Unit Energy Consumption as Benchmark to Select Energy Positive Retrofitting Strategies for Finnish Wastewater Treatment Plants (WWTPs): a Case Study of Mikkeli WWTP

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Abstract Retrofitting municipal wastewater treatment plants (WWTPs) to energy positive is a major challenge faced by many water utilities. Selection of innovative technologies to achieve retrofitting goals is critical for capital improvement programs in WWTPs. This paper aims to provide a statistical analysis method of unit energy consumption in conventional Finnish WWTPs, presenting Mikkeli WWTP as a case study. The average energy consumption at Finnish WWTPs was quantified as a mean of 0.49 kWh/m³ with a standard deviation of 0.197. The statistical analysis showed that the total energy consumption in Finnish WWTPs are positively correlated with inflow rate and sludge production. However, the unit energy consumption decreases with increasing plant capacity. The energy benchmarking of Mikkeli WWTP confirmed the energy gap of 0.11 kWh/kg COD in electricity. The major energy saving potentials are attributed to secondary treatment, screening and grit removal, and influent pump stations. A plausible innovative retrofitting strategy comprising four emerging energy-neutral or positive technologies is proposed to maximally harness the chemical energy content in wastewater: enhanced primary sedimentation, staged anaerobic fluidized membrane bioreactor (SAF-MBR) with completely autotrophic nitrogen removal over nitrite process (CAN-ON), and co-digestion of sludge with organic food-waste. The net energy balance of emerging technologies showed a maximum energy saving potential of 1.26 kWh/kg COD, which could be sufficient to overcome the energy gap of Mikkeli WWTP, providing net positive energy surplus of 1.15 kWh/kg COD.

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1 Introduction

Municipal WWTPs, which typically employ conventional activated sludge (CAS) processes, are intensive energy consumers (Dai et al. 2015; Daw et al. 2012; Gikas 2017; Shoener et al. 2014; Yan et al. 2017). WWTPs consume 30 to 60% of municipal energy demand (Scherson and Criddle 2014). The specific energy consumption of CAS plants generally ranges from 0.3 to 0.6 kWh/m³, of which about half is used for aeration to supply O₂ and convert organic pollutants to sludge (Dai et al. 2015; Scherson and Criddle 2014; Shoener et al. 2014). In the European Union (EU), the energy requirements in WWTPs account for more than 1% of the consumption of electricity in Europe (EU 2017). In the United States, wastewater treatment demands approximately 4% of the nation's electricity (~75 billion kWh) (USEPA 2010), whereas the energy consumed by WWTPs in China is 100 billion kWh of electricity (Yan et al. 2017). About \$7.5 billion is required annually to cover the electricity cost to deliver safe drinking water and provide effective wastewater treatment in the US (USEPA 2010). Over the next 20 years, the US water and wastewater infrastructures will require a huge investment of about \$600 billion for treating and transferring water and wastewater (EPA 2015). The electricity demand to operate WWTPs will increase by more than 20% in the next 15 years in the developed countries, contributing to climate change via green house gas (GHG) emissions due to the use of fossil fuels in power plants (Hao et al. 2015; Wang et al. 2012). If the current trend is to be continued, massive natural resource depletion, environmental risks, and substantial economic expenditures will be intensified (Yan et al. 2017). Therefore, sustainable wastewater treatment technologies are of prime interest to reduce the substantial amount of energy consumption and carbon footprints in WWTPs.

There are various methodologies to estimate energy consumption in WWTPs. Energy benchmarking in WWTPs is a powerful management tool which uses statistical data to determine the energy efficiency of a plant in comparison with other plants or standard benchmarks (Belloir et al. 2015), in an effort to achieve energy savings. Energy benchmarking can be an internal process, measuring WWTP performance against its own past performance, or an external process, comparing to the benchmarks of similar WWTPs. Poorly performing wastewater treatment facilities can be prioritized for immediate improvement. Nevertheless, the energy benchmarking methodology can be of limited use when comparing similar WWTPs in different locations, because of the different influent wastewater pollution loads, COD/N ratios, and effluent consents (Belloir et al. 2015). Even though it is very challenging to compare energy consumption across different locations, some common trends in energy consumption have been reported by previous benchmarking studies: unit electricity consumption decreases as the size of the plant increases. These processes include aeration, sludge treatment and pumping stations which are the most electricity demanding processes (Belloir et al. 2015). Energy consumption in WWTPs involves various forms of energy such as electrical, manual, fuel, chemical etc. Electrical energy is only about half of the total energy consumption in a wastewater treatment process (Singh et al. 2012).

