based stochastic optimization to handle the uncertainty of regulation price. Stochastic programming allows the inclusion of multiple scenarios that aim to represent the possible values of the regulation price with a certain probability π_ω satisfying Eq. (4).

$$\sum_{\omega} \pi_\omega = 1 \tag{4}$$

The objective function of balancing market optimization is shown in Eq. (5).

$$M^{BM} = \max \sum_{t} R_t^{BM} - C^{BM} \tag{5}$$

- M^{BM}: the profits of HPP estimated from operating in balancing market of the whole day.
- R_t^{BM}: the revenues of HPP obtained from offering regulation power in balancing market at hour t. The formulation is the expectation of revenues under all scenarios:

$$R_t^{BM} = \sum_{\omega} \pi_\omega \cdot (\lambda_{t,\omega}^{up} \cdot P_t^{up} - \lambda_{t,\omega}^{dw} \cdot P_t^{dw}) \tag{6}$$

  where P_t^{up} and P_t^{dw} are offered up and down regulation power at hour t. $\lambda_{t,\omega}^{up}$ and $\lambda_{t,\omega}^{up}$ are up and down regulation prices under scenario ω.
- C_t^{BM}: the degradation costs of battery in balancing market.

IV. Case Study

In this study, we assume a HPP that is located at Western Denmark, therefore applying market rules in DK1. The HPP consists of a 120 MW wind power plant and a 30MWh/10MW battery energy storage system. Other parameters can be found in [11], [12]. The wind power time series are generated via CorRES using 2012 weather year. The demand time series in balancing tool chain also correspond to 2012. There are a lot of scenario generation methods in literature [13], [14]. The detail of scenario generation is beyond the scope of the paper, hence one approach is used for generating regulation price scenarios. A one day example for generated regulation price scenarios is shown in Fig. 2. In each hour, there are 3 scenarios considered with probability 25%, 50%, and 25%, respectively.

The optimization models are solved via IBM Decision Optimization Studio CPLEX through docplex python library[15], operating on DTU HPC cluster [16].

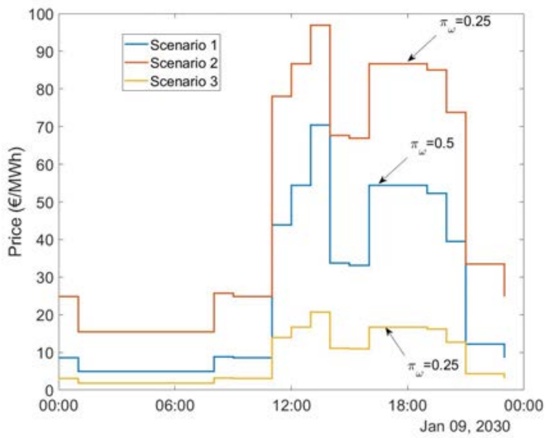

Fig. 2. One day example of regulation price scenarios

A. Comparisons of market prices and regulation requirements between 2020 and 2030

This part compares 2020 and 2030 market scenarios in terms of number of hours requiring regulation, differences between balancing up prices and spot prices, and differences between balancing down prices and spot prices. Fig. 3 shows the regulation requirements in 2020 and 2030. Apparently, in 2020, power system does not require regulation services in 6530 hours, while in 2030 the number is 225 hours. The reason for this big difference is that in 2030 the VRE penetration are much higher than it in 2020. The variability and uncertainty of VRE create more regulation requirements in 2030.

Fig. 4 and Fig. 5 further compare the market prices between 2020 and 2030. In Fig. 4, it can be seen that the accumulated average differences in 2030 (the green line) are much higher than it in 2020 (the yellow line). This reveals that in 2030, there maybe bigger revenue potentials in providing up regulation service. In Fig. 5, the green line is below than yellow line in some hours, which illustrates that the opportunities in providing down regulation services in 2030 may be better than 2020.

B. Simulation results with 2030 markets

Fig. 6 shows the statistics about how many hours that market require regulation service and how many hours the HPP provides regulation service. We can see that in 7132 hours in the year, system requires up regulation services. HPP provides the up regulation services in around 45% of the time. Similarly, in 2076 hours in the year, system requires down regulation services. In around 60% of the time, HPP provides the down regulation services. In total, HPP helps system balance in approximately half of the time.

We design two cases to understand the value of HPP on participating in balancing market. Case 1 is that HPP only

