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Upgrade of the Taskila WWTP with an MBR line: the first treatment results, performance assessment and lessons learnt

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Abstract

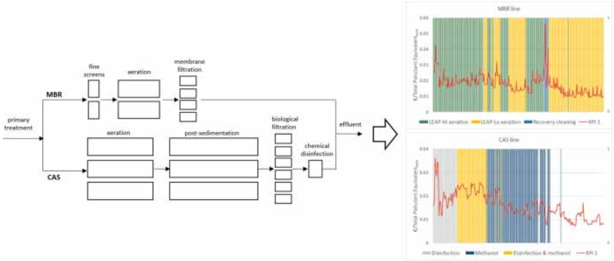
In this paper, we present the first results of a large-scale membrane bioreactor application implemented for increasing the wastewater treatment plant capacity. The Taskila plant in Finland was upgraded in 2018 and is now operated as a hybrid system with parallel membrane bioreactor and conventional biological lines. The results showed that membrane filtration improved the plant performance significantly in terms of the solids and pathogens removal. Nitrogen removal has been stable with the current operating set-points and notably better than before the plant expansion. The analysis using key performance indicators showed that there were no significant differences in operational expenditures between the membrane and conventional lines. The membrane filtration results highlight the importance of maintaining the good sludge filterability properties that enable higher operational fluxes and reduced energy consumption. The low membrane aeration flow-rate mode, the standard operating mode with good sludge filterability, enabled reduction of total aeration energy consumption by 34% for the membrane bioreactor, including both activated sludge and membrane aeration. Fine-tuning of the hybrid plant is still going on and, therefore, improved overall results are expected in the forthcoming years.

Key words: hybrid configuration, key performance indicators (KPI), membrane bioreactor (MBR), plant expansion, sludge filterability, wastewater treatment plant

Highlights

- The first treatment results of a large-scale MBR in a municipal WWTP are presented.
- WWTP is operated as a hybrid system with parallel MBR and CAS lines.
- KPIs are proposed to assess the wastewater treatment process performances.
- Assessment showed no significant differences in OPEX between MBR and CAS lines.
- Good sludge filterability enabled notable reduction of the MBR aeration energy consumption.

Graphical Abstract



INTRODUCTION

Tightening wastewater purification requirements and increasing influent loading often necessitate expanding the treatment capacity of Wastewater Treatment Plants (WWTP). One potential technology for capacity enhancement is the membrane bioreactor (MBR, Judd & Judd 2011), where biological treatment is combined with membrane filtration.

Membrane technology allows for more efficient separation of solid substances from wastewater than gravity sedimentation, which is used in the Conventional Activated Sludge (CAS) process. Another advantage of MBRs is the lower footprint requirement in comparison with CAS, resulting from higher activated sludge concentration in the biological treatment process and from using membrane separation to replace secondary sedimentation basins, which require a large surface area (Judd & Judd 2011). On the other hand, membrane fouling and the high energy consumption of the membrane maintenance routines have been reported as the most challenging issues in MBR operation (Wang *et al.* 2014; Meng *et al.* 2017). MBR suppliers, researchers and practitioners have paid attention to the challenges of energy consumption in MBR operation and developed energy-saving solutions in recent years (Krzeminski *et al.* 2017).

A common practical challenge in dimensioning treatment processes is the high ratio between maximum and average influent flow-rates of WWTPs. Capital expenditures of MBR is still higher than those of CAS (Roccaro & Vagliasindi 2020) due to membrane installation, which emphasises the significance of not oversizing the process. A cost sensitivity study showed that a cost-efficient alternative for an MBR plant designed to treat maximum inflow is a hybrid plant consisting of two parallel lines: an MBR line designed to treat a constant daily flow-rate and CAS line designed to treat the remaining excess flow-rate (Verrecht *et al.* 2010). Hybrid MBR configurations have also been found to be successful for upgrading WWTPs (e.g., Giesen *et al.* 2008; Lousada-Ferreira *et al.* 2010; Krzeminski *et al.* 2012).

The number of MBR applications for wastewater treatment is growing rapidly: the total installed MBR treatment capacity globally was recently reported to have increased by over half in five years (Hai *et al.* 2019). The increasing MBR capacity includes brand new WWTPs, adding new MBR lines to existing WWTPs and retrofitting existing WWTP process basins with membrane technology. For instance in Stockholm, Sweden, the CAS processes of two large existing WWTPs will be upgraded to MBR processes in the near future (Andersson *et al.* 2016). In Finland, the first MBR processes were commissioned in 2018, the largest one of those being in the Taskila WWTP.

Taskila WWTP (165,000 Personal Equivalent) located in Oulu is the largest municipal treatment facility in Northern Finland. The plant was upgraded by implementing a new MBR process line that is operated in parallel with the old CAS process in a hybrid manner (Risteelä 2019). With the new MBR, the biological treatment capacity of the WWTP was increased by approximately 35% targeting for more efficient nutrient removal. To the best of our knowledge, Oulu is the northernmost location where a large-scale municipal MBR is in operation, which makes the Taskila case unique. The influent temperature drops down to 6 °C in wintertime, and the low water temperature is known to reduce membrane permeability (Yoon 2015). For that reason, the cold climate was considered in dimensioning the MBR process and designing the operational practices.

The impact of the aforementioned energy-saving solutions developed for MBRs can be assessed, for instance, by using Key Performance Indicators (KPI). There are plenty of KPIs suggested for water utilities, some of which consider simultaneously resource consumption and effluent load on the recipient (Ingildsen & Olsson 2016). The functional units of KPIs can relate with, for instance, treated wastewater volume, personal equivalent load, specific type of pollutant removal or they can include all the relevant pollutants as a combined measure (Longo *et al.* 2016).

The paper is organized as follows. First, we provide the WWTP process and data description with emphasis on the new MBR process and describe the performance assessment methodology. Then, we present and discuss the results with highlight on operational experiences, treatment results and pervasive process performance. Eventually, the conclusions are drawn in the last section.

