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Coupling of weather forecasts and smart grid-control of wastewater inlet to Kolding WWTP (Denmark)

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Abstract

The increasing focus on renewable energy sources has caused many countries to initiate a shift to a more intelligent and flexible electricity system – the Smart Grid. This allows for the optimization of the electricity consumption according to the fluctuation in electricity prices. In this study four strategies for controlling the wastewater flow to Kolding Central wastewater treatment plant (WWTP) based on the Smart Grid concept are investigated. The control strategies use the storage volume in the pipe system upstream the WWTP to detain water during hours with high electricity prices, releasing the water when the price decreases. A lumped conceptual model was constructed based an existing highly detailed hydrodynamic model of the catchment. The conceptual model was used to assess the performance of the four control strategies, which were evaluated based on savings in operation cost and emitted CO_2 equivalents. Weather forecasts were used to empty out the system prior to a rain event, ensuring that the control strategies did not lead to increases in combined sewer overflow. The largest savings obtained were 833 EUR/month and 3909 kg CO_2 equivalents/month, which were achieved by only sending wastewater to the treatment plant during the six cheapest hours of the day. The savings achieved with the other control strategies were however in the ranges 65–300 EUR/month and 196–910 kg CO_2 equivalents/month. These evaluations were generally done with limited storage space of just around 20 % of the daily wastewater flow and relatively simplistic control schemes. Larger savings would be anticipated with more complex control schemes utilizing larger storage volumes.

Keywords

Smart Grid, Renewable energy, Model Predictive Control, Numerical Weather Prediction, Real Time Control, Model Predictive Control, Dry-weather flow, Sewer system, Wastewater Treatment plant.

INTRODUCTION

The role of renewable energy sources in electricity production is increasing (UNEP, 2015): for example, the members of the European Union (EU) are committed to achieve a 20 % energy consumption from renewable sources by 2020, and a target of 27 % has already been set for 2030 (European Commission, 2015). Denmark has defined even more ambitious targets: to cover half of the electricity consumption with wind power by 2020 and to completely rely on renewable energy sources for the energy supply by 2050 (Klima-, Energi- og Bygningsministeriet, 2015). The implementation of renewable energy puts a lot of pressure on the existing electricity network, which is generally too rigid and not well suited for this shift in electricity production. As a consequence, several countries are making efforts to implement a more intelligent and flexible electricity network – the Smart Grid (Dansk Energi and Energinet.dk, 2010; ENBALA Power Networks, 2011).

Essentially, the Smart Grid tries to re-distribute energy consumption in the systems by using electricity prices as incentive for the consumer to move non-essential electricity consumption to hours of the day where prices are lower (and the system is less strained). It is believed that moving the electricity consumption from strained and expensive hours of the day to cheaper hours will yields both an economic profit and environmental benefits (Dansk Energi and Energinet.dk, 2010).

The existing literature reports only few examples dealing with the potential of Smart Grid control on wastewater treatment plants (WWTP) (Leu et al., 2009; ESWA. 2014; Aymerich et al., 2015; Rieger et al., 2015). The findings have generally been positive, but somewhat limited by the rigidity in process operations and the limited storage capacity at the plants (Leu et al., 2009). To our knowledge, the potential for utilizing the storage capacity of urban drainage networks upstream the WWTP in order to optimize its electricity consumption has not been investigated yet.

This study investigates the potential for integrating the storage capacity of the sewer network as part of a Smart-Grid control of a WWTP. Four control strategies are compared, each utilizing the storage volume in the drainage system in different manners and thereby controlling the inlet to the WWTP, leading to reduced costs for transport (pumping) and treatment of wastewater (mainly aeration). The strategies are compared for the Kolding catchment area (Denmark), for which both a conceptual and a detailed hydrodynamic model are available. The effects of the control strategies are evaluated based on savings in the monetary operation cost and savings in emitted CO_2 equivalents. Weather forecasts were used to empty out the system prior to a rain event, as it was essential that the control strategies did not lead to increases in combined sewer overflow (CSO). To estimate both the full- and the realistic potential of the control strategies they were tested with “perfect” forecasts (i.e. using recorded rainfall time series shifted in time), “surrogate radar” forecasts (perfect rain gauge information from a gauge at a nearby location) and numerical weather predictions (NWP), dependent on the required forecast horizon.

