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Investigating energy and operation flexibility of membrane bioreactors by using benchmark simulations

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ABSTRACT

Wastewater volumes are increasing globally as a result of increased population and industrial growth. This, together with increasingly stringent discharge limits, has resulted in a consequent rise in energy demand for wastewater treatment. Activated sludge process has been successfully used for more than a century with various configurations for the removal of organic carbon and nutrients. Compared to conventional activated sludge plants, membrane bioreactors (MBRs) offer a higher treatment efficiency, however, they are energy-intensive. The aim of this study is to investigate the operational and energy flexibility of MBRs by mathematical modeling. Based on a variable electricity price tariff, an appropriate optimization strategy can save 9%–41% of the energy cost without violating exiting discharge standards. The results of dynamic simulation revealed that, under variable energy price structures, hybrid MBRs can provide significant flexibility for reducing energy costs while maintaining satisfactory effluent quality.

Keywords: Aeration control; Benchmark simulation model; Conventional activated sludge; Energy; Membrane bioreactor; Wastewater treatment

1. Introduction

Water abstraction for various uses, such as domestic, agriculture and industry, has increased 2–3 times more than the rate of population growth [1]. Higher sanitation needs for the protection of human health, the aquatic environment and freshwater sources have led to a continuous increase in the energy demand for wastewater treatment in many regions [1]. Furthermore, extensive industrialization has accelerated the use of various persistent organic pollutants, surfactants, industrial chemicals and pesticides, which have potential bioaccumulation, carcinogenicity and toxicity effects [2]. Increasing emerging pollutants, that have an adverse impact on human health, in natural water sources, pose a challenge to existing wastewater treatment facilities [2].

Membrane bioreactor (MBR) technology, that combines activated sludge process with membrane filtration, has been widely used for the treatment of both industrial and municipal wastewater when high-quality effluent is required (i.e., for water reuse or discharge to sensitive water bodies) [3]. Besides, MBRs can reduce the footprint of activated sludge plants by replacing secondary clarifiers and this makes them an attractive technology [4]. A small footprint is a significant advantage of MBRs, especially for cities where land is scarce or land price is high [5]. Compared to the conventional activated sludge (CAS) treatment process, MBRs can significantly increase effluent quality due to superior biomass retention and rejection of particulate organics from effluent. MBR technology also has an important advantage in removing a wide range of emerging pollutants such as antibiotics, pesticides and industrial chemicals [6,7]. Over the last twenty years, the market

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penetration of MBRs has maintained a sustained growth up to 15% driven by increasing water scarcity and stringer legislations [3,4]. The development of MBR technology promotes progress in the wastewater treatment industry and stimulates the confidence in the market to accept new technologies. Currently, MBRs are implemented in more than 200 countries, in which around 40 municipal plants have over 100,000 m^3/d in capacity [3]. According to Xiao et al. [5], about 50% of these super-large MBR plants are located in China and their cumulative capacity has already reached 10 million m^3/d in 2017.

The most significant disadvantage of MBRs is their high energy cost due to high air demand to ensure both bio-oxidation of pollutants and the prevention of membrane fouling. Fouling, a major factor that impacts the MBR performance, reduces permeability and increases the transmembrane pressure. Therefore, fouling control in MBRs adds significantly to operating costs [8]. Although a lot of research has been conducted to understand membrane fouling mechanisms, it is still difficult to reach a consensus on the optimal conditions for MBR operation [9,10]. Aeration demand for bio-oxidation of pollutants and membrane fouling control was reported in the range of 0.4–2.3 kWh/m^3 treated effluent which varies with the scale and optimization of MBR plants [11]. Typically, the energy consumption of MBRs is two-four times higher than that of the traditional treatment process, which exceeds their advantages in terms of treatment quality [12]. According to the survey carried out by Judd [3], the wastewater treatment community (industry and academia) perceives the energy consumption of MBRs as the most important factor that needs to be improved in the future. Thus, proper optimization for MBR aeration is necessary to reduce the operation cost and to increase the technology's competitiveness.

