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Interfacing Energy Management with Supervisory Control for Hybrid Power Plants

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***Abstract*—Variability and uncertainties of wind and solar bring significant challenges into power system operation and control. Hybrid power plants (HPPs), which incorporates the complementary nature of wind and solar together with other technologies, such as energy storage, is a solution to cope with these challenges. To maximize the revenue and enable the operation of HPPs, the energy management system and the supervisory controller are both needed, namely the HPP EMS and the HPPC. The HPP EMS provides optimal dispatch strategies in order to maximize the revenue through market bids. Meanwhile, the HPPC executes dispatch plans from the HPP EMS in a real-time fashion. The paper highlights a new design of HPP EMS and HPPC with a focus on interface design between the two. The variables exchanged between the HPP EMS and the HPPC are presented, and practical issues such as time coordination and robustness over communication failure are discussed in detail.**

***Keywords*--Energy management, supervisory control, hybrid power plants.**

I. INTRODUCTION

Due to policy support and cost reduction, electricity from renewable energy sources has played an important role in power systems. However, variability and uncertainties of wind and solar bring significant challenges into power system operation and control. Hybrid power plants (HPPs), which incorporates the complementary nature of wind and solar together with other technologies, such as energy storage, is a solution to cope with such challenges [1]. To maximize the revenue and enable the operation of systems with such complexity, the HPP energy management system (HPP EMS) and the HPP controller (HPPC) are both in need. The objective of the HPP EMS is to make optimal bidding plans for the HPP that participates into markets, and the objective of the HPPC is to execute dispatch plans from the HPP EMS in real time.

HPPs, as a price taker, bidding in electricity markets has been investigated in many existing works [2]-[6]. Authors in [6] proposes an optimal offering strategy for wind-storage in day-ahead market. A linear decision rule is introduced to adjust day-ahead decisions in real-time operation. The following work [7] further studies HPPs, as a price maker, offering in electricity markets. The impact of HPP's offering on cleared prices and volumes is modeled via historical supply-demand curves, which is updated to market participants after about one month of operation day. Supervisory control for HPPs have also been explored in the recent studies. Authors in [8] describe the implementation of a HPPC that consists of a PI controller and a dispatch function. In a subsequent work [9], an online optimal dispatch algorithm is proposed for the HPPC to maximize the revenue, given the HPPC receives market prices from the HPP EMS. The HPPC design for advanced active power functions, like power smoothing and frequency control, have also been investigated in [10-12]. However, how the HPPC is interfaced with the HPP EMS remains to be studied.

The motivation of interfacing the HPP EMS and the HPPC is two-fold. First, with the interface in place, it is easy to better understand the interactions between the HPP EMS and the HPPC, and the influence of market-related functions on real-time control of the HPP. A mismatch is always expected between the actual dispatch and the dispatch schedule from the HPP EMS, since the HPP EMS and the HPPC have different operating objectives as well as control granularity. The interface allows this mismatch to be studied in detail. Second, the HPP EMS must be updated with the latest relevant information, such as the latest available energy capacity from energy storage, by the HPPC, to guarantee the accuracy of the optimization model. To date, few research studies address questions related to the interface between the HPP EMS and the HPPC. For example, what are the variables exchanged via the interface and in what time resolution? How to design the interface with considering robustness over communication failure?

To address these problems, this paper highlights a new design for the HPP EMS and the HPPC with a focus on designing an interface between the two. In this study, the electricity market for Nordic regions is considered, and the main scope focuses on reserve markets (RM), spot markets (SM) and balancing markets (BM). The HPP EMS is designed such that it optimally decides power reserve bids into RM, energy bids into SM, and regulation power bids in BM. The HPPC consists of two dispatch algorithms, active power dispatch (APD) that decides active power setpoints for each individual plant, and active power reserve dispatch (APRD) that decides the targets of frequency reserves for each individual plant. Section II presents the design of the HPP EMS and the HPPC. Section III describes the interface design and how the robustness over communication failure is taken into account. Simulation results are discussed in Section IV. Section V is the conclusion.