To achieve energy positive wastewater treatment, increasing numbers of cutting edge technologies, such as enhanced primary separation by diverting BOD to anaerobic digestion, biological removal of ammonia through anammox, anaerobic digestion (AD), biological

microbial fuel cells (MFCs), microalgae cultivation processes have been commercially implemented (Dai et al. 2015; Hahn and Figueroa 2015; McCarty et al. 2011; Meerburg et al. 2015; Remy et al. 2014; Scherson and Criddle 2014). So far, anaerobic digestion (AD) is considered as the key technology to create net-zero energy WWTPs via recovery of organic chemical energy to electricity or heat (Gao et al. 2014; McCarty et al. 2011; Yan et al. 2017). The energy self-sufficiency via AD treatment of wastewater has been realized partially (~30%) or fully (~100%) in many WWTPs (McCarty et al. 2011; Shen et al. 2015; Yan et al. 2017). With an enhanced primary treatment process using microsieving facilities, about 54–85% of energy reductions (net energy balance of 0.115–0.32 kWh/m³) have been reported (Gikas 2017; Remy et al. 2014). A net-zero energy (NZE) model (Yan et al. 2017), based on the adjustment of metabolic material allocation, showed about 80% offsetting of electricity and sludge disposal cost as compared to conventional WWTPs. Mainstream short-cut nitrogen removal techniques (e.g., CANON with anammox) showed excellent net energy balance of 0.09–0.23 kWh/m³ (Dai et al. 2015; Scherson and Criddle 2014). A pilot-scale anaerobic baffled reactor (ABR) as enhanced primary treatment in psychrophilic conditions showed excellent net electrical energy potential of 0.15–0.24 kWh/m³ (Hahn and Figueroa 2015). To further enhance biogas production through AD process, activated-sludge was co-digested with fat-oil-grease (FOG) to provide 30 to 100% more biogas production (Lauwers et al. 2012).

The main objective of this paper is to perform a statistical analysis of energy consumption in Finnish municipal WWTPs and to assess retrofitting strategies for the Mikkeli WWTP as a case study. A major energy gap in Mikkeli WWTP (case study) was quantified by comparing with the unit energy consumption benchmarks. An innovative configuration comprising four emerging technologies, i.e., (1) enhanced primary sedimentation, (2) staged anaerobic fluidized membrane bioreactor (SAF-MBR), (3) completely autotrophic nitrogen removal over nitrite process (CANON), and (4) co-digestion of sewage sludge with organic waste, were evaluated for their feasibility to achieve energy self-sufficiency at the Mikkeli WWTP.

2 Database and Methods

2.1 Database

The database for unit energy consumption at various WWTPs was critically reviewed and extracted from extensive peer-reviewed and original research papers (Dong et al. 2017; Gu et al. 2017; Rodriguez-Garcia et al. 2011; Wang et al. 2012; Yan et al. 2017). Various guideline manuals for energy positive WWTPs from the Environmental Protection Agency (EPA), the Water Environment Research Foundation (WERF), the Water Environment Foundation (WEF) (Crawford and Sandino 2010; Daw et al. 2012; Fillmore et al. 2011; Goldstein and Smith 2002; Tarallo et al. 2015; USEPA 2010; Wisconsin 2016) were reviewed. Moreover, peer-reviewed articles for energy-neutral or positive emerging technologies were analyzed for theoretical data and net energy savings calculations (Ali and Okabe 2015; Dai et al. 2015; Gao et al. 2014; Kartal et al. 2010; Katuri et al. 2014; Kim et al. 2011; Lauwers et al. 2012; McCarty et al. 2011; Meerburg et al. 2015; Nowak et al. 2015; Remy et al. 2014; Scherson and Criddle 2014; Shen et al. 2015; Shoener et al. 2014; Yoo et al. 2012). IBM SPSS software was used in statistical analysis and regression analysis. The theoretical data used in this study are summarized in Table 1.