MATERIAL AND METHODS

Case study - Kolding

The combined sewer system of Kolding city consists of three main pipes that transport the water from a total drainage area of 1,300 ha to the area around downtown, where a pre-treatment plant is located. Additionally the pre-treatment plan receives wastewater from an area of 2,000 ha (separate system) (Nielsen et al., 2010). At the pre-treatment plant the water is treated for large particles, sand and fat before it is transported 8 km to Kolding Central WWTP where it undergoes chemical and biological treatment (Kolding Spildevand AS, 2013). Kolding Central WWTP has a capacity of 125,000 person equivalent (PE) and an average load rate of 65 % (Kolding Spildevand AS, 2013). The water is first pumped 6 km and 36 vertical meters and then gravitates the last 2 km. Due to the water filled pipe in the first part of the stretch, the delay in flow from the pre-treatment plant to Kolding Central WWTP is only 30 min, whereas the residence time is approximately 3 hours.

During dry-weather, water only enters the pre-treatment plant through a pumping station (P1), which has a maximum pump capacity of 1500 L/s. In the pipe system just upstream of P1, a total storage capacity of 4,000 m^3 has been estimated. This storage volume in the pipes leading down to P1 is the storage volume that is utilised in the control strategies. Since 2011 a system-wise rule-based Real Time Control (RTC) strategy has been implemented in the Kolding sewer network to reduce combined sewer overflow (Kolding Spildevand AS, 2013). Additionally a RTC for optimization of the treatment processes at Kolding Central WWTP is in place to ensure that the treatment is done as energy efficient as possible (Kolding Spildevand AS, 2013)**.** Initial tests have shown that water can be detained in the sewer system for 12 hours, possibly longer, without affecting the treatment.

Modelling tools

A detailed Mike Urban (MU) model was available for the Kolding study area. This model provides an accurate description of unsteady flow in pipes and channels (DHI, 2015), but with long computation times. For the implementation of model predictive control (MPC) strategies, as investigated in this study, it is essential to have short computation times. This allows for running a large number of scenarios within a short time period. Therefore, a simpler (and faster) conceptual model of the Kolding system was developed, based on the WaterAspects (WA) software (Grum et al., 2004). WA is based on time-area method with simple transport functions in the pipes: it is therefore capable of estimating Combined Sewer Overflow (CSO) volumes, but it fails to simulate more complex hydraulic processes, such as backwater effects.

Control strategies

Four control strategies to optimize the wastewater flow from the pre-treatment plant were investigated in this project (Table 1). All the control strategies store wastewater during periods with high power prices by exploiting the storage volume in the pipe system just upstream pumping station P1, as well as by controlling its outlet. Consequently, by modifying the wastewater flow, it is possible to move the energy consumption from expensive to cheaper hours of the day. The control strategies should not interfere with the primary function of the drainage systems, i.e. they should not lead to an increase in the risk of flooding and CSO. Therefore, the Smart Grid control operates only during dry weather periods. When rain is forecasted the drainage system is emptied and the control returns to the existing RTC strategy.

Performance Indicators for Control Strategies

The performance of the control strategies are evaluated based on cost savings and savings in CO_2 emissions. This requires translating flow volumes [m^3] into electricity consumption [MWh]. In this study the transportation of wastewater from the pre-treatment plant and the treatment of wastewater at Kolding Central WWTP are the only energy consuming processes included. The average flow from the pre-treatment plant to Kolding Central WWTP from 2009-2013 was 10,200,000 m^3/year (Kolding Spildevand AS, 2013). In this period the average electricity consumption for pumping water from the pre-treatment was 1470 MWh/year and the average electricity consumption at Kolding Central WWTP was 2725 MWh/year. Assuming a linear relation between water volume and the energy consumption and that 65 % at the electricity consumption at Kolding Central WWTP is used for wastewater treatment (Siemens, 2015) conversion factors were found to be 144 Wh/m^3 for the pre-treatment plant (F_{Pre}) and 174 Wh/m^3 for Kolding Central WWTP (F_{KC}).