METHODS

Process description

The Taskila WWTP treats an average influent flow rate of 47,000 m^3/d and the average raw wastewater characteristics are presented in Table 1. Wastewater treatment requirements given in the environmental permit of the WWTP are shown in Table 2. Additionally, effluent disinfection is obligatory in the period between May and August.

Table 1 | Influent wastewater characteristics of the Taskila WWTP

Variable	Unit	Value, average
SS	mg/l	390
$BOD_{7,ATU}$	mg/l	230
COD_{Cr}	mg/l	600
TN	mg/l	67
TP	mg/l	9.5

Table 2 | Treatment requirements of the Taskila WWTP

Variable	Effluent concentration, mg/l	Reduction rate, %
$BOD_{7,ATU}$	≤15	≥90
TP	≤0.5 (≤0.3*)	≥90 (≥95*)
TN**	–	≥70

*after 1.1.2021.
**when T > 12 °C.

A simplified plant layout is provided in Figure 1. Primary treatment consists of screening, grit removal, chemical flocculation and primary sedimentation units. After the common primary treatment, the wastewater flow is split into the two parallel biological treatment processes. The new

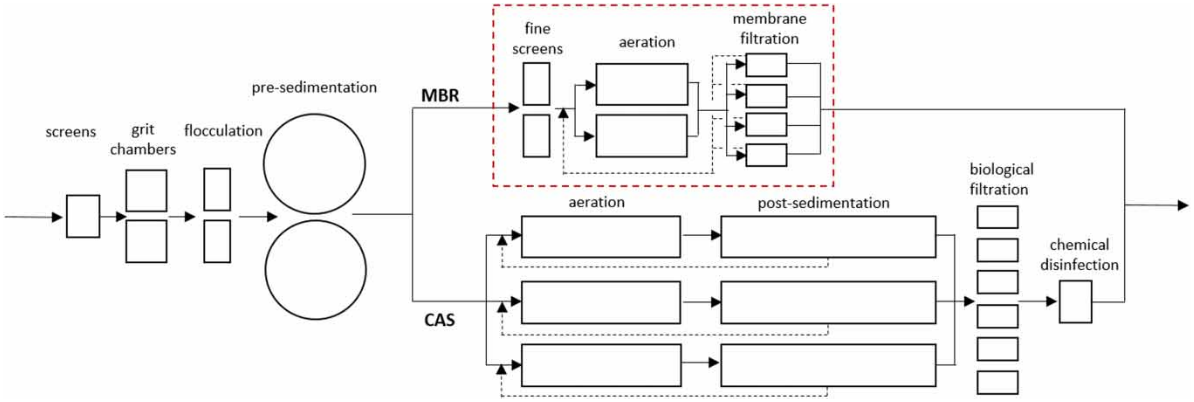


Figure 1 | Simplified layout of the Taskila wastewater treatment process. MBR indicated with red dashed line.

MBR process is designed to treat roughly a constant load that corresponds to 35% of the plant average influent flow and the rest is treated in the old CAS process that is designed to receive a larger hydraulic load variation, for instance, during the storm water events.

Excess sludge from both CAS and MBR lines is pumped to headworks of the plant and is removed together with the primary sludge from the pre-sedimentation process. The sludge treatment line consists of chemical sludge conditioning (KemiCond process by Kemira) followed by sludge dewatering with centrifuges.

The CAS line includes an aeration process with DN-configuration, post-sedimentation, post-filtration and chemical disinfection (DesinFix by Kemira) units. The aeration process is divided in three parallel aeration lines with the total volume of 15,000 m^3. The post-filtration process is operated as a biological denitrification process in summertime.

Online instrumentation of the CAS line includes nutrient analyzers after post-filtration (PO_4-P, NH_4-N, NO_3-N) and after filtration (PO_4-P, TP, NO_3-N). Aerobic volume of the two swing zones in the aeration basins are controlled manually and Dissolved Oxygen (DO) cascade control is applied for the aeration process.

The MBR unit consists of a fine screening unit and an aeration process with DN-configuration that are followed by an ultrafiltration (UF) process (Table 3). The aeration process includes two parallel lines with total volume of 4,500 m^3. The aeration basins are divided in two anoxic, three swing (anoxic/aerobic) and two aerobic zones. The operational flux and Mixed Liquor Suspended Solids (MLSS) concentration values are designed based on the process temperature as indicated in Table 3.

The MBR line is equipped with nutrient sensors (PO_4-P, TP, NH_4-N, NO_3-N) and plentiful other instruments. The aerated volume of the aeration process (swing zones) can be controlled with a rule-based system and on-line measurements or manually. DO cascade control was used for aeration control during the investigated period, but NH_4-N cascade control is also implemented in Distributed Control System (Valmet DNA). UF-membrane process is equipped with train-specific turbidity sensors that are applied for anomaly monitoring.

Table 3 | Membrane filtration design values

Variable	Unit	Design value
Fine screening		
Units	pcs	2
Pore size	mm	2
Aeration		
Basins	pcs	2
V, basin	m^3	2,250
V, tot	m^3	4,500
MLSS, aeration	g/l	7.0*/10.0**
Membrane filtration		
Trains	pcs	4
Cassettes/train	pcs	8
Cassettes, total	pcs	32
Flux, average flow (peak flow)	lmh	18/24 (24*/35**)
Membrane area, total	m^2	48,950
Pore size	µm	0,04
MLSS, membrane tanks	g/l	8.75*/12.5**
T, min	°C	6

*when $T < 12$ °C; ** when $T \geq 12$ °C.

ZeeWeed 500D hollow fibre membranes are used in the UF process. The design values of the UF process are given in Table 3. The UF unit comprises four parallel trains allowing for a flexible process control scheme with repeated production cycles. The number of the trains simultaneously in production is controlled using the Plant Flow Demand value, which is calculated based on the surface level in the bioreactor. Membrane cassettes are submerged in each train.