Table 1 Theoretical data used for energy estimations

Description	Unit	Value	References
Max. theoretical energy potential in medium strength US wastewater	kWh/m ³	1.96	McCarty et al. 2011
Energy content of domestic wastewater (COD basis)	kJ/g COD	13.5	Metcalf and Eddy 2003
Methane content of biogas yield	%	60–70	Kim et al. 2011
Per capita COD load in municipal wastewater	g COD/capita/day	120	Nowak et al. 2015
Energy yield from methane combustion	kWh/mol CH ₄	0.222	Yoo et al. 2012

The benchmarking analysis of electricity consumption in Finnish municipal WWTPs were assessed from a previously conducted survey database that was based on a questionnaire of large (> 100,000 PE), medium-sized (30,000–100,000 PE), and small-scale WWTPs (Haimi et al. 2009). The following information was asked in the questionnaire: influent flow rate; influent and effluent organic loads; dosing capacity; population served; type of sewerage system; and electricity consumption. Furthermore, on-site survey of the Mikkeli WWTP was made and information was collected as a case study. 22 municipal WWTPs, including the case study WWTP, were evaluated based on their scales and electricity consumption. The selected WWTPs comprised activated sludge facilities with different configurations and capacities. Among them, fourteen plants were designed for total nitrogen removal, six (including the case study plant) for ammonial removal, and two plants for biological phosphorus removal. Though the total energy consumption for WWTPs is the sum of electrical, manual, mechanical and chemical energy consumptions, this paper focuses on the electrical energy consumption. Two relevant unit energy consumption indicators were calculated, as follows:

- 1) Energy consumption per unit of treated wastewater $\left[\frac{\text{kWh}}{\text{m}^3} \right] = \frac{\text{Energy Consumption } \left(\frac{\text{kWh}}{\text{d}} \right)}{\text{Treated wastewater } \left(\frac{\text{m}^3}{\text{d}} \right)}$
- 2) Energy consumption per unit COD removed $\left[\frac{\text{kWh}}{\text{kg COD}} \right] = \frac{\text{Energy Consumption } \left(\frac{\text{kWh}}{\text{d}} \right)}{\text{COD removed } \left(\frac{\text{kg COD}}{\text{d}} \right)}$

3 Results and Discussion

3.1 Current Electricity Consumption in Finnish WWTPs

The unit energy consumption of 22 WWTPs were statistically analyzed to present the current energy use in Finnish WWTPs. The histogram of unit energy consumption of the Finnish WWTPs is depicted in Fig. 1. The unit energy consumption in the Finnish WWTPs ranges from 0.18 to 0.96 kWh/m³. The observed data are comparable to unit energy consumption in conventional activated sludge process in Japanese WWTPs (Mizuta and Shimada 2010). The mean energy consumption value is quantified at 95% confidence interval as 0.49 ± 0.197 kWh/m³ varying between 0.39 and 0.57 kWh/m³. The statistical data confirms that the current trend of energy consumptions in Finnish WWTPs is energy intensive.

Similarly, the total energy consumption of Finnish WWTPs was expressed as kWh/year with an immediate estimation of the annual bill. The regression analysis of total energy consumption was assessed with respect to different plant scales and amount of sludge produced as shown in

Fig. 1 Histogram of unit energy consumption in Finnish municipal WWTPs

Fig. 2. The total energy consumption increases with increasing influent load, i.e., the scale of the WWTP (Fig. 2a). Similar trend of energy consumption has been reported by others (Vaccari et al. 2018). Likewise, the increasing sludge production also increases the total energy consumption (Fig. 2b). An average sludge production of about 1.2 kg TS/kg BOD₇ was observed, with water content varying from 68 to 94% (Haimi et al. 2009). Therefore, sludge handling processes including thickening, anaerobic digestion and dewatering (centrifugation) consume significant energy. The large amount of sludge production from the secondary treatment process and the

Fig. 2 Total energy consumption as function of: (a) daily inflow rate (annual average); and (b) sludge production (annual average)

energy consumptions are the major issues in most of the CAS processes worldwide (Tang and Sillanpää 2018). Moreover, the fitting of the observed data with a power law gives a good correlation of total energy consumption to influent flow rate and sludge production with regression coefficients (R^2) of 0.97 and 0.93, respectively.