As the delay in flow from the pre-treatment plant to Kolding Central WWTP is 30 min the electricity cost or the amount of MWh produced from wind power at the i-th time step, can be calculated using:

$$Y_i = Q_i * X_i * F_{Pre} + Q_{i-30min} * X_{i-30\,min} * F_{KC} \qquad (1)$$

where Q_i is the flow from the pre-treatment plant at time step i; $Q_{i\text{-}30\ min}$ is the flow from the pre-treatment plant 30 minutes earlier. To calculate the electricity cost in a given time step (Y_i = total electricity cost in time step i) X_i denotes the electricity price in time step i (P_i) and $X_{i\text{-}30\ min}$ denotes the electricity price 30 minutes ago ($P_{i\text{-}30\ min}$). In this study historic hourly electricity prices from the Nord Pools Spot market (Energinet.dk (a), 2015) was used, as this corresponds approximate to the electricity price Kolding Spildevand AS is settled in accordance with. To calculate the amount of wind power in a given time step (Y_i = total amount of wind power in time step i) X_i denotes the fraction of wind power in time step i (W_i) and $X_{i\text{-}30\ min}$ denotes the fraction of wind power 30 minutes ago ($W_{i\text{-}30\ min}$). The fraction of wind power in a given hour was determined by dividing the wind power production of a given hour with the sum of the primary-, local- and wind power production of that hour (Energinet.dk (b), 2015). The energy shifted to wind power was translated into kg saved CO_2 equivalents by using a factor of 0.542 kg CO_2 saved for each kWh (Rensmart, 2015).

Control Strategy I – Diurnal Flow Equalization. Studies have showed that even small shifts in peak hour consumption could result in considerable cost savings (Spees and Lave, 2008). This control strategy therefore aims at equalizing the flow throughout the day. Examinations of historic dry-weather flow data from 2014, to the pre-treatment plant showed that average wastewater flows of 20346 m^3 during weekdays and 19494 m^3 during weekends. The control is set to keep a constant outlet capacity from P1 of 239 L/s during weekdays and 228 L/s in the weekend. One hour prior to a forecasted rain event the system is emptied out with a capacity of 1,000 L/s. At the beginning of a rain event the existing RTC is activated and runs until the system is completely emptied.

Control Strategy II – Flow Scaling Based on Mean Energy Price. This control strategy determines the outlet capacity of P1 for a given hour based on how the electricity price of that hour deviates from the average electricity price of that particular day:

$$Q_{Out}(hour;day) = Q_{ave}(day)\left(1 + \frac{P_{ave}(day) - P(hour;day)}{P_{ave}\,(day)}\right) \tag{2}$$

where $Q_{Out}(hour;day)$ is the outlet capacity of a specific hour of a specific day; $Q_{ave}(day)$ is the average wastewater flow of that day (235 L/s for weekdays and 226 L/s for weekends); $P_{ave}(day)$ is the average electricity price of that day and P(hour;day) is the electricity price of the specific hour of that day. To test the impact of available storage capacity this control strategy is tested with a storage capacity of 4,000 m^3 and 20,000 m^3. For the version with a storage volume of 4,000 m^3 the outlet capacity is set to 1250 L/s to empty the system if rain is forecasted within the subsequent 2 hours. The same holds true for the version with a 20,000 m^3 storage volume if rain is forecasted within the subsequent 6 hours. The existing RTC is activated at the beginning of the rain event and remain active until the system is once again emptied. To ensure that the control strategy does not store too much water in the sewer system the outlet capacity is set to 500 L/s for the duration of 1 hour, if the storage volume upstream of P1 is full.

Control Strategy III – Flow During Six Cheapest Hours of the Day. This control only leads water to the pre-treatment plant during the six cheapest hours of the day. During these hours the outlet capacity is set to 1,000 L/s. This means that wastewater will potentially be retained for 18 consecutive hours. Therefore, a substantial storage capacity of 20,000 is required. A 6-hour forecast horizon is used and the outlet capacity is set to 1250 L/s if rain is forecasted in the following 6 hours. In the case of rain the existing RTC is activated and runs for the duration of the rain event. The rainwater that remains in the sewer system once the rain event ends will therefore be controlled in accordance with control strategy III. To prevent overflow from the system the outlet capacity is raised to 500 L/s for the duration of 1 hour, if the storage volume upstream of P1 is full.