The increased penetration of renewable energy into the overall energy mix has led to increased uncertainty in power generation due to the dynamic and less predictable nature of renewable sources such as wind and solar [13]. As a result, a need for energy flexibility, which can provide several benefits for both power generators and end-users, has become apparent. Energy flexibility of large consumers such as water and wastewater treatment plants can be transferred to economic benefits under complex contracts with power providers, that is, variable tariff structures, charges/subsidies applied to peak demand [14,15]. As a result, energy consumers need to take 'a set of actions to reduce electricity demand when contingencies such as emergencies or congestion occur that threaten supply-demand balance and/or market conditions occur that raise electric supply costs', which is defined as demand response (DR) [16]. DR does not necessarily mean reducing the energy consumption, but it can decrease the cost paid by consumers/end-users by smart usage of energy due to shifting or shedding their consumption when there is high wholesale market prices or malfunction of system reliability [17]. By applying DR, consumers can manage their electricity costs to reduce the risk of power outages and postpone capacity investments by adjusting their energy demand according to the fluctuation of electricity supply [18].

Variable energy price tariffs provide potential energy flexibility for wastewater treatment plants (WWTPs) to reduce their operation costs. For instance, Brok et al. [19] reported that regulating the aeration equipment in a WWTP according to nitrate and ammonium concentrations can save 1.15% of energy costs if only the day-ahead market is considered. They also mentioned that if the regulating and special regulating power prices are included, the savings can be in the magnitude of 7.23% and 27.32%, respectively. Similarly, Musabandesu and Loge [20] report that the California Santa Rosa wastewater treatment plant could achieve up to 4.8% energy cost savings through the proxy demand resource program. They also highlighted the difficulty of correctly timing demand reduction periods and the inaccuracy of using standard baseline methods to measure the energy load reduction. Therefore, utilities and operators of WWTPs need more explicit tools, that is, bioprocess and data-driven forecast models integrated to decision support systems, to qualify and quantify the benefit provided by energy management and applying DR actions [14,21].

In this context, MBR plants can also benefit from dynamically changing energy prices by using aeration control for pollutant removal and membrane scouring. This paper focuses on the DR potential of MBRs for municipal wastewater treatment. In order to investigate the flexibility of MBRs in the context of variable energy prices, the benchmark simulation model for MBRs (BSM-MBR) described in Maere et al. [22] was used. The performance of MBR was tested in terms of energy cost and treatment efficiency in six different operation scenarios.

2. Material and methods

2.1. Implementation of BSM-MBR model

BSM-MBR [22], based on Benchmark Simulation Model No.1 (BSM1) [23], was used in the study. A modified version of BSM-MBR was implemented into BioWin 6.0 (EnviroSim, Canada) software which uses a plant-wide activated sludge digestion model (ASDM). Considering the difference in definition of some state variables between ASDM and Activated Sludge Model No.1 (ASM1) [24], which is used for describing the biological processes in BSM-MBR, parameters including biokinetics and stoichiometry was modified to match the results of the default BSM-MBR outputs [22]. The methodology outlined in Dereli et al. [25] was implemented for benchmarking MBRs under several scenarios.

The general configuration and layout of BSM-MBR are shown in Fig. 1a. Each bioreactor has the same volume of 1,500 m^3. The depth of anoxic and aerobic bioreactors is 5 m and the membrane tank is 3.5 m. The membrane area and packing density were set to 71,500 m^2 and 47.5 $m^2/m^3_{reactor}$, respectively [22]. Specific membrane aeration demand (SAD_m) was set to 0.3 $Nm^3/h/m^2$ of membrane area which results in an air-flow of 21,450 Nm^3/h. Fine and coarse bubble aeration was used for the aerobic bioreactors (Aer 1 and 2) and membrane tanks, respectively. Fine bubble air-flow for Aer1 and 2 was set to 4,250 and 2,250 Nm^3/h, respectively.