The distribution of unit energy consumption in Finnish WWTPs is depicted in Fig. 3. The unit energy consumption of WWTPs with flow rate of $<20,000 \text{ m}^3/\text{d}$ is highly fluctuating and ranging from 0.18 to 0.96 kWh/m^3 . Similar tendency of unit energy consumption has been reported in Slovakian municipal WWTPs (Bodík and Kubaská 2013). The smaller WWTPs are characterized by a high energy consumption compared to relatively larger-scale WWTPs. Even though small-scale WWTPs have simplified configuration and wastewater and sludge handling processes, the unit energy consumption is greater than larger WWTPs due to less frequent optimizations and hurdles associated with simplified management (Foladori et al. 2015).

The unit energy consumption as function of plant scale of Finnish WWTPs is compared with worldwide small to large-scale WWTPs, as shown in Table 2. The unit energy consumption decreases substantially when plant scales increase from $3800 \text{ m}^3/\text{d}$ to greater than $378,500 \text{ m}^3/\text{d}$, which confirms the economy of scale (Vaccari et al. 2018).

3.2 Energy Self-Sufficiency at Mikkeli WWTP

3.2.1 Description of Mikkeli WWTP

The Mikkeli WWTP employs the CAS process, and treats about $5 \times 10^6 \text{ m}^3/\text{year}$ of wastewater (Gurung et al. 2016). The aeration plants are equipped with fine-bubble aeration and mixing devices. The treatment plant was in operation since the 1960s and the only process optimizations were performed by changing and upgrading the mechanical devices.

Table 3 shows the annual wastewater load, COD removal efficiency, sludge production from aeration (secondary) treatment, and corresponding energy consumption of the case study plant. The following operational data from 2007 to 2016 were obtained, showing mean influent load of about 63,506 PE. No significant changes in the treated wastewater flow,

Fig. 3 Distribution of unit energy consumption with respect to annual average of treated wastewater inflow

Table 2 Unit energy consumption of WWTPs with respect to different plant scales

	Flow (m ³ /d) × 10 ³						References
	3.8–18.9	18.9–37.8	37.8–75.5	75.5–189.3	189.3–378.5	>378.5	
Energy consumption (kWh/m ³)	0.430	0.334	0.292	0.251	0.196	0.155	Fillmore et al. 2011
	0.392	0.375	0.371	0.372	0.372	0.372	Crawford and Sandino 2010
	1.437	0.661	0.604	0.604	0.604	0.604	Wisconsin 2016
	0.591	0.362	0.318	0.294	0.278	0.272	Goldstein and Smith 2002
	0.490	0.470	–	–	–	–	This study

incoming plant load, and subsequently energy consumption trends were noticed during the past ten years. The plant has an anaerobic digester, which produces about 0.2 million m³ of biogas per year with the aid of a small scale *in-situ* boiler plant. The average unit energy consumption as function of treated wastewater volume was 0.46 kWh/m³, whereas, in terms of COD removal from wastewater, the load was 0.81 kWh/kg COD. As there was no electricity production in the plant, the energy self-sufficiency in electricity is 0%. However, biogas was utilized to produce thermal heat, fulfilling most of the heating demand of the site, achieving almost 100% self-sufficiency in heat. The methane content of the biogas was assumed to be 60% CH₄ by volume (Remy et al. 2014) and the energy produced from biogas combustion was 0.222 kWh/mol CH₄ (Kim et al. 2011). The process-flow diagram including the unit energy consumptions of the major units of Mikkeli WWTP is shown in Fig. 4.