Control Strategy IV –Optimization using Dynamically Dimensioned Search Algorithm. This strategy uses the Dynamically Dimensioned Search (DDS) algorithm (Tolson and Shoemaker, 2007) to optimize the flow from P1. A Fourier series is used to express the diurnal wastewater flow variations from the catchments upstream from P1:

$$Q_i = \mu + a_0 * \sin\left(\frac{i}{1440} * 2\pi + b_0\right) + a_1 * \sin\left(\frac{i}{1440} * 4\pi + b_1\right) \tag{3}$$

The DDS algorithm determines the variables μ, a_0, b_0, a_1, and b_1 to minimize the objective function (electricity cost) over a time horizon of one day (1440 minutes), starting at 00:00:

$$Cost = \sum_{i=1}^{1440} Q_i * P_i * F_{Pre} + Q_{i-30min} * P_{i-30\,min} * F_{KC} \tag{4}$$

The perturbation parameter is set to 0.05 and a maximum number of function evaluations to 200. Constraints are set to ensure that the control strategy does not lead to increased CSO, stating that the stored volume is never to exceed the storage volume and that the outlet capacity is not to exceed the total pumping capacity of P1. To empty out the system prior to a rain event the existing RTC is set to run if rain is expected in the following 6 hours and until the end of the rain event. For simulating this strategy a special module had to be implemented in WA.

Table 1. Summary of Control strategies

Control Strategy I – Diurnal Flow Equalization	
Control Type	Integrated Rule Based RTC with a scope of forward planning
Outlet Capacity	Constant
Storage volume	4,000 m^3
Precipitation forecast types	Perfect forecast and “Radar” forecast
Forecast horizon	1 hour
Existing RTC active	During the rain event and until the system is emptied out
Empties system if P1 is full	No
Control Strategy II – Flow Scaling Based on Mean Energy Price	
Control Type	Integrated Rule Based RTC with a scope of forward planning
Outlet Capacity	Dependent on the hourly electricity price
Storage volume	4,000 m^3 and 20,000 m^3
Precipitation forecast types	Perfect forecast, “Radar” forecast and NWP
Forecast horizon	2 hour and 6 hours
Existing RTC active	During the rain event and until the system is emptied out
Empties system if P1 is full	Yes. Outlet capacity set to 500 L/s for 1 hour if P1 is full
Control Strategy III – Flow During Six Cheapest Hours of the Day	
Control Type	Integrated Rule Based RTC with a scope of forward planning
Outlet Capacity	Dependent on the hourly electricity price
Storage volume	20,000 m^3
Precipitation forecast types	Perfect forecast and NWP
Forecast horizon	6 hours
Existing RTC active	During the rain event
Empties system if P1 is full	Yes. Outlet capacity set to 500 L/s for 1 hour if P1 is full
Control Strategy IV –Optimization using Dynamically Dimensioned Search Algorithm	
Control Type	Integrated MPC
Outlet Capacity	Optimized using genetic algorithm
Storage volume	4,000 m^3
Precipitation forecast types	Perfect forecast
Forecast horizon	2 hours
Existing RTC active	6 hours prior to and during the rain event.
Empties system if P1 is full	Constraints ensures storage volume is not exceeded

Weather Forecasts

The control strategies were all investigated using a historic rain series covering the period 01-01-2014 to 31-05-2015 from rain gauge 5251 located at the pre-treatment plant, see Figure 1. To estimate the full potential of each of the control strategies, they were tested with a perfect forecast by shifting the rain series forward in time and using it as a forecast. To get a more realistic indication of potential savings, the control strategies were also tested using “radar” forecast and Numerical Weather Prediction (NWP) model forecasts. As radar data were not available for this study, a historical rain series from the nearby rain gauge 5247 (covering the same period) was shifted forward in time. This mimics the uncertainty of radar forecasts. The NWP forecasts were produced by the DHI-HIRLAM-SO5 model for the 5km×5km grid point 1700 (Figure 1). A new forecast was produced every 6 hours, giving four ensemble forecasts a day, with a forecast horizon of 54 hours (Courdent et al., 2014). Historic NWPs were available for the period 01-06-2014 to 30-04-2015.