Membrane aeration, back-pulses, relaxation phases and chemical cleanings are applied for the membrane maintenance. LEAPmbr Aeration Technology (LEAPmbr AT) is the ZeeWeed aeration system that uses multi-stage coarse bubble diffusers that are incorporated into the cassette frame. The LEAPmbr AT aeration devices release large mushroom-cap bubbles, which create high scouring forces along the surface of the membrane fiber. The membrane scouring air flow-rate is optimized based on the operating conditions and the calculated process indicators, particularly membrane cake resistance values for each production cycle. Based on those indicators, the decision algorithm selects a higher (LEAP-Hi) or a lower (LEAP-Lo) membrane air flow-rate to be used.

Chemicals used in the wastewater treatment process are summarized in Table 4. Usually, chemical dosing in the WWTP is realized with flow-proportional control schemes. Polyaluminium chloride (PAC), polymer and sodium carbonate are dosed to the common primary treatment process. Precipitation chemical is also used in a second dosing point both in the CAS and MBR: ferric sulphate is used in the CAS line and PAC in the MBR line. Polymer can be dosed to post-sedimentation of the CAS line to improve the sludge settling properties. Methanol is used in summertime as an external carbon source in the biological post-filtration units of the CAS line. Methanol is dosed using a feed-forward controller based on mass balancing combined with feedback correction. Formic acid and hydrogen peroxide are mixed together to form performic acid in the disinfection process of the CAS line during warm summer period. Citric acid and sodium hypochlorite are applied for membrane maintenance cleaning (each 1–2 times a week) and recovery cleaning (each 1–2 times a year) in the MBR line.

Table 4 | Chemical used in the wastewater treatment process of Taskila WWTP

	Process unit			
Chemical	**Primary**	**CAS**	**MBR**	**Purpose**
Polyaluminium chloride	x		x	Precipitation
Ferric sulphate		x		Precipitation
Polymer	x	x		Flocculation
Methanol		x		Carbon source for TN removal
Sodium carbonate	x			Alkalinity adjustment
Citric acid			x	Membrane cleaning
Sodium hypochlorite			x	Membrane cleaning
Formic acid		x		Disinfection
Hydrogen peroxide		x		Disinfection

Data description

Historical data of online measurements, laboratory analyses and calculated variables of the Taskila WWTP were acquired for the investigation from two sources: *VeRa* reporting and operations diary software (FCG) and *InSight* remote monitoring system (SUEZ). Data recorded in VeRa covers the whole plant and they were utilized for the operational period of January 2015–March 2020. The InSight data focus on the monitoring parameters of the membrane filtration unit and they were available for the research for the MBR operation period.

Energy consumption data for the MBR unit was available only starting from June 2019, which restricted the period used for the overall performance assessment.

The bacteria analysis data used in the study were partly acquired from Risteelä (2019) and partly from the ongoing EMCOLD project of the University of Oulu.

Performance assessment

KPI approach is applied for assessing the wastewater treatment processes of Taskila WWTP. Because operational costs and treatment performance are of high interest, we combined both of those features in a KPI. Operating expenditures (*OPEX*) included in this study relate with the aeration energy use (both activated sludge and membrane aeration) and the chemical use in the treatment processes. Due to the fact that primary treatment performance clearly affects the operation of the consecutive biological units, the chemicals used in the primary treatment are also included in the assessment. The expenses of the primary treatment chemicals are allocated to the CAS and MBR lines based on their flow-rates. Pumping energy use is not included in the assessment because of the shortcomings in the available energy data. OPEX is calculated according to Equation (1).

$$\mathrm{OPEX}(t) = \sum_{i=1}^{k} (E_k \times P_E) + \sum_{i=1}^{m} (C_m \times P_{C,i}) \tag{1}$$

where k is the number of energy consumption sources, E is energy consumption of a single source, P_E is the price of energy, m is the number of chemicals, C is the amount of a single chemical type used and P_C is the price of a single chemical type.

In this work, we apply the Total Pollutant Equivalent removed (TPE_{rem}, Longo *et al.* 2019) index, which combines pollutants removed in a wastewater treatment process as a single variable (Equation (2)).

$$TPE_{rem}(t) = \sum_{i=1}^{n} W_i \times POL_{rem,\ i}(t) \tag{2}$$

where n is the number of pollutant types, W is the weight for different pollutants, POL_{rem} is the amount of a single pollutant removed in the treatment process (kg/d) and t is time.

The latest available laboratory data and the daily average flow-rates were used for calculating POL_{rem} of the considered n water quality parameters.

KPI 1, used for assessing process performances, is calculated using Equation (3).

$$KPI\ 1(t) = \frac{OPEX}{TPE_{rem}}(t) \tag{3}$$

Different weights, W, have been used for the single pollutants (see, e.g., supplementary material in Longo *et al.* 2016). In this work, we apply the pollutant weights reported in Benedetti *et al.* (2008) that are summarised in Table 5.

Table 5 | Weights of the pollutants for KPI calculation

	BOD	COD	SS	TN	TP
Weight, W	2	1	2	20	100

KPI 2 is another measure used for process performance investigation (Equation (4)).

$$KPI\ 2(t) = \frac{OPEX}{Q}(t) \tag{4}$$

where Q is flow-rate of treated wastewater (m^3/d).

RESULTS AND DISCUSSION

MBR operating parameters

Monitoring indicators of the MBR process are presented and discussed in this subsection. Figure 2(a) represents time series of Mixed Liquor Suspended Solids (MLSS) concentration in the MBR aeration basin and Time-To-Filter (TTF) test during February 2019 – November 2019. The MLSS concentration has ranged from 4.5 g/l to 12.5 g/l during the investigated period (Figure 2(a)). Time series of the calculated Solids Retention Time (SRT) show large variation in the first half of the year 2019 (Figure 2(b)), which was a consequence of operational actions taken to cope with the high loads caused by the unstable primary treatment performance.