In the Mikkeli WWTP, the total energy consumption was 2,100,603 kWh/year with major energy shared by aeration, pumping and dewatering processes. The percentages of the aeration, pretreatment/dewatering, and lighting, including miscellaneous processes, were 30%, 34%, and 36%, respectively. The sludge age in Mikkeli WWTP is maintained normally at 15–25 days. Thus, the process is more close to conventional activated sludge process than extended aeration unit. Moreover, the mechanical aeration was equipped with energy efficient fine-bubble diffusers and highly efficient compressors controlled with variable frequency drives (VFDs).

3.2.2 Energy Benchmarking of Mikkeli WWTP

In energy benchmarking, unit energy consumption or specific energy consumption can be expressed as per cubic meter of treated water (kWh/m³), per unit of COD removed (kWh/kg COD), and per population equivalents (kWh/PE/year) (Vaccari et al. 2018). The most common parameter for defining the unit energy consumption in WWTPs is kWh/m³. However, it is more likely that larger volume of wastewater are received in the WWTPs due to some factors such as stormwater flow, groundwater infiltrations, melting of ice to sewerage system that could possibly offers apparent energy discount due to higher denominator in the calculation of the kWh/m³. Therefore, the unit energy consumption as a function of treated wastewater volume may be misleading due to diluted wastewater (Foladori et al. 2015). The unit energy consumption per unit of COD removed (kWh/kg COD) of both influent and effluent concentrations of COD can be more equivalent and suitable (Vaccari et al. 2018).

Therefore, the energy benchmarking of the Mikkeli WWTP as a function of COD removal was established by using the benchmark data provided by a guide to net-zero energy solutions

Table 3 Annual wastewater load, COD removal efficiency, sludge production, and energy autarky of Mikkeli WWTP

Year	Flow rate (m ³ /d)	Incoming COD (mg/L)	COD removal efficiency (%)	Energy use (kWh/m ³)	Energy use (kWh/kg COD)	Sludge production (t/a)	Heat energy recovered from Biogas (kWh/m ³) ^{a,b}	Energy self- sufficiency in electricity (%)	Energy self- sufficiency in heat (%)
2007	13,185.13	535.00	93.18	0.44	0.88	904.53	0.40	0	100
2008	13,863.71	492.08	92.54	0.41	0.90	973.12	0.34	0	100
2009	11,957.00	576.33	94.28	0.44	0.82	958.21	0.40	0	100
2010	12,434.58	604.25	92.76	0.43	0.77	914.81	0.36	0	100
2011	13,619.96	554.40	93.85	0.39	0.75	1014.94	0.31	0	100
2012	13,811.21	537.33	93.73	0.41	0.81	1115.69	0.29	0	100
2013	11,916.05	581.80	93.54	0.50	0.92	1110.73	0.26	0	100
2014	12,206.50	693.33	95.41	0.49	0.74	1162.2	0.41	0	100
2015	11,867.37	–	95.58	0.52	0.77	1268.1	0.33	0	100
2016	11,448.54	–	95.41	0.56	0.78	–	0.37	0	100
Mean	12,631.00	571.82	94.03	0.46	0.81	1046.93	0.39	0	100

^a Methane content of the biogas 60 vol.% CH₄ (Remy et al. 2014)^b Energy produced from methane combustion is 0.222 kWh/mol CH₄ (Kim et al. 2011)

Table 4 Energy benchmarking analysis of Mikkeli WWTP with respect to best available technical benchmark data

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was estimated, which revealed a great potential to implement various retrofitting approaches to modify energy intensive Mikkeli WWTP into energy-positive WWTP. The major energy saving potentials at Mikkeli WWTP are attributed by 0.089 kWh/ kg COD at biological reactors and final clarifiers, 0.029 kWh/ kg COD at screening and grit removal, and 0.006 kWh/ kg COD at influent pump stations.