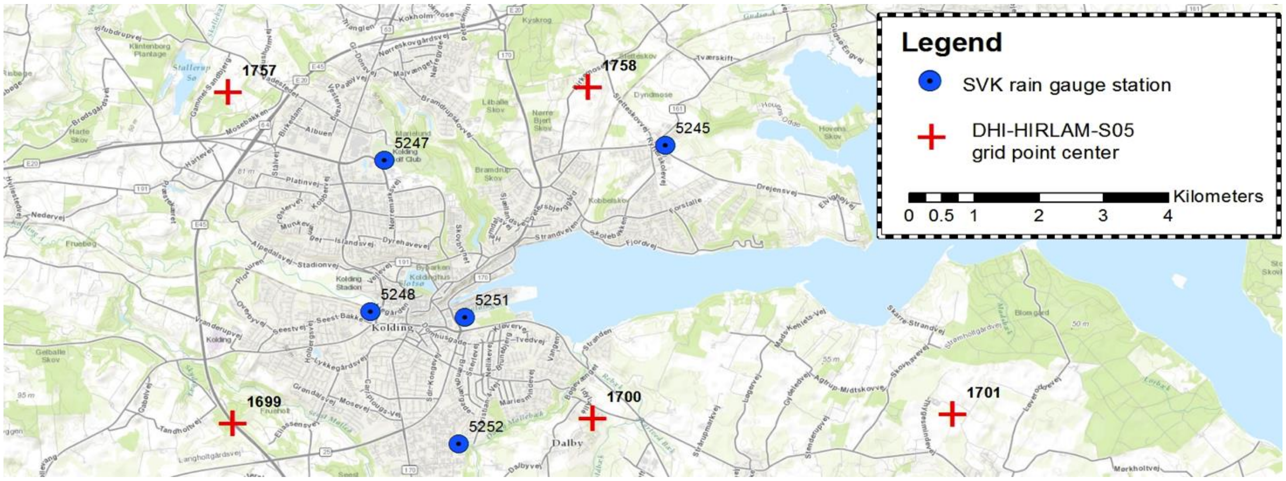


Figure 1. Location of rain gauge stations in the Kolding area (blue circle) and centre of the 5×5 km grid points used by the DHI-HIRLAM -S05 model (red cross)

RESULTS AND DISCUSSION

Summary of performance

Table 2 lists the results of the simulation for the four different control strategies for the periods when NWPs, perfect and “radar” forecast were available. Differences compared to the existing situation are shown. Results for control strategy IV are only available for January 2014.

In Table 2 the average difference in overflow is presented. This value expresses the sum of overflow from all nodes in the model. This includes intern overflow from one node to another node within the system and hence does not necessarily give the volume of CSO that exits the system. This distinction between intern and extern overflow was realized late in the process and it is therefore not possible to evaluate if increases in CSO will affect the CSO discharged to the recipient.

Table 2. The average difference in CSO from the system, the reduction in total cost, how many kWh has been moved to wind power, reduction in CO_2 equivalents presented for each of the tested control strategies. Values are express as monthly averages.

		Control Strategy I (4,000 m^3) Perfect forecast	**Control Strategy I (4,000 m^3)** "Radar" forecast	**Control Strategy II (4,000 m^3)** Perfect forecast	**Control Strategy II (4,000 m^3)** "Radar" forecast	**Control Strategy II (20,000 m^3)** Perfect forecast	**Control Strategy II (20,000 m^3)** NWP	**Control Strategy III (20,000 m^3)** Perfect forecast	**Control Strategy III (20,000 m^3)** NWP	**Control Strategy IV (4,000 m^3)** Perfect forecast
Cost red. [EUR/ month]	*	65	65	207	211	215	-	833	-	-
	**	69	68	210	204	212	171	857	689	-
	***	99	97	282	279	330	-	1172	-	300
Diff. in CSO [m^3/ month]	*	0	4	0	848	0	-	0	-	-
	**	0	0	0	20	0	2,399	0	471,656	-
	***	0	0	0	0	0	-	0	-	20.195 m^3
Energy moved to wind power [kWh/month]	*	361	339	1,326	1,344	1,390	-	7212	-	-
	**	501	506	1,552	1,575	1,612	979	8314	6,563	-
	***	335	400	1,082	1,230	1,023	-	5124	-	1.678
Emission red. [kg CO_2 eq./ month]	*	196	184	719	729	753	-	3909	-	-
	**	271	274	841	854	874	531	4506	3,557	-
	***	181	217	587	667	555	-	2777	-	910
Max stored water volume [m^3]		-	-	-	-	10,422	10,422	19,813	19,813	-

* Average based on the period from January 2014 to May 2015.