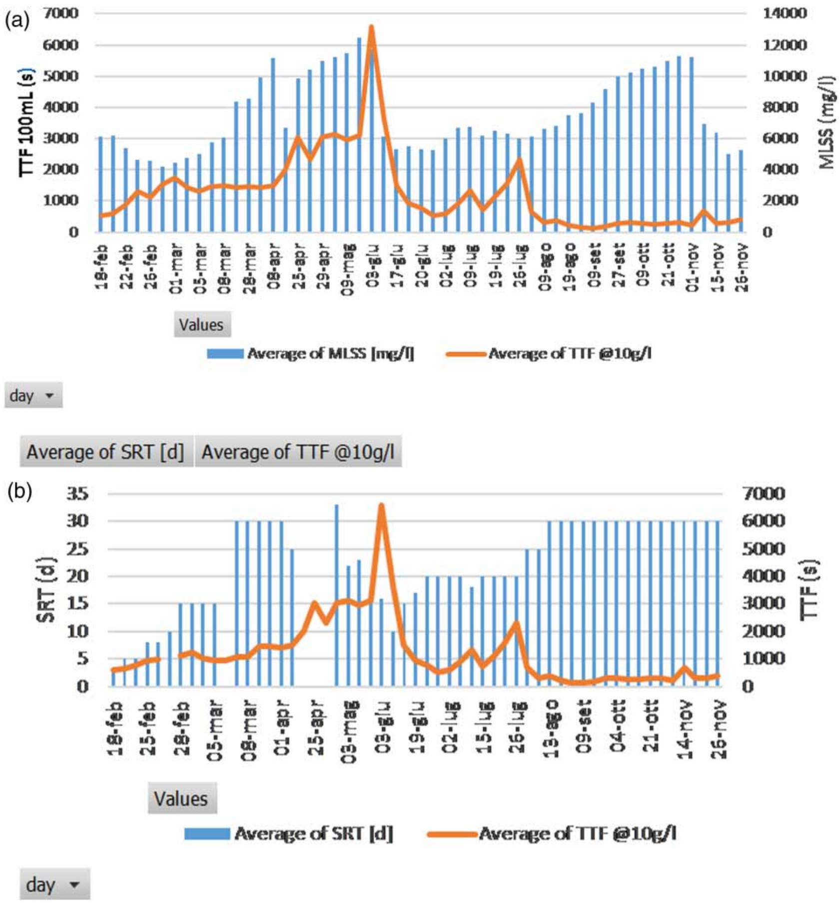


Figure 2 | Time series of MLSS and TTF (a) and SRT (b) in MBR aeration basin.

TTF is a field test performed for monitoring the sludge filterability, described, for instance, in Andersson *et al.* (2019). The TTF values were increasing in winter and spring 2019, which indicated worsening of the sludge filterability properties. Because of that, several actions were carried out to improve the sludge quality of the MBR:

- SRT was gradually increased to 30 days and then maintained stable, starting from August 2019 (Figure 2(b)). The earlier practical experience at the Taskila facility had shown that a higher SRT improves sludge filterability, which, according to our hypothesis, is associated with an increased content of metals in the sludge.
- PAC dosing to the aeration basins of the MBR line was started in August 2019. The higher aluminium content in activated sludge was shown to improve the sludge filterability, presumably by trapping colloidal matter to a more dense sludge structure. Prior to PAC dosing, jar tests were conducted to investigate the influence of different aluminium and iron dosages on TTF in order to find an effective precipitant dosage.
- Optimization of the primary treatment chemical dosages and changing the polymer type from cationic to anionic during Spring 2019 improved the primary treatment performance and, therefore, enabled a more stable influent load to the MBR. These activities improved solids separation in the primary treatment and reduced the amount of fine solids accumulating in the wastewater treatment process.

Resulting from these actions, the sludge filterability improved significantly, which is indicated as the low TTF results since August 2019 presented in Figure 2.

Two different cake resistance values are calculated as monitoring parameters of membrane filtration: (1) the initial resistance of the sludge cake on the membranes before each cycle and (2) resistance of the sludge cake formed on the membranes during each cycle. Time series of those parameters for membrane train 1 are shown in Figure 3. Impact of the aforementioned actions to improve the sludge filterability can be noticed: the cake resistance values have been clearly lower since August than before that date. The lower resistance values enable the dominant use of the lower membrane