3.3 Analysis of Emerging Technology Options for Retrofitting the Mikkeli WWTP to Energy Positive Operation

The benchmarking analysis results indicate that there are great potentials of optimizing the energy consumption trends of the Mikkeli WWTP. Since the Mikkeli WWTP is an energy intensive municipal wastewater process based mainly on ‘pollutant removal philosophy’, energy positive operation is possible via the optimum use of chemical energy content of wastewater. The potential recovery of energy and valuable resources from wastewater can shift the paradigm of wastewater treatment to energy positive direction (McCarty et al. 2011; Verstraete et al. 2009). Domestic wastewater contains a significant amount of chemical energy in terms of chemical oxygen demand (COD, mg of O₂/L) (Gao et al. 2014; Gikas 2017; McCarty et al. 2011; Shoener et al. 2014; Yan et al. 2017). The organic energy contained in wastewater is approximately 9–10 times higher than that required to treat it (Hao et al. 2015; Yan et al. 2017). The chemical energy of wastewater embedded in organic matter could offset the energy requirements of CAS processes if only 40% of the total chemical energy is recovered from the wastewater. Therefore, a net energy-neutral or positive municipal wastewater treatment approach is realistic if the chemical energy in wastewater is effectively harnessed via innovative technologies (Meerburg et al. 2015). It is possible to retrofit the Mikkeli WWTP by adopting energy efficient technologies where major energy gap exists to achieve energy self-sufficiency. The proof of energy-positive WWTPs has already been experienced in many full-scale plants (Gu et al. 2017; Remy et al. 2014).

To aim this, an innovative configuration comprising four emerging technologies, i.e., (1) enhanced primary sedimentation, (2) staged anaerobic fluidized membrane bioreactor (SAF-MBR), (3) completely autotrophic nitrogen removal over nitrite process (CANON), and (4) co-digestion of sewage sludge with organic waste, were evaluated to achieve energy self-sufficiency at the Mikkeli WWTP. The energy balance of four emerging technologies, based on unit energy produced per COD removal, is shown in Table 5. The net energy savings are estimated by taking into consideration all the energy expenses required for operating the unit processes of emerging technologies and the energy generated by methane gas and syn gas extracted from organic compounds (COD) of wastewater via either AnMBR or gasification. The proposed innovative energy positive retrofitted WWTP is shown in Fig. 5.

Enhanced primary solids removal technology based on microsieving (100–300 µm size) could significantly increase the energy recovery from biosolids either via anaerobic digestion or gasification (Gikas 2017; Remy et al. 2014). Microsieving can extract upto 65% of the total organic load measured as COD in the sludge (Gikas 2017). Thus, enhanced primary sedimentation could produce sludge with a higher anaerobic digestibility than CAS sludge, and gasification of extracted organic matter could have higher net energy production potential compared to anaerobic digestion (Gikas 2017). The produced high quality syn gas from gasifier can produce 0.53 kWh/kg COD of electricity in CHP, whereas the electricity consumption for operating the microscreen, auger press is not higher than 0.02 kWh/kg COD. A net energy saving of 0.514 kWh/kg COD can be achieved. In subsequent step, the microseived

Table 5 Energy balance of four emerging technologies to create energy-self-sufficiency at Mikkeli WWTP

SN	Process	Organic load, COD (mg/L)	COD removed/inserted (mg/L)	Energy consumed (kWh/kg COD)	Energy produced (kWh/kg COD)	Energy saving (kWh/g COD)	References
1	Enhanced Primary sedimentation						
	Microsieving	500		0.02	0.53	0.514	Gikas 2017
2	Anaerobic Membrane bioreactor (AnMBR)						
	Staged anaerobic fluidized membrane bioreactor (SAF-MBR)	154	129.36	0.36	0.634	0.271	Yoo et al. 2012
3	Co-digestion						
	Co-digestion of sludge with organic waste (bio- waste)	229900 ^a	6800 ^b	—	0.59	0.59	Zupančič et al. 2008
4	Anaerobic ammonium oxidation (CANON)						
	Anammox (CANON)	1020	986.34	0.11 ^c	— ^c	−0.11	Dai et al. 2015

^a Total COD load of organic waste (OW)^b Total COD load of sludge (primary sludge + waste sludge + OW) (kg COD/day)^c Energy consumed only by CANON MBR (No energy was recovered and used to treat high rate ammonia load from SAF-MBR + Co-digestion)

wastewater enters to SAF-MBR. The remaining organic load (~ 35%) can be further extracted in AnMBR process under anaerobic digestion. SAF-MBR alone could save maximum net energy of 0.271 kWh/kg COD via yield of biogas. On the other hand, the use of granular activated carbon (GAC) used for fluidized medium can support biological growth, thus helps positively in reducing membrane fouling (Kim et al. [2011](#)). The total unit energy demand of 0.36 kWh/kg COD for combined SAF-MBR is quite less than that of secondary treatment processes in conventional WWTPs.