** Average based on the period from June 2014 to March 2015.

***Values for January 2014.

- Results are not available for the entire period.

Control Strategy I – Diurnal Flow Equalization. The results show that the effect of this strategy is very limited, both with regards to cost savings and reduction in CO2 equivalents. Monthly savings of 65 EUR and 196 kg CO2 equivalents have been estimated. Control strategy I is based on the assumption that the wastewater flow to the pre-treatment plant is high during the periods of the day where the electricity price is high and low when the electricity price is low (during the night). The equalization aims at increasing the wastewater flow during cheap hours and decreasing it during expensive hours. However, the examination of the average diurnal flow and the average hourly electricity prices showed that the equalization did not always achieve the strategy's goal, with short periods where the strategy worsened the situation compared to the current status. These periods may explain the limited savings achieved with strategy I. Additionally, the most intense wastewater flow coincides with a local minimum in the average electricity price, which contributes to the limited effect of control strategy I. Based in this it is assessed that the conditions in Kolding are not well suited for flow equalization.

Control Strategy II – Flow Scaling Based on Mean Energy Price. Generally the savings in cost and CO2 equivalents achieved by strategy II are 3-4 times higher than those achieved by strategy I. Control strategy II was tested with 4,000 m^3 and 20,000 m^3 storage volume.

Table 2 shows how the increase in storage volume had very little effect on the achieved savings. Furthermore it can be seen that the control strategy never utilizes the full 20,000 m^3. For several months the storage volume did not even exceed the 4,000 m^3 storage. This limited water volume stored in the system may explain the modest increase in CSO volume when the control strategy was tested with "radar" and NWP forecasts.

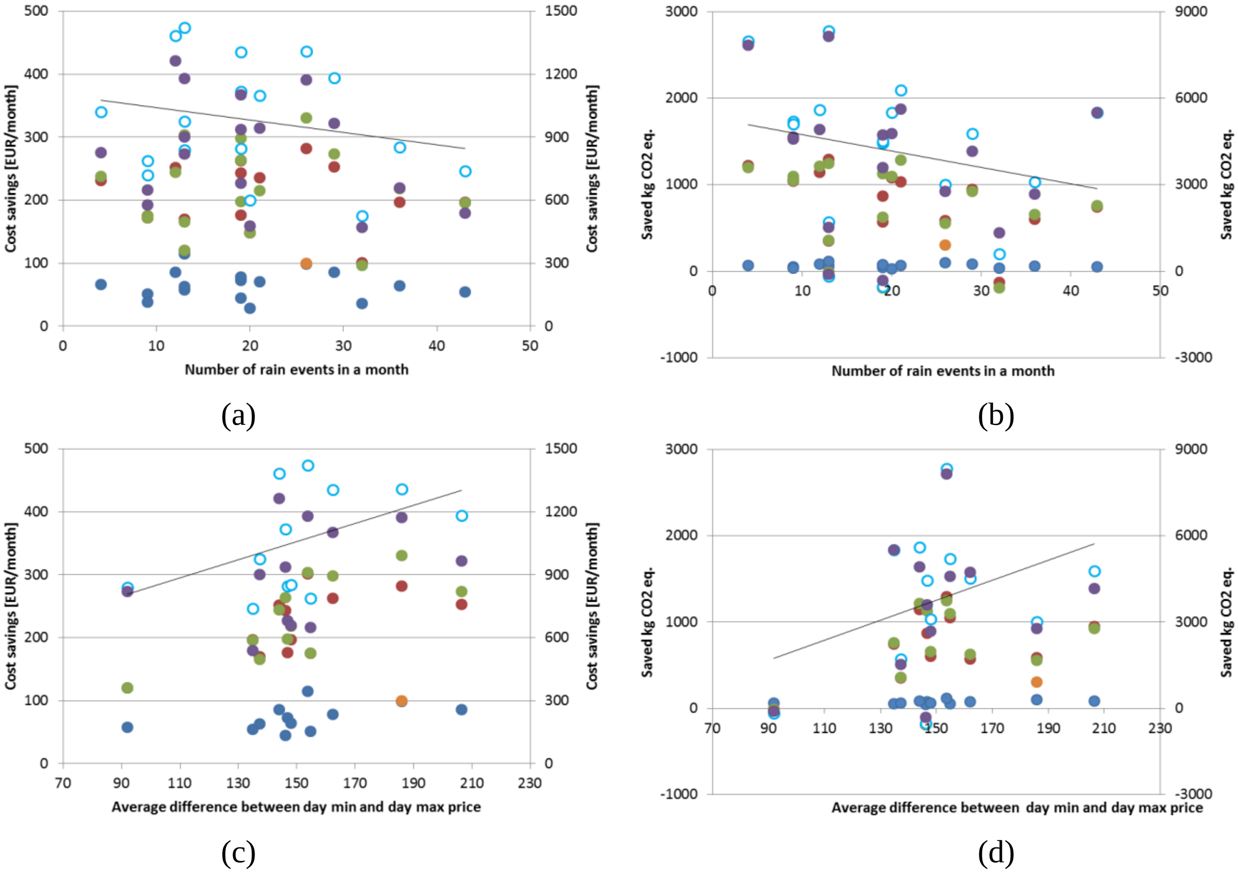
Control Strategy III – Flow During Six Cheapest Hours of the Day. This control strategy gives average saving of 833 EUR/month and 3909 kg CO2 equivalents/month and hence yields the largest savings of the tested control strategies. The six consecutive hours from 00:00 to 06:00 are generally the cheapest hours of the day, suggesting that the control strategy requires adequate storage volume to hold 18 hours of wastewater. The implementation of control strategy III in Kolding would therefore require an expansion of the existing system or incorporation of further upstream storage volumes in the control strategy.