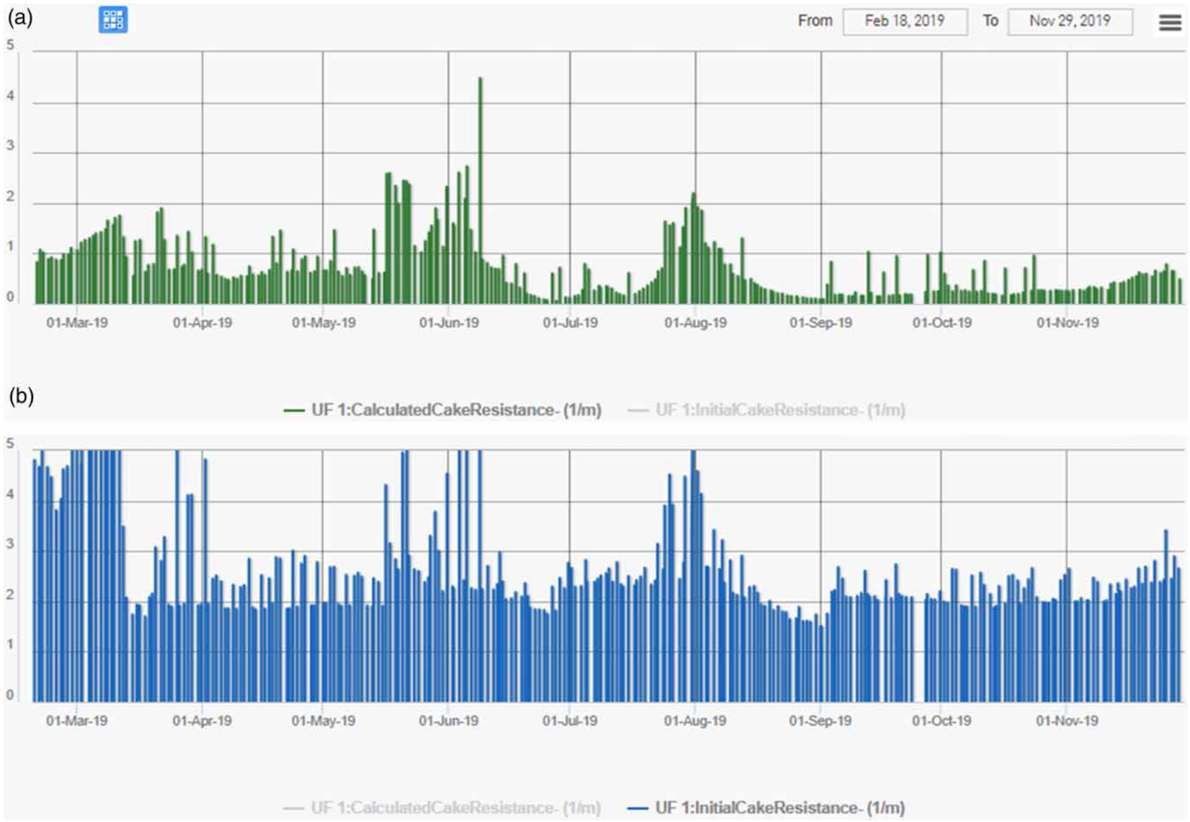


Figure 3 | Time series of calculated cake resistance (a) and initial cake resistance (b) of membrane train 1.

air-flow, LEAP-Lo, and which, alongside the higher membrane permeability, is a significant benefit from the point of view of resource-efficiency.

Based on the provided examples, it can be concluded that TTF is a key parameter in MBR systems. By improving sludge quality, a more stable operation of the membrane system is achieved at a reduced power consumption. Higher operating fluxes are also possible with good sludge filterability properties.

Treatment results

Treatment results and comparison between the MBR and CAS lines are provided in this section. Since the start-up of MBR, it has treated an average of 30% of the WWTP inflow. Figure 4(a) shows the operating conditions in terms of influent flow-rates of CAS and MBR and of temperature in the aeration process between January 2019 and March 2020. Table 6 collects the average treatment results before and after the WWTP expansion as well as the average results of the CAS and MBR lines after the plant upgrade. Data of effluent concentrations/values and reductions are represented for six water quality parameters: Suspended Solids (SS), Biochemical Oxygen Demand during 7 days ($BOD_{7,ATU}$), Chemical Oxygen Demand (COD_{Cr}), Total Phosphorus (TP), Ammonium Nitrogen (NH_4-N) and Total Nitrogen (TN). As for TN removal, it is emphasized that Table 6 shows year-round data correspondingly with the other variables, but TN removal is only demanded when the process temperature is >12 °C. The commissioning of the MBR was completed in October 2018. The 'before expansion'

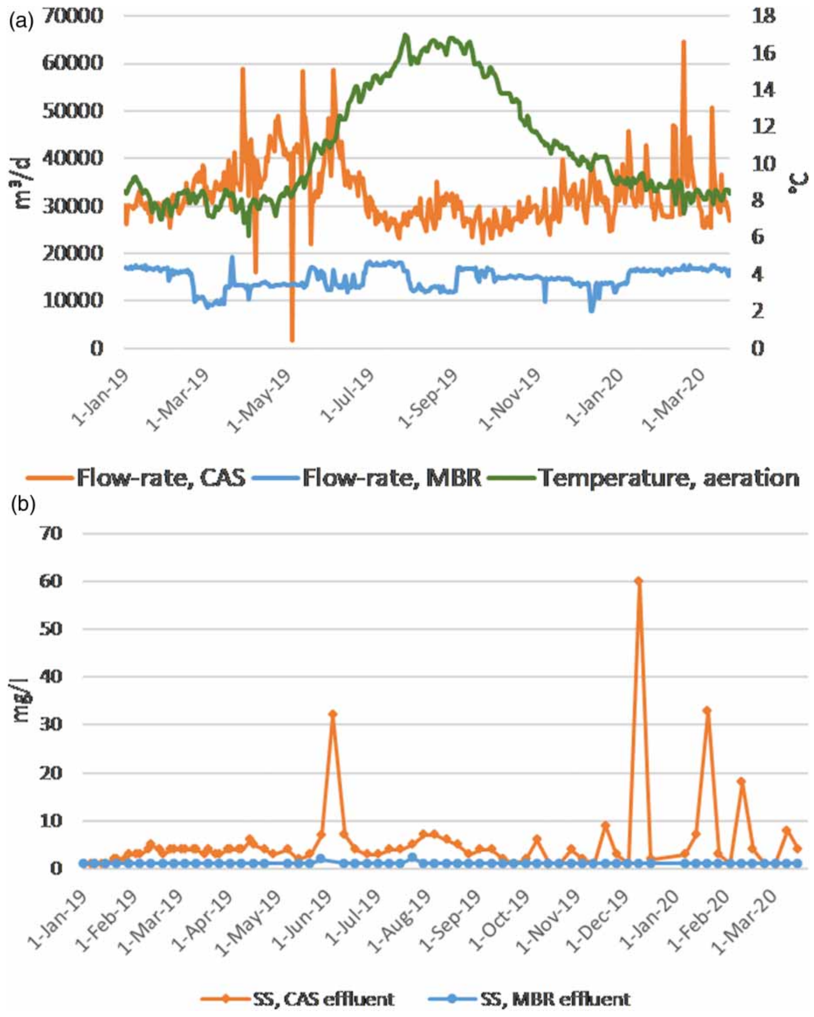


Figure 4 | MBR and CAS influent flow-rates, aeration temperature (a) and MBR and CAS effluent SS concentrations (b) in 2019–2020.

