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DEMAND RESPONSE FROM OPEN CANAL SYSTEMS IN THE DUTCH DELTA

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ABSTRACT

Participation in demand response (DR) has been explored for many large energy using assets based on day-ahead markets. However, little is known about the use of multiple energy markets or DR for open canal systems. In this article, we propose the use of multiple flexible energy markets to enable DR for open canal systems in the Netherlands, where many large pumping stations are used for flood mitigation. We observed that the Dutch market is not yet rewarding DR, with relatively low-priced fixed-price contracts. However, when applied to the German market scenario, a cost saving of 13% was found. In conclusion, the method of combining two flexible energy markets seems successful. However, more simulations and research are needed to explore the full potential.

Keywords: renewable energy, model predictive control, demand response, water systems, flood safety, energy markets.

1. INTRODUCTION

The Netherlands is a low-lying country in the Rhine-Meuse delta. The rivers Rhine, Meuse and Scheldt flow through the Netherlands. Besides that, a large part of the country lies below mean sea level (MSL). This makes managing water-levels of local and national water necessary.

The water-levels and type of management are decided locally by a Water board or nationally by Rijkswaterstaat (RWS), and are typically based on the agricultural needs, land-subsidence, shipping and flood probabilities. In the big canals and rivers there is room for more fluctuating water levels. This range makes it possible for the pumps to have a more flexible pump-schedule, to increase sustainable energy consumption. Demand response can be applied. This would reduce the carbon-emission caused by the pumping stations, and could contribute to stabilizing the Dutch electricity-grid.

2. ENERGY MARKETS

2.1 Day ahead market

The Dutch day ahead market (DAM) is governed by EPEX-group, and called the APX-market. The market closes at 12:00 CET, when the hourly day ahead prices for the next day are published simultaneously.

Since the prices are not known when bidding on the market, a SARIMA[2] model was used to forecast the day ahead price. This predicted price will be used in the optimization, while the actual price was used to calculate costs.

Fig 2 The NZK-ARK water system [2]

2.2 Intraday market

The Dutch intraday market (IDM), also governed by EPEX-group, is where 15-minute blocks of energy are traded up to 5 minutes before consumption. This time advantage gives it a higher potential for the trading of sustainable energy, since uncertainty in production is reduced.

Intraday market data is not freely available from EPEX-group, so a 25% random deviation around the day ahead market price was assumed.

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2.3 *Market strategy*

Combining the day ahead market and intraday market gives the energy security that is needed to maintain water safety standards. The use of the intraday market allows the pumping station to use of sustainable energy, while also allowing to correct for unforeseen circumstances and/or events.

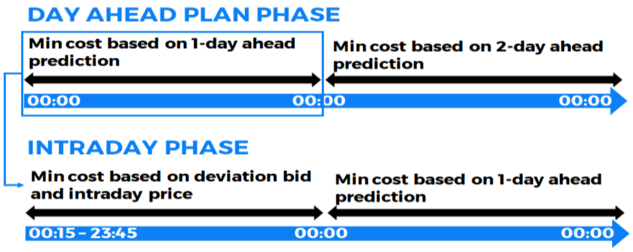

Fig 1 Market strategy

The market strategy applied can be seen in Figure 1. First, a plan is made based on the predicted day ahead price. After which, for the remaining time of the bid, a deviation of the plan is allowed at the cost of the intraday market price. For the remaining time of the prediction horizon, the cost are minimized based on the predicted day ahead price.

3. STUDY AREA

3.1 *General information*

The area that was studied for DR purposes is the water system of the Noordzeekanaal—Amsterdam-Rijnkanaal. This canal has 4 local water authorities discharging excess rainfall into the system. The canal is in open connection with the city waters of Amsterdam, and has to maintain ship traffic towards the port of Amsterdam. The water system is depicted in Figure 2.

The water system receives water from the lower tributaries of the Rhine, and from the Markermeer. At IJmuiden, a pumping station and gate-complex is constructed. The undershot gates are used to discharge water when the sea-level is low enough, the pumping station is used when the North Sea is too high to discharge under gravity.

The canal is managed for the water-level to be in between -0.3m NAP and -0.5m NAP.