Control Strategy IV –Optimization Using Dynamically Dimensioned Search Algorithm. This control strategy was only tested for January 2014 due to software problems. It is thus not possible to give a thorough evaluation of the performance of this control strategy. However, based on the available results, this strategy achieved the largest savings of the control strategies that only used a storage volume of 4,000 m^3. The distinction between intern and extern overflow was realized prior to running control strategy IV. Based on total overflow, control strategy IV caused a significant increase in overflow of 20.195 m^3 in January. However, the extern overflow out of the system showed not to increase.

Influence of wet-weather periods and energy price variations

Figure 2 shows the performance of the control strategies against the number of rain events in the month (a and b), and against the monthly average differences between daily minimum and daily maximum electricity price (c and d). All the control strategies are set to empty out the system prior to a rain event. It could therefore be expected that the performance of the control strategies would decrease during periods with frequent rain events. From Figure 2 a and b it can be seen that the performance of the control strategies does indeed seem to be inversely proportional to the number of rain events in a month. The goodness of fit (r^2) for the average performance of the control strategies is however only 0.051 for cost savings and 0.053 for saved kg CO_2 equivalent. It is therefore not possible to determine whether the performance of the control strategies depends on the number of rain events.

The idea behind the control strategies is to exploit the daily fluctuation in electricity prices. It would therefore be expected that the control strategies perform better during periods with large fluctuations. From Figure 2 c and d it can be seen that the control strategies appear to perform better during months with large differences between daily minimum and daily maximum electricity price. Again the goodness of fit of the average performance of the control strategies is quite low; r^2= 0.226 for cost savings and r^2= 0.146 for saved kg CO_2 equivalent. This indicates that the performance of the control strategies is more dependent on the fluctuation in electricity prices than on the number of rain events. However, more data would be required to assess such a relation adequately.



(a) (b)

(c) (d)

Figure 2. Top: The monthly saving in cost (a) and CO_2 equivalents (b) achieved with perfect forecasts as a function of the number of rain events in that month. Bottom: The monthly saving in cost (c), and CO_2 equivalents (d) achieved with perfect forecasts as a function of the monthly average difference between daily minimum and daily maximum electricity price. Control strategy I (blue), Control strategy II storage volume 4,000 m^3 (red), Control strategy II storage volume 20,000 m^3 (green), Control strategy III (purple) and control strategy IV (orange) and average value (blue circle). The linear regression of the average values is shown for each of the figures (black line).