Table 6 | Average treatment results of WWTP before and after the plant expansion and, individually, of CAS and MBR lines after the plant expansion

Variable	Unit	WWTP, before expansion	WWTP, after expansion	CAS, after expansion	MBR, after expansion
SS	mg/l	27	12	17	<2
	%	96	97	96	>99
$BOD_{7,ATU}$	mg/l	12	5.5	9.5	1.8
	%	95	98	97	99
COD_{Cr}	mg/l	75	47	45	35
	%	90	92	92	94
TP	mg/l	0.60	0.42	0.55	0.25
	%	95	95	94	97
NH_4-N	mg/l	34	15	12	9.5
	%	–	–	84	99
TN	mg/l	43	33	24	33
	%	32	52	60	51

data is calculated from the period January 2015–September 2018 and the ‘after expansion’ data from the period October 2018–March 2020.

Time series of SS concentrations of MBR and CAS effluents are presented in Figure 4(b). The MBR permeate SS concentration has typically been lower than the laboratory detection limit of 2 mg/l. The low SS concentration of the MBR effluent obviously improves the SS removal of the whole WWTP, but the plant expansion has also reduced the incoming load to CAS. That also has a positive effect on the SS removal rate, especially during the snow melting and storm events that were especially challenging before the plant expansion. For that reason, the average SS effluent concentration of CAS has decreased by more than half after the start-up of the MBR.

Purification performance of organic matter is presented as $BOD_{7,ATU}$ and COD_{Cr} effluent concentrations and removal rates (Table 6). $BOD_{7,ATU}$ and COD_{Cr} treatment results have improved since the plant upgrade by 61 and 37%, respectively. Moreover, the MBR has shown clearly better organic matter treatment performance than CAS.

The average TP concentration in the MBR effluent since the start-up of the unit has been 0.25 mg/l and in the CAS effluent 0.55 mg/l (Table 6), whereas the environmental regulation for the effluent TP is $\leq$0.5 mg/l. Particularly, the discharged effluent TP load has decreased by 40% since the WWTP upgrade.

Nitrification has earlier been a bottleneck in total nitrogen removal, which is obligated in summer conditions (>12 °C). Time series of the effluent NH_4-N concentrations in 2015–2020 are presented in Figure 5(a). In spring 2019, the upgraded WWTP began nitrifying several months earlier than in the previous years, especially in the MBR line, providing a basis for efficient nitrogen removal. Unlike the previous years, efficient nitrification has taken place also in the cold winter season after the WWTP upgrade and, hence, there obviously is a clear performance increase.

Time series of TN removal rates of the Taskila WWTP and, specifically, of the MBR and CAS lines in 2019–2020 are plotted in Figure 5(b). TN removal rate of $\geq$70% is demanded as an average of the period when process temperature is >12 °C, highlighted in yellow in the figure. In 2019, TN removal during the warm period was approximately 60%, which is remarkably better than in the previous years. TN removal performance of CAS was better than that of the MBR. An essential reason for this was that methanol was fed to the biological post-filters of the CAS line from July 12th to December 20th 2019 to enhance the denitrification rate, whereas in the MBR line denitrification relied only on the organic substrate of the incoming wastewater. The effect of methanol during the dosing period can be observed clearly in Figure 5(b). It needs also to be emphasised that the operation of the MBR with respect to TN removal was not yet optimized in 2019 and fine-tuning of operational practices is still ongoing. In the beginning of 2020, TN removal rates of the MBR are significantly higher than in

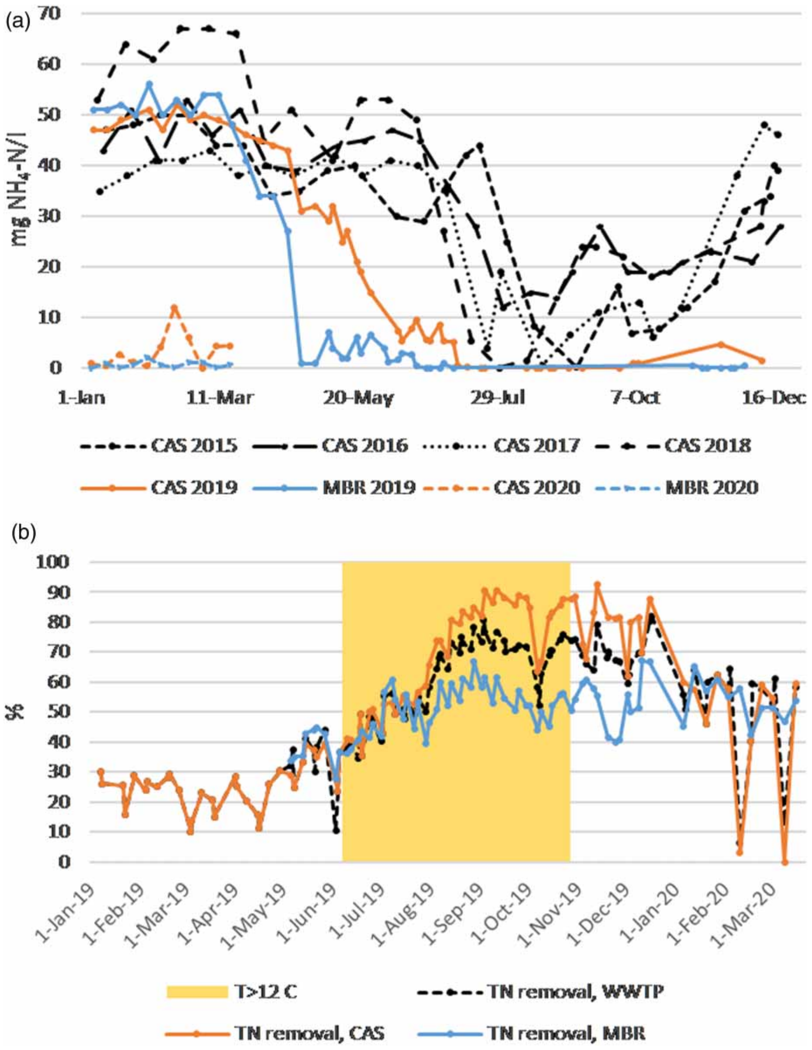


Figure 5 | MBR and CAS effluent NH$_4$-N concentrations in 2016–2020 (a) and MBR, CAS and WWTP TN removal rates in 2019–2020 (b).