Membrane flux was not a fixed operational parameter; it was calculated based on the influent flow and membrane surface area of the MBR. At average influent flow, the flux was calculated as 10.63 L/m^{2}h (LMH), which is lower than values reported in the literature for typical municipal sewage treatment [3]. In the steady-state simulation of BSM-MBR, the plant treated an influent flow of 18,446 m^3/d, producing a permeate flow of 18,246 m^3/d and wasted sludge flow of 200 m^3/d [18]. Mixed liquor was recirculated from the second aerobic tank to the first anoxic tank at a rate of 55,338 m^3/d (3 times the average influent flow) to recycle nitrate [22]. In addition, sludge was recirculated from the membrane tank to the first aerobic bioreactor at the same flow rate, providing sufficient biomass inoculation and evenly distribution over the whole tanks [22].

In order to evaluate the performance of a hybrid wastewater treatment system, a dual-stream layout (Fig. 1b) consisting of an MBR process and a CAS process was built based on the BSM-MBR model. The CAS stream consisted of a 5 m-depth aerobic bioreactor of 1,500 m^3 and a 4 m-depth secondary clarifier of 2,000 m^3 [23]. Modified Vesilind model was used to describe the settling process in the secondary clarifier.

2.2. Electricity tariff structure

It is important to evaluate the potential energy flexibility of WWTPs based on a realistic energy price structure. The energy cost model reported in the research of Aymerich et al. [26] was used as a time-of-use (ToU) electricity tariff. The price structure consisting of on-peak, mid-peak and off-peak times and it is shown in Fig. 2. The energy consumption profile of a WWTP is highly correlated to the diurnal hydraulic and pollutant loads which vary dynamically throughout a day. It also follows a similar pattern to the ToU prices which are determined based on the overall demand from an electricity grid (Fig. 2). Therefore, reducing the energy demand when the plant is highly loaded can provide flexibility to the power grid and energy cost reduction for the WWTP [14]. This can be achieved by regulating/rescheduling the operation of electromechanical equipment, such as pumps, blowers, mixers and centrifuges, with respect to the fluctuating energy price [27].

2.3. Scenario development and evaluation

In order to verify the energy flexibility of WWTPs under the ToU electricity tariff structure, six scenarios were developed. In each scenario (Table 1), the steady-state simulation was first run with the constant influent flow and then a 28-d dynamic dry weather simulation was performed starting from the result of the steady-state simulation [23]. The rationale behind the developed control strategies is reducing the aeration cost at the on-peak time and testing the impact of this operation on the MBR treatment performance.

BSM-MBR open-loop simulation without any controllers was considered as the default scenario (S0) [22]. Scenarios 1, 2 and 3 were used to investigate the impact of aeration control in the plant (Table 1). In scenario 1 (S1), dissolved oxygen (DO) concentration was controlled at 1.5 mg/L by using a proportional-integral (PI) controller (Table 2). Similarly, in scenario 2 (S2) DO concentration in the membrane tank was maintained at 5 mg/L. SAD$_m$ was adjusted inversely proportional to electricity price such as 0.1, 0.2, 0.3 Nm^3/m^{2}h at high-peak, mid-peak and off-peak periods, respectively, in scenario 3 (S3). The membrane was scoured at a higher intensity when the electricity cost was lower, whereas air scouring was reduced at high-peak periods. Judd [3] reported a broad range for SAD$_m$ extending from less than 0.2 to 1.4 Nm^3/m^{2}h in full-scale MBRs.