Future outlook

This study is based on a series of assumption and simplifications whose validity needs to be further investigated. This study assumes a linear relationship between water volume and energy consumption, i.e. the pollutant concentrations at the WWTP inlet are assumed constant in time. Further investigations should therefore also include water quality variations in the optimization of the systems.

For the estimation of cost savings and reductions in CO_2 equivalents it is assumed that the energy consumption for treatment of the water occurs instantaneously when the water reaches Kolding Central WWTP. The treatment of wastewater does, however, take several hours (Pedersen, 2015). Moving the transport of wastewater to cheap hours does therefore not necessarily give the most optimal treatment with regard to electricity prices. Therefore it is be possible that the most energy demanding treatments (e.g. aeration) are not taking place in the low-energy price hours. Similarly, the tested control strategies are based on hydraulic considerations, and the impact on the pollution load to the WWTP is not considered. Strategy III, for example, concentrates the daily pollutant loads within only 6 hours, with anticipated effect on the processes taking place at the plant. The implementation of such strategy would require a complete re-formulation of the WWTP controls.

Furthermore, chemical and biological processes in sewers are not included in the study. Storage of wastewater for long periods of time may lead to production of methane and hydrogen sulphide (Danva, 2008; Jørgensen, 2009), causing problems link to odours, health and safety issues, corrosion of the infrastructure and climate change impact. All these effects may compensate for the benefit obtained by the Smart Grid control and they should thus be considered by the control strategy.

CONCLUSION

Four different control strategies for optimizing the electricity consumption by controlling the wastewater flow to Kolding Central WWTP were investigated using a WaterAspects model. Based on the simulation results it can be concluded that:

- The strategy that sends water to Kolding WWTP during the six cheapest hours of the day (control strategy III) achieved the greatest savings: 833 EUR/month and 3909 kg CO_2 equivalents/month. However, this control strategy showed great increases in CSO when tested with NWP.
- Control strategy IV provided the best results among the control strategies utilizing the existing storage volume of 4,000 m^3. This control strategy used a DDS algorithm to optimize the flow and was the only control strategy to employ MPC. Due to time constraints it was only possible to test control strategy IV for January 2014. For this month the control strategy generated savings of 300 EUR and 910 kg CO_2 equivalents. This is slightly higher than the 282 EUR and 587 kg CO_2 equivalents that were generated with control strategy II (Flow scaling) with a storage volume of 4,000 m^3.
- The control strategy that yielded the smallest savings was control strategy I (flow equalization), which on average saved 65 EUR/month and 196 kg CO_2 equivalents by equalizing the wastewater flow.
- Employing perfect forecasts it was possible to prevent increases in CSO for all of the control strategies. Control strategy III showed large increases in overflow when tested with NWP, while the remaining control strategies only showed limited increases in overflow when run with

"radar" forecasts and NWP. In this study a distinction was not made between internal and external overflow and it is therefore uncertain whether this corresponds to increases in discharge to the recipient.
- The results indicated that the savings in cost and CO_2 equivalents achieved with the control strategies were inversely proportional to the number of rain events in a month, but proportional to the difference in daily minimum and maximum electricity price, with a slightly higher dependence on the fluctuation in electricity prices than on the number of rain events. Based on the limited data of this study it is, however, not possible to determine such relations with sufficient accuracy.

Based on the results obtained in this study it is concluded that only relatively limited savings in cost and CO_2 equivalents should be expected by implementing a Smart Grid control strategy in Kolding sewer system using the existing 4,000 m^3 of storage volume upstream from the pre-treatment plant. Greater savings would require an increase in the storage capacity of the system or the inclusion of further upstream storage volumes into the control strategy.

The particular design of the Kolding sewer system with a long transport pipe between the main catchments (including pre-treatment) and the treatment plant means that the wastewater flow in Kolding is already, to some degree, aligned with the diurnal fluctuation electricity prices, which may explain the limited savings achieved in this study. However, it is possible that larger savings could be achieved at other case areas.

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