spring 2019, which provides a better basis for a stable treatment performance for the forthcoming summer period.

The post-filtration effluent of the CAS line is treated in a chemical disinfection process during summertime in order to improve the hygienic quality of the water. In fact, the monitoring results indicate that *E. coli* (Figure 6(a)) and enterococci (Figure 6(b)) are largely present in the post-filtration effluent before the disinfection treatment. As for the MBR effluent, *E. coli* or enterococci has not been detected in any of the studied samples (Figure 6). As a conclusion, membrane filtration produces treated water of excellent quality according to the EU directive 2006/7/EC on bathing water quality.

Performance assessment

An investigation of resource use in water treatment is provided in this subsection. Consumption of two resource types, energy and chemicals, are converted to expenditures in order to enable a commensurate assessment. The time series of *KPI 1* and *KPI 2* are presented in Figure 7(a) and 7(b).

KPI 1, which combines OPEX with overall pollutant removal shows no significant differences between the CAS and MBR lines in normal operational situations during the studied period. The average *KPI 1* values for CAS and MBR are 0.016 €/TPE$_{\mathrm{rem}}$ and 0.018 €/TPE$_{\mathrm{rem}}$, respectively. The high peaks in

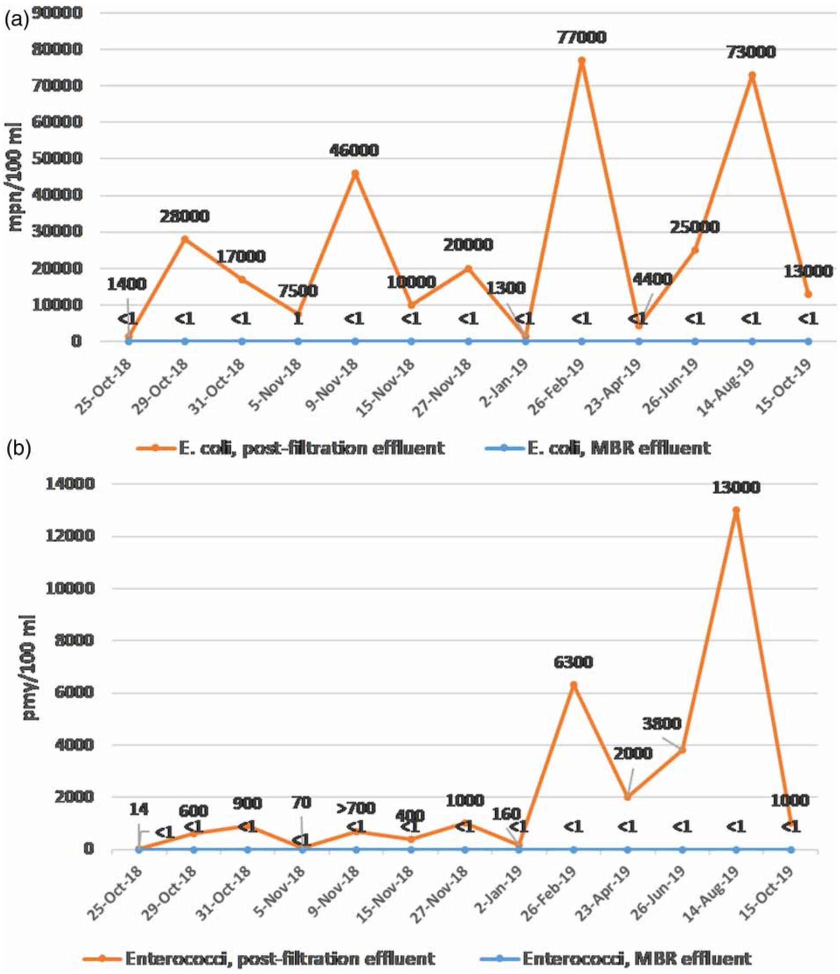


Figure 6 | *E. coli* (a) and enterococci (b) analysis results from effluent of the post-filtration unit of CAS line and from MBR effluent.

the *KPI* 1 values of the MBR in December 2019 are due to the recovery cleanings performed for the membranes, which obviously associate with increased cleaning chemical consumption. The small frequent peaks in the MBR time series originate from maintenance cleanings performed according to a weekly schedule. Interestingly, when considering only the days when LEAP-Lo aeration mode was principally used, the standard operating mode with good sludge filterability, the average *KPI 1* value for MBR is 0.014 €/TPE_{rem}, demonstrating the benefits received from the smaller energy consumption.

Time series of *KPI 2* in Figure 7(b) shows trends comparable to *KPI 1*. No major differences between CAS and MBR are observed. The average *KPI 2* values for CAS and MBR were 0.056 €/m^3 and 0.060 €/m^3, respectively. The trend of both CAS and MBR values are decreasing in since January 2020: for CAS, the reason for this is that the methanol use was stopped in December 2019 and for the MBR the reason is the dominant use of the LEAP-Lo aeration mode. The higher *KPI 2* values of the CAS line until September are due to the use of disinfection chemicals.