Most of the energy used in MBRs is consumed for fouling control, that is, scouring the membranes with air bubbles and/or recirculating mixed liquor to provide cross-flow operation, which makes this process a highly potent option for flexibility. Therefore, adjusting the amount of air used

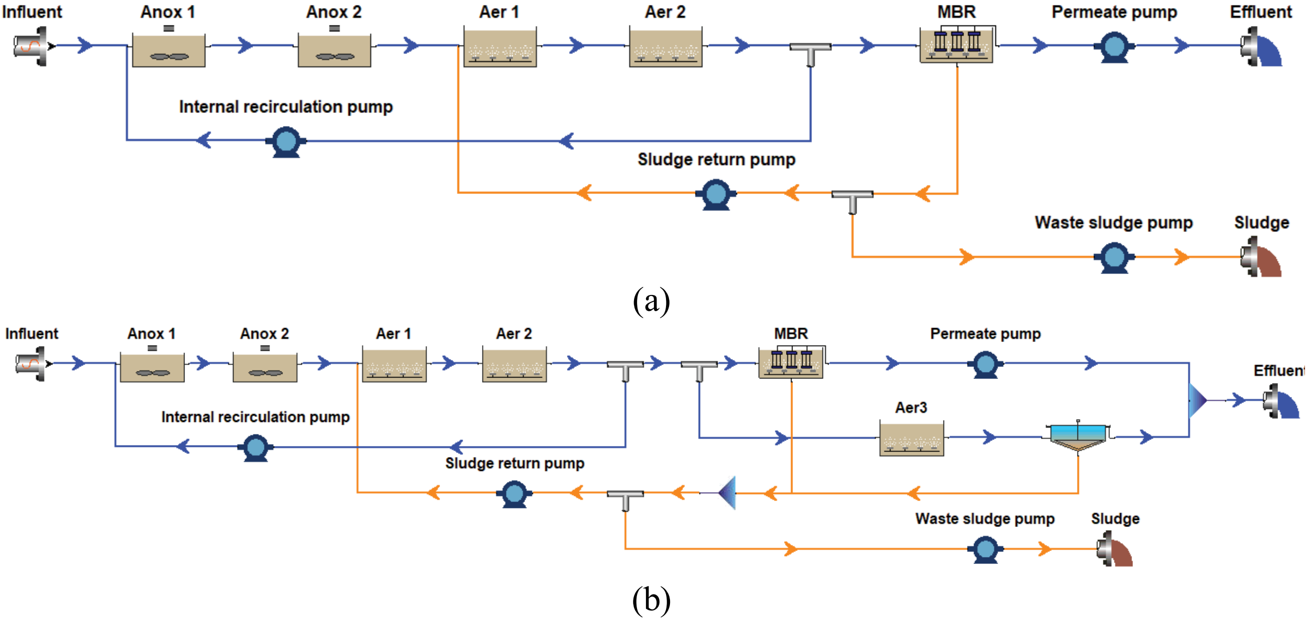

Fig. 1. (a) BSM-MBR configuration and (b) dual-stream configuration.

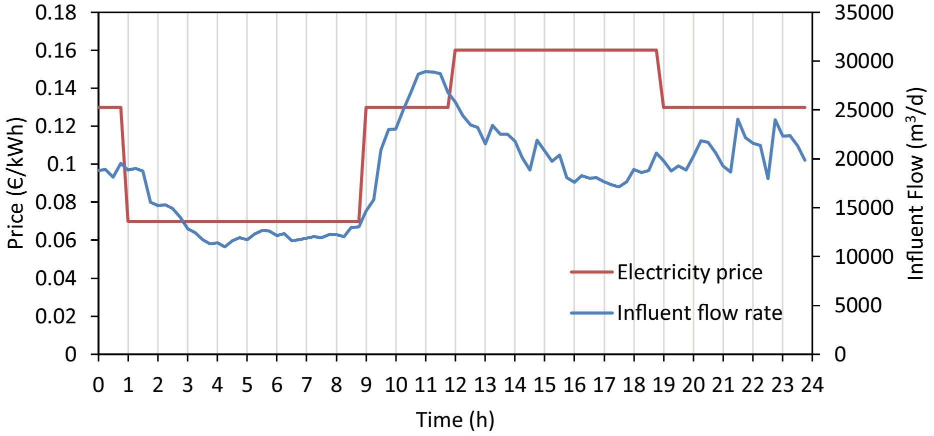

Fig. 2. Electricity price tariff structure and 28-d average influent flow rate of the plant.

for fouling control based on the energy price can be adopted as a strategy to optimize the energy demand and costs. On the other hand, this may have adverse consequences on the effluent quality and particularly membrane fouling in MBRs. Therefore, it requires a multi-objective optimization which priorities effluent quality and membrane fouling over energy costs.