II. HPP EMS AND HPPC

As is shown in Fig. 1, the operation of electricity markets is sequential. The HPP submits bids and receives offer in different time scales for different markets. Before SM opens, the HPP knows the committed reserve power and prices in RM. The main energy trades for HPP happens in SM, which operates one day before the operation day and usually closes

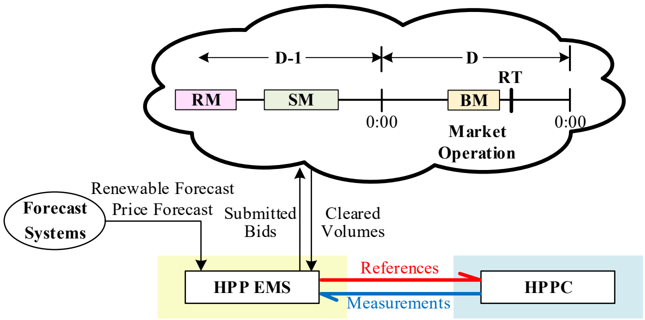


Fig. 1: An overview of interactions among markets, HPP EMS and HPPC.

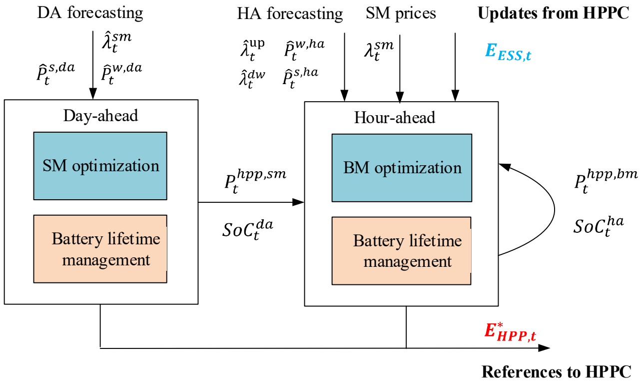


Fig. 2: An overview of EMS.

at 12:00. The SM price is then calculated by the market operator, and the traded volumes and prices are announced to the HPP subsequently. For the foreseen events, HPP is able to sell or buy energy in intraday market up to one hour before the real-time operation. To provide balancing services, HPP can bid regulation power in BM up to 45 minutes before the real-time operation [13]. The cleared regulation prices and volumes are known when time close to the real-time operation.

A. Design of HPP EMS

Fig. 2 presents the overview of EMS. In the EMS, we assume that reserve power is traded via long-term contracts. Therefore, the HPP EMS only includes spot market optimization (SMO) and balancing market optimization (BMO). SMO is applied for energy offers into SM incorporating day-ahead forecasting of spot prices $\hat{\lambda}_t^{sm}$ and RES power outputs $\hat{P}_t^{w,da}$, $\hat{P}_t^{s,da}$, while BMO is applied to re-optimize generation based on updated RES power forecasting $\hat{P}_t^{w,ha}$, $\hat{P}_t^{s,ha}$, balancing price forecasting $\hat{\lambda}_t^{up}$, $\hat{\lambda}_t^{dw}$ and realized information, e.g. state of charge (SoC). The main objective of the HPP EMS is to maximize the profits from markets and then generate active power and energy references for HPPC. The HPP EMS is a multi-time scale optimization model, where SMO run once a day to generate power and energy schedule and BMO runs hourly to update the schedules based on the most recent information. All energy schedules are 5 minutes basis. The models of SMO and BMO are as follows, respectively.

- SMO model:

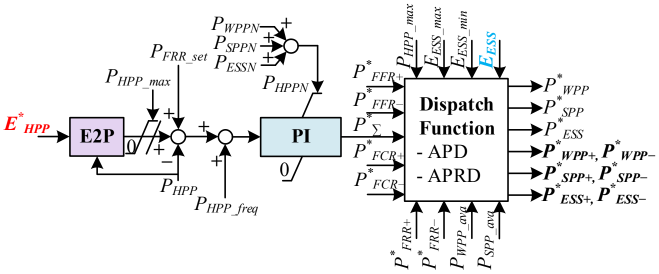


Fig. 3: HPPC diagram.