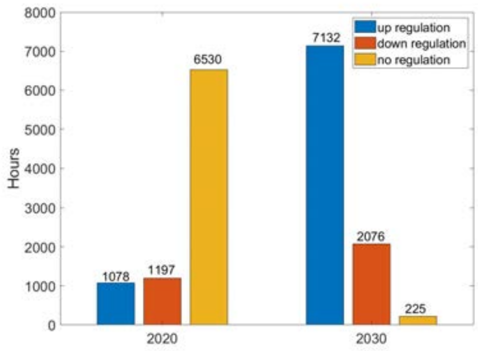

Fig. 3. Regulation requirements in 2020 and 2030

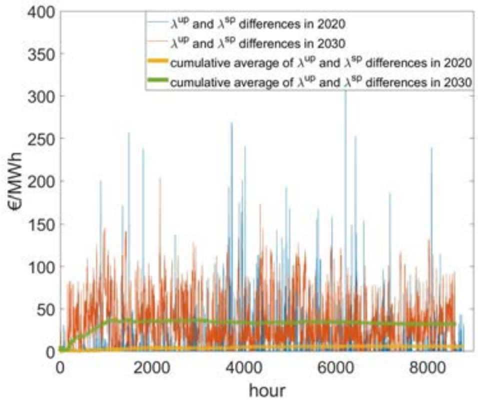

Fig. 4. Differences between balancing up prices and spot prices in 2020 and 2030

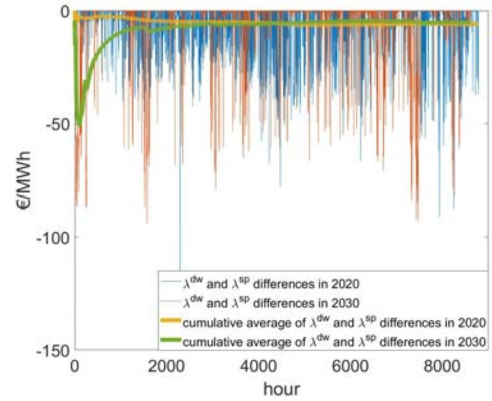

Fig. 5. Differences between balancing down prices and spot prices in 2020 and 2030

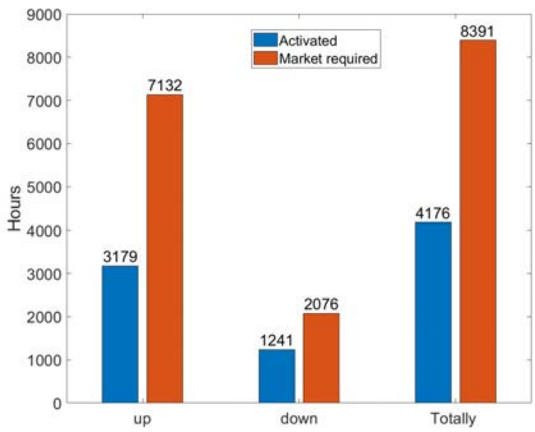

Fig. 6. Number of hours of activated and market required regulation power in the year

offers energy in spot market via the spot market optimization model in the previous section. This is a benchmark case. Case 2 is that HPP participates in both spot market and balancing market.

The accumulated profits over the year 2030 can be seen in Fig. 7. In this figure, we can see that participating in both spot and balance market earns 12.91 million €, which exceeds the profits of only participating in spot market by around 5.9%. More detailed comparison can be seen in Fig. 8, by participating in balancing market, HPP receives revenues of 14.25 million €, which is 11.2% more than only participating in spot market (12.81 million €). However, the degradation costs in Case 2 are almost doubled comparing with Case 1, i.e. the loss of battery lifetime is almost two times. This conforms with the intuition that in balancing market, battery is used more frequently. The profit potentials can be more higher if the battery cost decrease faster than expected.

V. Conclusion

This paper investigates energy management of HPP in balancing market through standard scenario based stochastic optimization. The comparison of 2020 market and 2030 market shows the potential of participating in balancing market for HPP. In the simulation setup, HPP is able to contribute to system balance by providing regulation services in almost half of the time. A comparison with benchmark case that HPP only participates in spot market reveals that balancing market has 11% revenue potentials for HPP. However, to capture the revenues, battery degradation needs to be around doubled. This makes the profit potentials of HPP in balancing market decrease to 5.9%.

It is noted that the results in this paper are based on several assumptions. The quality of price scenarios has impacts on the results. If the scenarios can cover the potential real price in a larger probability, some un-activated regulation power offers can be avoided, hence the profits can be higher than reported.

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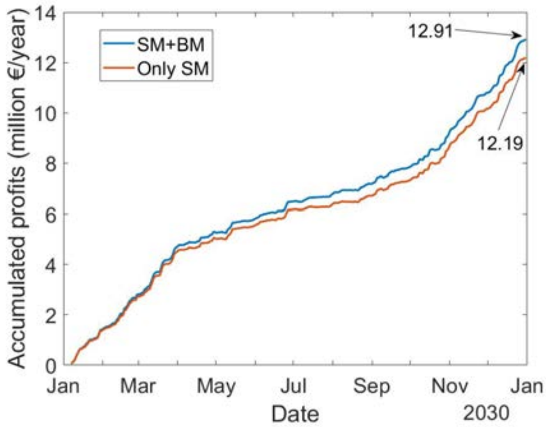

Fig. 7. Accumulated profits of two cases

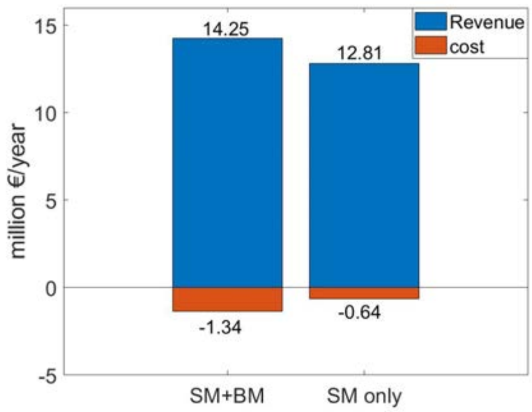

Fig. 8. Revenues and degradation costs of two cases

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