In scenario 4 and 5, a dual-stream treatment system was investigated. These two scenarios represent the case in which existing tanks and infrastructure are available on-site to combine the CAS process and MBR into a hybrid system (Fig. 1b). In scenario 4, 30% of the influent was diverted into the CAS stream and the DO concentration in Aer 1, Aer 2 and membrane tanks were controlled as in S2. Furthermore, the DO in the third aerobic bioreactor (Aer 3) was regulated at 1.5 mg/L. In order to verify the flexibility of the dual-stream system, in scenario 5 (S5), the CAS stream only works at the on-peak time.

The treatment performance of the WWTP was evaluated based on the 95 and 50 percentiles of effluent chemical oxygen demand (COD), NH_4–N and NO_3–N concentrations, effluent quality index (EQI) and net EQI. The 95 and 50 percentiles are defined as the part of effluent concentration that is exceeded 5% or 50% of the time in the last week of simulation. EQI (Eq. (1)) is a weighted sum of average pollutant loads over the last 7 d of the simulation [23]. Net EQI (Eq. (2)) describes EQI in excess of the discharge limit and is calculated based on the instantaneous difference between the concentration and discharge standard of each parameter (Table 3).

$$\text{EQI} = \frac{1}{t_{\text{obs}} \cdot 1{,}000} \int_{t=21\text{ d}}^{t=28\text{ d}} \left[\sum_{i=1}^{n} C_i(t) \cdot w_i \right] \cdot Q_e(t) \cdot dt \tag{1}$$

$$\text{Net EQI} = \frac{1}{t_{\text{obs}} \cdot 1{,}000} \int_{t=21\text{ d}}^{t=28\text{ d}} \left\{ \sum_{i=1}^{n} \text{Max}\left[0, C_i(t) - C_{i,\text{limit}}\right] \cdot w_i \right\} \cdot Q_e(t) \cdot dt \tag{2}$$

where EQI: environmental quality index, kg pollution unit/d; net EQI: net environmental quality index, kg pollution unit/d; t_{obs}: observation period, d (here, the last 7 d of simulation period); $C_i(t)$: effluent concentration of each pollutant parameter (Table 3) at time t, g/m³; $C_{i,\text{limit}}$: discharge standard of each pollutant parameter (Table 3), g/m³; w_i: weighing factor for each pollutant parameter (Table 3), g pollution unit/g; n: total number of pollutant parameters taken into account in the discharge standard (according to Table 3, $n = 7$); $Q_e(t)$: effluent flow rate at time t, m³/d; dt: differential time according to data frequency, d (here, it is 0.010417 d).

3. Results and discussion

3.1. Treatment performance

The effluent quality obtained in dynamic simulation of different scenarios is shown in Table 4. As shown in Table 4, the plant could attain high COD removal, nitrification and denitrification efficiency. The plant achieved full

Table 1
Scenarios used in the study

Scenario	Description
S0	BSM-MBR open loop (without any controllers)
S1	DO controlled in the first and second aeration tanks
S2	S1 together with DO control in membrane tank
S3	S1 together with SAD_m control in membrane tank based on electricity price
S4	S2 together with dual-stream (MBR for treatment of 70% influent) treatment for the whole day
S5	S2 together with dual-stream (MBR to treat 70% influent) treatment at on-peak time

Table 2
Parameters of PI DO controllers used in each tank

Parameter	Unit	Aer1	Aer2	Aer3	Membrane tank
DO set point	mg/L	1.5	1.5	1.5	5
Proportional gain	mg m^3/L h	500	500	500	2,000
Integral time	*d*	0.002	0.002	0.002	0.002
Minimum air flow rate	Nm^3/h	660	660	660	21,450
Maximum air flow rate	Nm^3/h	4,500	2,500	1,500	7,150