$$\max \sum_{t=1}^{24} \left(R_t^{sm} - C_t^{sm} \right)$$
$$s.t. \begin{cases} H\left(P_t^{sm,hp}, P_t^{RES,sm}, P_t^{b,sm}, SoC_t^{sm}\right) = 0 \\ G\left(P_t^{sm,hp}, P_t^{RES,sm}, P_t^{b,sm}, SoC_t^{sm}\right) \le 0 \end{cases}$$

where R_t^{sm} and C_t^{sm} are revenues from SM and battery degradation costs. $P_t^{sm,hp}$ is power offers of HPP in SM. $P_t^{RES,} = P_t^{w,sm} + P_t^{s,sm}$ is power dispatch of RES power including wind and solar power. $P_t^{b,sm} = P_t^{dis,} - P_t^{cha,sm}$ is power dispatch of batteries. The equality constraints represent power balance constraints and battery SoC evolution constraints; the inequality constraints include power and energy constraints of batteries, grid power constraints, RES power constraints.

- BMO model:

$$\max \sum_{t=1}^{24} \left(R_t^{bm} - C_t^{bm} \right)$$
$$s.t. \begin{cases} H\left(P_t^{bm,hpp}, P_t^{RES,b}, P_t^{b,bm}, SoC_t^{bm}, \Delta P_t^{up}, \Delta P_t^{dw}\right) = 0 \\ G\left(P_t^{bm,hp}, P_t^{RES,}, P_t^{b,bm}, SoC_t^{bm}, \Delta P_t^{up}, \Delta P_t^{dw}\right) \le 0 \end{cases}$$

where ΔP_t^{up} and ΔP_t^{dw} are up and down imbalance power between BM and SM schedules. Other variables are the similar to SM, but are for BM. The equality and inequality contains same constraints of SM as well as the calculation of imbalance power.

B. Design of HPPC

Fig. 3 presents the diagram of HPPC. Only active power control is discussed here. Reactive power control is beyond the scope of the paper and therefore not included here. The main HPPC blocks include E2P, anti-windup PI control and dispatch function. E2P converts energy reference into active power reference. The energy reference, E_{HPP}^{*}, corresponds to the energy block bid with the highest resolution, and is determined by a combination of the SM bid and the BM bid from the HPP EMS. The active power reference, subject to a saturation limiter and a rate limiter, compares the active power measurement at HPP point of connection P_{HPP}, and the error between the two passes the anti-windup PI controller. Extra control inputs are P_{FRR_set}, the active power setpoint for frequency restoration reserve activated by system operator, and P_{HPP_freq}, the cancellation signal for coordinating local frequency responses. The anti-windup PI controller is used to avoid error accumulation if there is any input error, and to constrain the output between zero and the HPP maximum capacity.

The HPP dispatch function consists of two dispatch algorithms, APD and APRD. Both algorithms run in real time to follow references from the HPP EMS. APD, which is a rule-based control, determines the operating mode for wind power plants (WPP) and solar power plants (SPP) (i.e. maximum power or power curtailment) as well as the operating mode for energy storage systems (ESS) (i.e. charge, discharge or standby) and the charging/discharging rate. APRD is implemented using a priority list where the reserve requirement is always firstly allocated to the power plant with the highest priority, followed by the second highest priority plant, and so on so forth, until the requirement is fully met. In the HPPC design, APRD is assigned to a higher priority than APD because there is a heavy penalty incurred by the failure of securing the reserve. Besides, there is a trade-off between active power regulation and frequency reserve. Once the APRD updates the operating limit for each power plant based on the secured reserve, the operating range to participate in APD is limited. It is assumed that the trade-off is handled by the HPP EMS, which optimizes the bids between energy markets and ancillary service markets.

III. INTERFACE DESIGN

Variables from the HPP EMS to the HPPC include energy reference E^*_{HPP} and reserve references P^*_{FFR+}, P^*_{FFR-}, P^*_{FCR+}, P^*_{FCR-}, P^*_{FRR+} and P^*_{FRR-}. All the references are designed to have 288 reference points for the whole day schedule with the resolution of 5 minutes. The energy reference E^*_{HPP} is updated every 5 minute and tracked by the PI control, along with the APD. It is updated by two dispatch plans sent from the HPP EMS to the HPPC. One is a day-ahead dispatch plan (DADP) with one-day time horizon and one-day update rate. The other is an hour-ahead dispatch plan (HADP) with one-hour time horizon and one-hour update rate. The DADP is sent to the HPPC on the day ahead when the volume and price of SM bids for the whole day are known to the HPP EMS. Although the DADP has 5-minute time resolution, energy references within the hour can have identical values if the time resolution of SMO is larger than 5 minutes. The HADP is sent to the HPPC one hour ahead, when the volume and price of BM bids are known to the HPP EMS. The HADP only updates 12 reference points within the hour on top of the DADP. Fig. 4 and Table I show an example of the energy reference obtained from these two dispatch plans.