It can be concluded that for similar effluent quality for TN (no methanol addition to the CAS) and microbiology (disinfection of the CAS post-filtered effluent), the KPI values are practically the same for CAS and the MBR. However, the latter provides a simpler process scheme, MBR only, versus three different process steps in the conventional scheme: secondary treatment, tertiary treatment and final post-disinfection.

The Taskila MBR process is still being optimized. Work has been done to improve the sludge quality and, because of that, LEAP-Lo has been mainly used for membrane aeration for the last months of the studied period (Figure 8, LEAP-Lo mode highlighted with orange colour). The aforementioned sludge

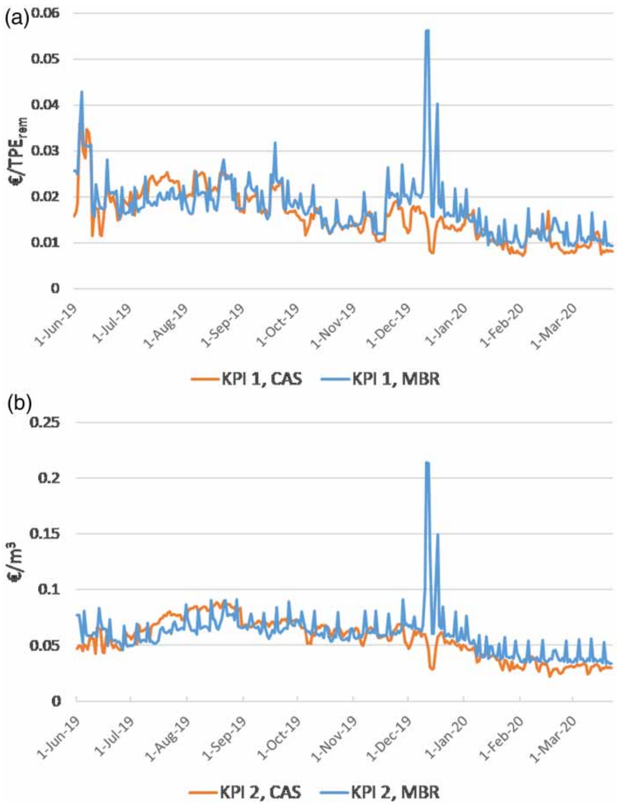


Figure 7 | Time series of *KPI 1* (a) and *KPI 2* (b) for CAS and MBR lines.

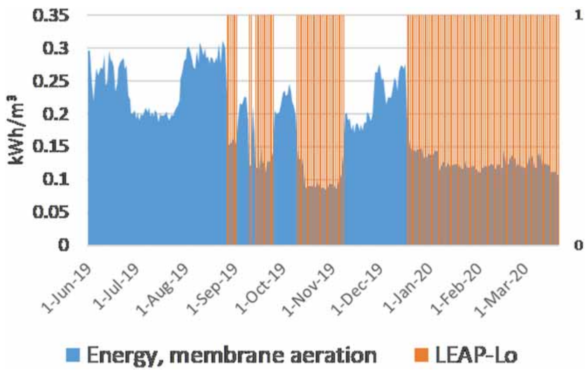


Figure 8 | Time series of membrane aeration energy consumption; use of LEAP-Lo mode highlighted.

quality optimization efforts have allowed reduction of the aeration energy consumption of the membrane aeration at approximately 0.12 kWh/m^3. The energy consumption (kWh/m^3) of the membrane aeration has been 49% smaller in LEAP-Lo mode than in LEAP-Hi mode. Similarly, the use of LEAP-Lo lowered the total aeration energy consumption (both activated sludge and membrane aeration) of the MBR line by 34%. There is also further energy saving potential in the activated sludge aeration of the MBR line by means of fine-tuning the process control scheme.

We applied two different KPIs for the treatment process assessment. The treatment performance (TPE$_{rem}$) is included in *KPI 1*, which obviously is appropriate considering the purpose of WWTPs. However, there are a few challenges in evaluating the treatment performance. Firstly, there are many different pollutant weights suggested in the literature and selecting which ones to apply is not straightforward. For instance, sensitivity of receiving water bodies for different pollutant types differs, which could be considered when setting the weights. Secondly, selecting the pollutants included in the evaluation is also challenging. One option is to consider the pollutants that are currently regulated in the WWTP, but if removal of other substances is also targeted, including such substances would be justified. In this case study, *KPI 1* covers only traditionally regulated pollutants (Table 5), but as a future work, it could be adjusted to include, for instance, pathogens or microplastics (see, e.g., Talvitie *et al.* 2017), which, presumably, would emphasize the benefits of membrane filtration treatment. Benefits of using *KPI 2* include its simplicity: no pollutant data, which are collected less frequently and need laboratory analyses associated with time delay, are required. Nevertheless, when targeting for holistic process performance assessment and time delays are acceptable, we recommend including pollutant removal rates in KPIs.

As a future work, the KPIs can be implemented in the WWTP reporting system. Furthermore, pumping and mixing energy use can be added to the OPEX calculation. The new information provided by the KPI assessment allows for recognition of the efficient plant optimization activities.

CONCLUSIONS

In this paper, we described the current process set-up of the upgraded Taskila WWTP and operational experiences of the new MBR process. Furthermore, the treatment results of the first 18 months and an assessment of the overall performance with KPIs including operational expenditures were given. Results of the KPI investigation did not show significant differences in the total resource costs between the old CAS line and the new MBR line. However, it is obvious that more costs of the CAS line were associated with the treatment chemicals whereas the operation of the MBR line was more energy-intensive. Fine-tuning the process optimization and operational practices of the hybrid plant are still going on. The most recent results demonstrate that with current process operating set-points the sludge filterability is good, allowing for energy-efficient membrane operation and stable biological treatment performance. Therefore, improved overall results of the MBR and of the whole WWTP are expected in the forthcoming years.

DATA AVAILABILITY STATEMENT

All relevant data are included in the paper or its Supplementary Information.

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