Table 3
Discharge standards and weighing factors for effluent parameters

Parameter (C_i)	Discharge standard ($C_{i,\text{limit}}$) (g/m^3)	Weight (w_i) (g pollution unit/g)
Total suspended solids	30	2
Chemical oxygen demand	100	1
Biochemical oxygen demand	10	2
Total nitrogen	18	–
Total Kjeldahl nitrogen	6	30
NH_4–N	4	–
Oxidized nitrogen (NO_2–N + NO_3–N)	12	10

nitrification in all scenarios thanks to the efficient retention of nitrifiers by the membrane. Effluent COD concentration was similar in S0, S1, S2 and S3, however, it slightly increased when dual-stream treatment (MBR and CAS) was applied in S4 and S5. Controlling DO concentration in aerobic reactors (S1, S2, S3) significantly reduced effluent nitrate concentration due to less penetration of DO into the anoxic tanks. This is also indicated by remarkably decreased net EQI. Over aeration in MBRs can retard their denitrification performance depending on the plant configuration. Therefore, efficient control of aeration is crucial for optimized MBR performance. Gabarrón et al. [28] achieved a 27% improvement in nitrogen removal efficiency and decreased the biological aeration energy costs by 7% by implementing reduced DO set-points (from 1.2 to 0.8 mg/L) in the aeration tank prior to membrane tank in a full-scale MBR.

Dual-stream scenarios (S4 and S5) showed similar NH_4–N removal performance. On the other hand, slightly higher effluent COD concentrations compared to single MBR configuration were observed due to uncaptured biomass flocs in the final clarifier. This also had a negative impact on effluent COD concentrations and was reflected by elevated EQI values. On the other hand, the net EQI in S4 was significantly lower than the MBR scenarios. This is mainly due to the improved denitrification efficiency of the system. In S4, 30% of the influent wastewater was treated in CAS system, operated at a DO concentration of 1.5 mg/L, for the whole day and the mixed liquor was recycled to the anoxic zone of the main plant. This reduced the oxygen input to the anoxic tanks and enhanced denitrification performance. However, the result of S5 showed an increased net EQI by 14% which is demonstrating a negative effect on nitrogen removal performance of the dual-stream system. This may be due to improper DO control in CAS which received discontinuous feeding (only at the on-peak time between 12:00 and 19:00). An on/off controller may be more suitable instead of a PI controller for this particular case. Krzeminski et al. [29] evaluated three full-scale MBR plants (one stand-alone MBR and two-hybrid MBRs) in the Netherlands and found there is also no substantial difference in single and hybrid MBR effluent quality by analyzing the performance data. In addition, compared to the CAS process, MBRs are more often impacted by unsteady-state conditions, causing operational perturbation such as poor filterability of activated sludge [29]. Dual-stream systems have better stability of treatment performance, in which the CAS stream provides a hydraulic and biological buffer zone to ensure more stable conditions for the activated sludge in the plant [29].

Thus, it can be concluded that the selection of a dual-stream MBR configuration for municipal WWTPs has no significant impact on effluent quality, especially with respect to the current discharge standards. Nevertheless, potential differences in the effluent quality should be considered in terms of the disinfection and total suspended solids concentration. Moreover, the ageing rate of the membrane may be faster in a dual-stream system, because the membranes have often shorter out of operation periods compared to the membranes in stand-alone configurations [29].

3.2. Energy performance

Table 5 gives the cumulative energy cost calculated by using the ToU electricity price tariff and cumulative aeration energy of the plant. Compared to S0, all optional strategies can reduce the energy-cost to some extent. Controlling DO in aerobic bioreactors (S1) had only a minor impact on aeration energy demand and total energy costs.