The reserve references for each frequency service are updated every day and sent on the day ahead when the volume and price of reserve bids are known to the HPP EMS. It is assumed in this paper that the volume is identical within the day. However, the design can accommodate various bid requirements if other market operators allow reserve volume to vary during the day.

Variables from the HPPC to the HPP EMS include the latest ESS available energy E_{ESS} at the beginning of each hour, in order to make sure the HPP EMS accurately optimizes the utilization of the ESS in both BMO and SMO. This variable is updated every hour. The latest ESS available energy is used for the HADP for the next hour.

TABLE I
AN EXAMPLE OF DISPATCH PLANS AND ENERGY REFERENCES

Time (hh:mm)	**07:00**	**07:05**	**07:10**	**07:15**	**07:20**	**07:25**
DADP (MWh)	10	10	10	10	10	10
HADP (MWh)	-0.5	-0.2	0.1	0.5	0.8	-0.2
E^*_{HPP} (MWh)	9.5	9.2	9.9	10.5	10.8	9.8
Time (hh:mm)	**07:30**	**07:35**	**07:40**	**07:45**	**07:50**	**07:55**
DADP (MWh)	10	10	10	10	10	10
HADP (MWh)	-0.6	0.2	0.6	0.9	1.1	1.3
E^*_{HPP} (MWh)	9.4	10.2	10.6	10.9	11.1	11.3

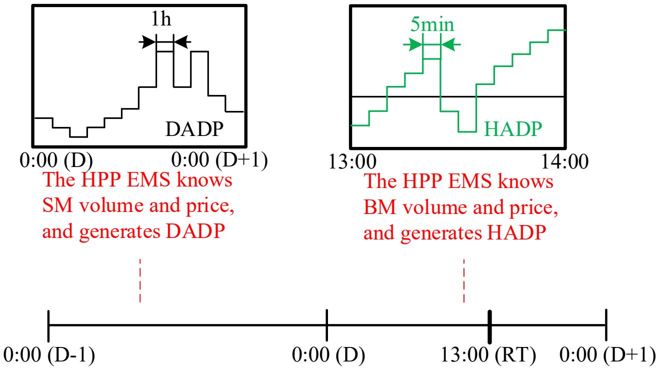


Fig. 4: An example of dispatch plans from HPP EMS.

The above-mentioned interface enhances the robustness over communication failure by designing dispatch plans as time series data instead of single reference point. In terms of short-term communication failure, the HPP still maintains the optimal operation. In the case where communication failure lasts for over 1 hour, the worst case is when the latest HADP is not able to reach the HPPC. However, the HPPC should still follow the DADP schedule for every hour.

IV. SIMULATION RESULTS

In this study, the electricity market for eastern Denmark is considered. For simplicity, the following assumptions are made: 1) the HPP does not trade in the intraday market; 2) in ancillary services market, the HPP promises reserve capacities for frequency support by long-term contract. Zero reserve bids are assumed. The HPP consists of 120 MW WPP, 40 MW SPP and 10MW/30MWh ESS. The dynamic model of the HPP is developed in MATLAB/Simulink while the EMS optimization model presented in the previous section are solved using the simplex solver of IBM Decision Optimization Studio CPLEX through the docplex python library [14]. The historical data for wind speed and solar irradiance is generated by a modeling tool CorRES [15-16] using ERA5 analysis data [17] and used as the input for both dynamic model and forecast system, as shown in Fig. 5. A two-hour window from 13:00 to 15:00 is chosen when both solar irradiance and wind speed are nontrivial.