3.2 *Controlled structures*

In this study, the pumping station in IJmuiden is controlled together with the gate-complex. The pumping station consists of 6 pumps with different specifications, who together can discharge up to 260 m^3/s. The pumping station has been modelled as one single pump, with properties of the 6 combined pumps. The Q-dH curves have been combined in a way that the controller never overestimates the maximum possible discharge. The power curve of the pumping station was achieved by optimizing the 6 pumps separately for all feasible combinations of discharge and pump-height. This was done using GUROBI[4] as solver, with the objective to minimize energy use for all feasible combinations of discharge and pump-height. A power-curve, more elaborately described in [5], was fitted over the results of the optimization.

The gates can be used to discharge up to 500 m^3/s. The original undershot-gate formula was piecewise linearized, since water-level differences can become negative. This makes undershot gates typically hard to formulate optimization problems. Beside the piecewise linearization, a slack variable is introduced, which together with a complementary constraint acts as a binary switch to indicate that the sea water-level is lower than the minimum required to overcome density differences between salt and fresh water.

4. OPTIMIZATION PROBLEM

4.1 *Methods*

The optimization problem is solved using the continuous NLP-solver IPOPT[6], where the python optimization modeling language Pyomo[7,8] was used to formulate the problems and interface with IPOPT.

4.2 *Constraints*

The following constraints were implemented in the optimization problem.

- Water level range (min/max)
- Wind effect on water level
- Volume balance
- Storage-water level relationship
- Maximum gate discharge
- Maximum pump discharge
- Pump power consumption

A complete formulation of the problem and internal model schematics can be found in [7].

4.3 Objectives

4.2.1 Day ahead planning phase

The objective function

$$\min_{(\cdot)}(f_1+f_2+\underbrace{\sum_{t=0}^{N}(P[t]*\frac{\Delta t}{3600*10^{-3}}*c_{DA}[t])}_{\text{day ahead bid}}), \tag{1}$$

was used to create the day ahead plan. Where f_1 and f_2 result from the slack variables in the optimization problem, as described in [5]. P[t] is the pump power consumption at time t, N the prediction horizon length, Δt the timestep size (15 minutes) and $c_{DA}[t]$ the DAM price at time t.

4.2.2 Intraday trading phase

The objective function

$$\min_{(\cdot)}(f_1+f_2+\underbrace{\sum_{t=0}^{t_d}((P[t]*\frac{\Delta t}{3600*10^{-3}}-E_{plan}[t])*c_{ID}[t])}_{\text{intraday trading}} + \underbrace{\sum_{t=t_d}^{N}(P[t]*\frac{\Delta t}{3600*10^{-3}}*c_{DA}[t])}_{\text{day ahead bid preparation}}, \tag{2}$$

was used for intraday trading purposes. Where $E_{plan}[t]$ is the energy bought on the DAM at time t, t_d the time at IDM trading switches to DAM trading and $c_{ID}[t]$ the IDM price at time t.

5. RESULTS AND DISCUSSION

5.1 Fluxes and trading

Dutch Market

Figure 3 shows the actual and planned (at time of day ahead plan) control actions and fluxes of the system. The figure shows that the MPC decided to pump at times the water level difference is low, resulting in a low energy use.

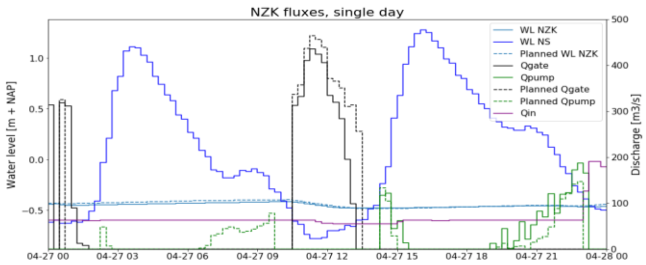

Fig 3 Fluxes of the NZK, plan at time of DAM bid and after IDM optimization

Figure 4 shows the planned and actual energy use, combined with the energy market prices. It can be seen that the MPC generally buys energy when the price is low. It can also be seen that the MPC traded energy bought on the DAM on the IDM for advantageous rates.

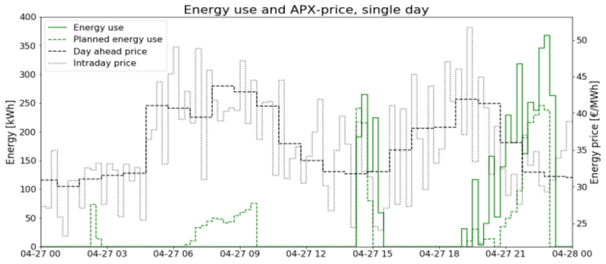

Fig 4 Energy use and price, plan at time of DAM bid and after IDM optimization

German market:

When applying the MPC to German market data, a negative price occurred (Figure 6). This changes the MPC's incentive to optimally reduce its energy use, to maximizing it. This can be seen through the increased gate discharge (Figure 5), right before the time of pumping. Increasing the energy use of pumping. In the reference scenario, where energy use was minimized, the MPC did not make use of the pumping station at all in the same period.