Table 4
Treatment performance of the system in different scenarios

Scenario	50%–95% of COD concentration (mg/L)	50%–95% of NO_3–N concentration (mg/L)	50%–95% of NH_4–N concentration (mg/L)	EQI (kg/d)	Relative change of EQI (%)	Net EQI (kg/d)	Relative change of net EQI (%)
S0	31.4–34.1	11.4–16.1	0.1–0.3	3,126	–	139	–
S1	31.4–34.1	10.8–15.7	0.1–0.4	3,023	–3.3	111	–20.1
S2	31.4–34.1	10.7–15.7	0.1–0.4	3,004	–3.9	106	–23.7
S3	31.4–34.1	10.7–15.5	0.1–0.4	3,005	–3.9	101	–27.3
S4	33.9–35.9	11.5–13.6	0.1–0.4	3,320	6.2	49	–64.7
S5	32.2–35.8	11.1–15.9	0.1–0.4	3,188	2.0	159	14.4

Table 5
Comparison of scenarios based on cumulative aeration energy demand and cost for 28 d

Scenario	Cumulative energy cost (€)	Relative change of cumulative energy cost (%)	Cumulative aeration energy (kWh)	Relative change of cumulative aeration energy (%)
S0	58,977	–	408,708	–
S1	53,679	–9	360,575	–12
S2	36,871	–38	211,977	–48
S3	42,523	–28	283,584	–31
S4	34,613	–41	202,738	–50
S5	36,285	–39	209,208	–49

It is clear that the energy cost of MBRs is dominated by the membrane aeration costs and controlling airflow for membrane scouring is the most critical operation strategy. Krzeminski et al. [29] reported that membrane scouring corresponds to 70%–97% of aeration energy in full-scale MBRs. Therefore, the optimization of air used for membrane scouring is essential to obtain significant energy reduction. The results of S2 and S3 show that there is a large potential for saving energy by using flexible aeration control in MBRs, achieving energy cost saving that ranges from 28%–38%. Manina et al. [30] obtained similar results by implementing sophisticated aeration control in an MBR. They attained 32% and 82% reduction in aeration energy by implementing ammonium and ammonium-nitrate-based DO cascade controllers, respectively. In our study, we applied a PI controller for adjusting DO concentration in the membrane tank in S2. Even a simpler aeration strategy was adopted for the membrane tank by taking the energy costs into account in S3. Thus, less air was fed during the on-peak time for avoiding high energy costs. Decreased scouring of the membrane at peak flow times may have an adverse effect on fouling but this might be compensated by implementing increased scouring rates during the off-peak energy price period. It is worth mentioning that the proper distribution of membrane aeration based on a variable electricity price tariff can significantly decrease the energy bill of the plant.

S4 and S5 demonstrate that dual-stream WWTPs can have operational flexibility under a variable electricity price structure. When upgrading existing CAS plants to MBRs, making use of parallel treatment trains, such as already existing bioreactors and clarifiers, can offer flexibility to the system. Furthermore, CAS facilities can act as buffer tanks in cases of high influent load or peak-time electricity price. Moreover, dual-stream treatment can reduce air demand and energy costs by about 50% and 40%, respectively. Gabarrón et al. [31] evaluated two operation strategies (i.e., buffering the influent flow and optimizing both the biological aeration and membrane air-scouring) in a hybrid MBR in Northeast Spain. They decreased the specific energy demand by 14%. Krzeminski et al. [29] found that a hybrid wastewater treatment process can save at least 17% operation cost compared to a single MBR process. Therefore, in the case that old infrastructure, such as the CAS system, is still operational, a dual-stream configuration is usually a better-retrofitting strategy.

4. Conclusions

Energy management in WWTPs is attracting increased attention due to the changing energy market. However, there is still very little knowledge about the optimization of MBRs with regards to their operational flexibility in the context of variable electricity prices. This study investigated the energy management of MBRs by using a BSM. The performance of optimization strategies was evaluated with EQI and a typical ToU electricity tariff structure. The result of dynamic simulation showed that an advanced operation control can save up to 9%–41% of the total energy cost. It is concluded that WWTPs with MBR configurations have energy flexibility under a variable energy price structure. In the future, models that combine flexible energy management technologies with economic analysis can help to better optimize the wastewater treatment process and develop novel energy-saving strategies.

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