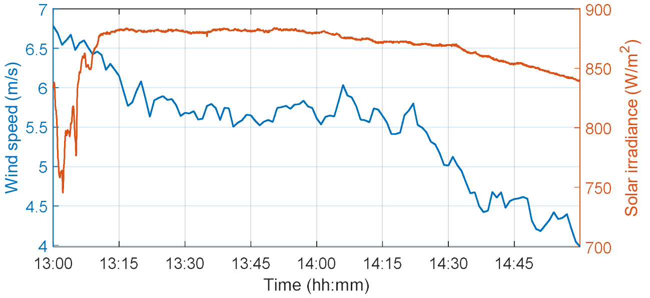


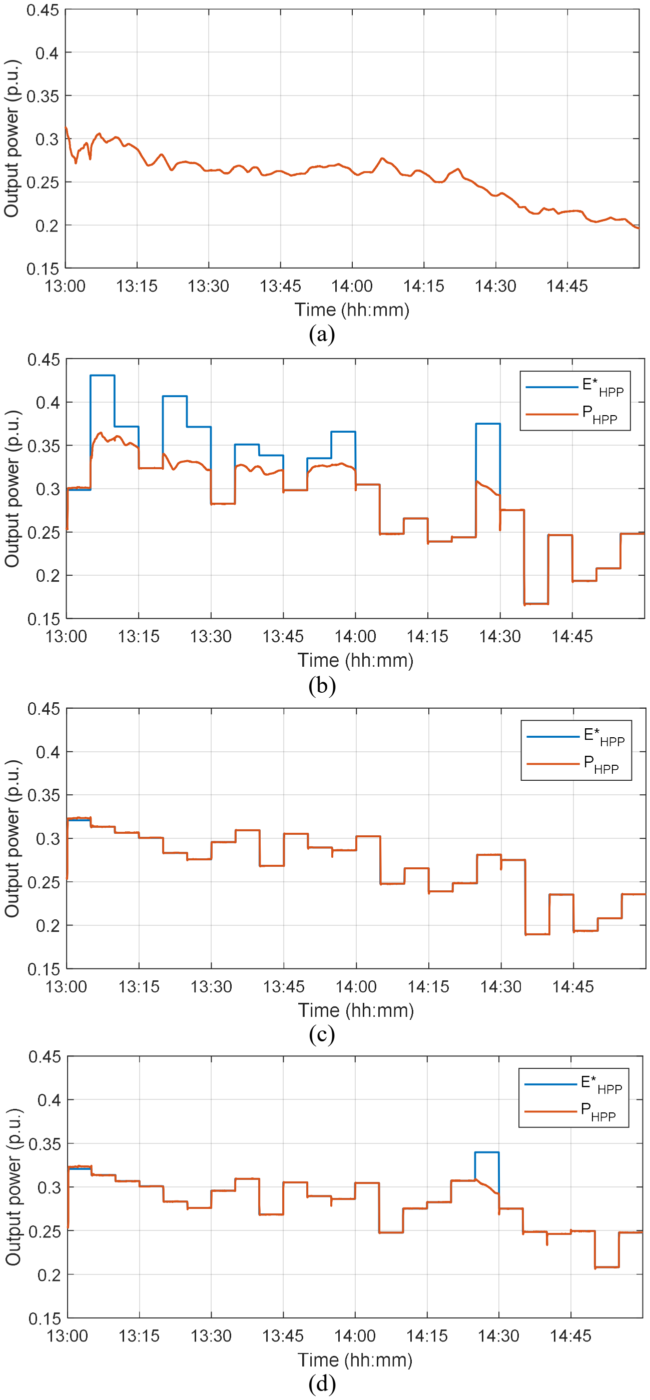
Fig. 5: Historical data for wind speed and solar irradiance generated by CorRES.

TABLE II
DESCRIPTION OF CASE STUDIES

Case #	Description	Period of Communication Failure
1	No dispatch plan received	From prior to 14:00 (D-1) to 15:00 (D).
2	Only DADP received	From 14:00 (D-1) to 15:00 (D).
3	Both DADP and HADP received, E_{ESS} update failure	From 12:00 (D) to 15:00 (D).
4	Both DADP and HADP received, E_{ESS} update success	From 12:00 (D) to 13:00 (D).