Fig. 5 A proposed innovative energy positive retrofitting technology for Mikkeli WWTP

Meanwhile, the co-digestion of raw sludge with food waste can be a great opportunity to recover the potential of food waste as renewable energy (Koch et al. 2016). Co-digestion not only results in a higher methane yield, but also in higher rate of methane production. The on-site electricity production can be increased by 130–180% of plant's own energy demand by co-digestion of food waste with wastewater sludge in an anaerobic treatment (Zupančič et al. 2008). The electric energy production of 0.59 kWh/kg COD can be achieved when the total organic waste of 1700 kg/d is co-digested with sludge (Zupančič et al. 2008). In co-digestion, degradation of organic waste could reach up to 100% with non-residual solids (Zupančič et al. 2008), which means that no excess sludge load is produced. However, one of the major disadvantages of co-digestion is the high nitrogen load reject water with reduced dewaterability (Koch et al. 2016). To treat the excess nitrogen load from rejected supernatant, a CANON-MBR process is proposed which further polishes the treated wastewater. CANON-MBR has revolutionized the removal of nitrogen from NH_4^+ -rich residual streams in anoxic conditions with the aid of anammox bacteria (Dai et al. 2015). The anammox process has shown excellent performance in: reducing the aeration demand of conventional nitrification/denitrification by 60%, decreasing 100% the organic carbon source demand and 90% the sludge generation (Ali and Okabe 2015). The energy consumption of CANON-MBR could be 0.11 kWh/kg COD, with the majority of expenses in biogas scouring and biological aeration. As the motive was to treat the digester supernatant with high rate of ammonia, no energy recovery was estimated. The removal of ammonia and total nitrogen can reach as high as 89 and 82%, respectively (Dai et al. 2015).

As a result of estimating the net energy balance of four emerging retrofitting technologies, the maximum energy saving could reach as high as 1.26 kWh/kg COD. This energy saving is possible for overcoming the energy gap (0.11 kWh/kg COD) of Mikkeli WWTP, providing a net positive energy surplus of 1.15 kWh/kg COD. From an energy perspective, the four emerging technologies have demonstrated a great deal of potential for retrofitting the Mikkeli WWTP into energy positive. However, several issues are still needed to be addressed and upgraded before its practical application in the future. Moreover, the capital cost for retrofitting technologies could be costly. The calculation of the capital cost for the construction of proposed energy-positive plant was not within the scope of this paper. However, achieving a breakeven point of the cost/benefit ratio might be possible within certain years because of the net surplus energy production from the retrofitted plant.

4 Conclusions

The paper concludes that the conventional Finnish wastewater facilities utilize energy intensive processes, and are commonly regarded as being only an energy sink. The statistical analysis of data from 22 WWTPs showed that the total energy consumption in Finnish WWTPs are positively correlated with inflow rate and sludge production. However, the unit energy consumption decreases with increasing capacity of plants. The energy benchmarking of the Mikkeli WWTP revealed an energy gap of 0.11 kWh/kg COD. The major energy saving potentials are attributed to secondary treatment, screening and grit removal, and influent pump stations. Four emerging technologies, such as enhanced primary sedimentation, staged anaerobic fluidized membrane bioreactor, CANON MBR, and co-digestion of sludge with organic food waste were suggested as an innovative configuration based on maximum harnessing of chemical energy content in wastewater. The maximum energy savings could reach as high as

1.26 kWh/kg COD, which is possible for overcoming the energy gap of Mikkeli WWTP, providing net positive energy surplus of 1.15 kWh/kg COD.

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Compliance with Ethical Standards

Competing Interests The authors declare that they have no conflict of interests in relation to this work.

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