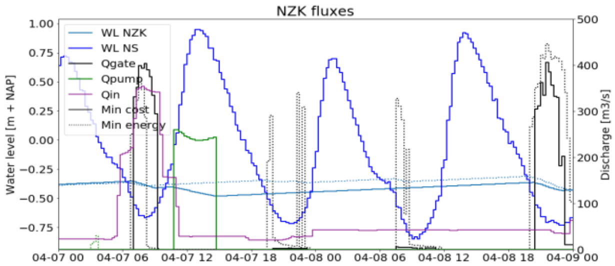

Fig 5 Fluxes of the NZK, scenarios where cost and energy use are minimized

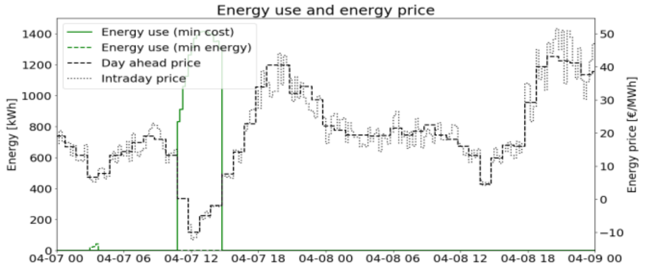

Fig 6 Energy use and price, scenarios where cost and energy use are minimized

5.2 Receding horizon implementation

Figure 7 shows the cumulative cost for the energy use of the pumping station for a scenario where cost was minimized using the DAM and IDM, and a scenario where energy use was minimized, combined with a fixed price contract (ENDEX).

It can be seen that using flexible energy markets is not yet rewarding in the Netherlands, due to low-priced fixed price contracts. The German market has relatively high priced fixed-price contracts, and shows a 13% cost decrease after a month.

Table 1 shows that CO_2 emission increases in both markets. Indicating that the relationship between renewable energy and energy price is not yet strong enough to cause CO_2 emission savings. Secondary CO_2 savings (preventing a more polluting source to be active at a later moment) are not well quantifiable. However, in the German market it can be partially explained by the negative energy price, effectively maximizing the energy use.

The amount of energy sold on the intraday market is expressed as regulating volume, since the energy is sold at times with high prices, and thus scarcity. The results show that the German market caused higher incentives to sell. This can be explained by a higher variation in prices, however this is also affected by the assumed IDM prices.

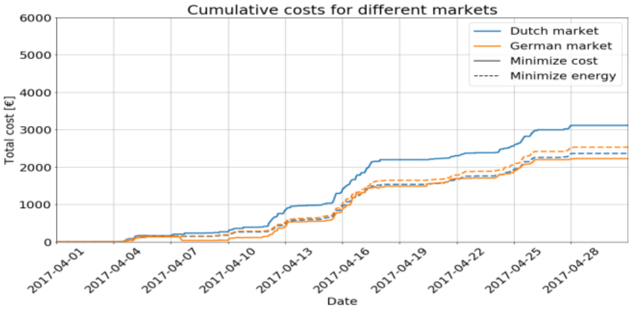

Fig 7 Cumulative cost for Dutch and German market

	Dutch	German
Cost	+5%	-12%
CO2	+20%	+26%
Reg.vol.	25MWh	41MWh

Table 1 Summarized MPC performance on Dutch and German markets, relative changes in performance of minimizing cost compared to minimizing energy use .

6. CONCLUSION

Participating on the day ahead market gives more certainty of supply and costs. The intraday market (IDM) on the other hand allows for short-notice trading, to make up for unforeseen events or dealing with uncertainties in the state of the open-canal system. The IDM also has a large potential for the trading of renewable energy, making the market more interesting for grid balancing purposes. A larger profit can be realized when prices fluctuate more, which is expected when renewable energy becomes more present on the grid. This can be seen in the difference between German and Dutch market scenarios analyzed. Although the CO_2 savings are not yet present or well quantifiable (either through secondary CO_2 savings, or a lack of production data), DR makes room for sustainable energy on the grid.

The research presented in this paper was performed with a perfect knowledge on incoming discharge, wind and IDM price. More research will be performed on the influence of these uncertainties on the MPC performance.

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