Four case studies are defined to validate the effectiveness of the proposed interface design. Table II shows the definition of each case. **Case 1** is a base case corresponding to an extended communication failure event where no dispatch plan from the HPP EMS reaches the HPPC. To maintain operation, the HPPC operates WPP and SPP at maximum power without charging or discharging ESS. In **Case 2**, a communication failure event leads to the interruption of the communication for the HADP. The HPPC operates only based on the DADP that was received by the HPPC before the event occurs. In **Case 3**, the HADP is received and followed by the HPPC. However, due to the communication failure event, the latest ESS available energy at 13:00 is not updated for the HPP EMS. Therefore, the HADP for 14:00 to 15:00 is based on the estimated ESS available energy from the HPP EMS. **Case 4** is when all the variables are communicated properly. For illustration purpose, it is assumed that the DADP is sent every 14:00 on the day ahead. The communication failure event for each case is also identified in Table II.

Fig. 6 shows how the HPPC follows energy reference E^*_{HPP} received from the HPP EMS. In Fig. 6 (a), no energy reference is received by the HPPC, and then the HPPC operates the WPP and the SPP at maximum power. In Fig. 6 (b), the mismatch between the reference and the actual output can be clearly seen. It is because the HPPC only has access to the DADP, which is based on an inaccurate day-ahead forecast. Fig. 6 (c) and Fig. 6 (d) both show that the energy references are closely followed in both cases, thanks to the HADP obtained via a more accurate hour-ahead forecast. The difference between Case 3 and Case 4 only lies in the hour from 14:00 to 15:00. No mismatch is seen in Case 3 while a mismatch occurs from 14:25 to 14:30 in Case 4. In Case 3, without the latest ESS available energy at 13:00, the HPP EMS only uses the updated value from 12:00 and then generates a more conservative HADP because the estimation for the ESS available energy at 13:00 is much lower than the actual value. Therefore, the HADP for the hour from 14:00 to 15:00 is followed without any mismatch. However, in Case 4, with the latest ESS available energy at 13:00, which is larger than the one in Case 3, the HPP EMS generates an HADP for the hour from 14:00 to 15:00 that sells more energy than that in Case 3. Due to forecast error, the HPPC



(a)

(b)

(c)

(d)

Fig. 6: Simulation results for the HPPC dispatch following energy reference from the HPP EMS: (a) Case 1, (b) Case 2, (c) Case 3, and (d) Case 4.

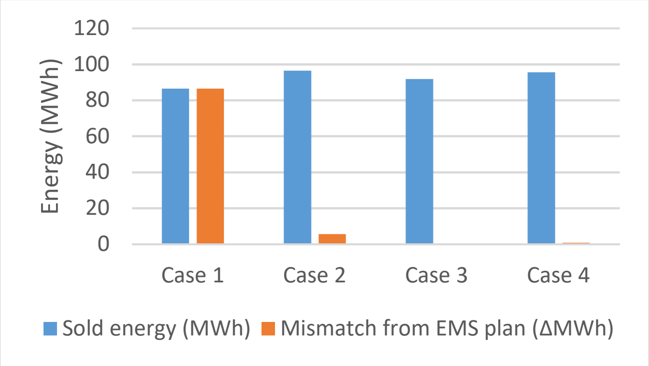


Fig. 7: Sold energy and its mismatch from the HPP EMS dispatch plan for each case.

can't compensate the mismatch from 14:25 to 14:30 even if the ESS operates at maximum discharging rate.

From Fig. 7, it can be seen that the sold energy is the lowest in Case 1, as the communication fails and the ESS stands by. The highest sold energy is found in Case 2, where the HPPC follows the DADP. However, there is 5.5 MWh mismatch from the DADP as the DADP overestimates the available power. This scheme leads to a deeper discharging of the ESS during the communication failure, which results in suboptimal operation for the whole day. In both Case 3 and Case 4, the mismatch is minimal. The difference between Case 3 and Case 4 is explained as above. Note that, if, in Case 3, the HPP EMS estimates a higher ESS available energy at 13:00 than the true value, and is not updated, a large mismatch is still expected.

V. CONCLUSION

The paper presents a novel design for the HPP EMS and the HPPC, with detailed discussion on interfacing the two. Under the proposed design, the references from the HPP EMS are time series data instead of single data point. This design improves the system robustness against communication failure as both DADP and HADP are 'preloaded' in the HPPC. For short-term communication failure, the optimal operation is unaffected. For longer communication failure when the latest HADP from the EMS can't reach the HPPC, the HPPC still operates the system using the DADP. For communication failure that lasts even longer, heuristic control can be designed to maintain the HPP operation, such as running renewable power plants at maximum power. However, it could imply a potential revenue loss for the HPP.

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