Evaluating the effect of different operational strategies on the carbon footprint of wastewater treatment plants – case studies from northern Poland

M. Maktabifard, E. Zaborowska and J. Makinia

ABSTRACT

Nowadays, low greenhouse gas (GHG) emission is expected at wastewater treatment plants (WWTPs). However, emission quantification and evaluation still faces difficulties related to data availability and uncertainty. The objective of this study was to perform carbon footprint (CF) analysis for two municipal WWTPs located in northern Poland. Slupsk WWTP is a large biological nutrient removal (BNR) facility (250,000 PE) which benefits from on-site electricity production from biogas. The other studied plant is a medium-size BNR facility in Starogard (60,000 PE). In this WWTP, all the required electricity was provided from the grid. Both wastewater systems were composed of activated sludge, with differences in the nutrient removal efficiency and sludge treatment line. The CF calculations were based on empirical models considering various categories of input parameters, afterwards summing up the emissions expressed in CO_2 equivalents (CO_{2e}). After sensitivity analysis, significant contributors to GHG emissions were identified. The total specific CF of the Slupsk and the Starogard WWTP was 17.3 and 38.8 CO_{2e} per population equivalent (PE), respectively. In both cases, sludge management, electricity consumption and direct emissions from wastewater treatment were found to significantly influence the CF. A substantial share of the total CF originated from indirect emissions, primarily caused by the energy consumption. This negative impact can be partially overcome by increasing the share of renewable energy sources. Reduction of over 30% in the total CF could be achieved while applying energy recovery from biogas by combined heat and power plants. Farmland and farmland after composting were found to be the most appropriate strategies for sludge management. They could create a CF credit (8% of the total CF) as a result of substituting a synthetic fertilizer. Reliable full-scale measurements of N_2O emissions from wastewater treatment are recommended due to high uncertainty in CF estimation based on fixed emission factors (EFs). While applying the lowest and the highest N_2O EFs reported in the literature, the total CF would change even by 2–3 times.

Key words | CO_2 equivalent unit, emission factors, energy consumption, greenhouse gases, sludge management

M. Maktabifard (corresponding author)
E. Zaborowska
J. Makinia
Faculty of Civil and Environmental Engineering, Gdansk University of Technology, Narutowicza Street 11/12, 80-233 Gdansk, Poland
E-mail: *mojtaba.maktabifard@pg.edu.pl*

INTRODUCTION

Modern wastewater treatment plants (WWTPs) should not only cover stringent effluent limits, but they should also be energy efficient and have a low carbon footprint (CF) (Jenkins & Wanner 2014). It is estimated that the waste and wastewater industry holds a 3% share in total global greenhouse gas (GHG) emissions (Xu 2013). Carbon neutrality has become a hot topic for WWTPs and carbon neutral operations have emerged recently (Hao *et al.* 2015). Sustainability of WWTPs has gained much more attention and the focus of discussion for WWTP performance has turned to CF and GHG emission reductions (Ødegaard

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doi: 10.2166/wst.2019.224

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2016). In the total CF, the major GHGs include carbon dioxide (CO_2), methane (CH_4) and nitrous oxide (N_2O). In a 100-year perspective, the global warming potential (GWP) expressed in CO_{2e} (CO_2 equivalent) emission of CH_4 and N_2O is as high as 28 and 265, respectively (IPCC 2013). WWTPs produce a considerable amount of GHGs directly within biological treatment (Xu *et al.* 2017). Furthermore, indirect GHG emissions, such as those related to energy consumption, cannot be ignored (Figure 1). Therefore, CF analysis becomes an important tool in WWTPs to recognize which sections emit more GHGs and discover the potential solutions to reduce CF. Annual GHG emissions vary significantly in terms of the treatment schemes employed (Mamais *et al.* 2015).

The CF of WWTPs is strongly related to the source of electricity used at the plant (depending on the share of green energies), wastewater treatment technologies, additional amount of fossil carbon source (either for denitrification or co-digestion), and influent and effluent characteristics (Wang *et al.* 2016). The carbon emissions due to energy consumption account for 38%–50% of the total GHG emissions in WWTPs (Bao *et al.* 2016). Hence, there are numerous studies focused on reduction of CF by enhancing energy recovery from wastewater (Sweetapple *et al.* 2015). The highest values of CO_{2e} emissions were usually obtained from indirect emissions by electricity consumption for aeration (Mamais *et al.* 2015). Increasing the aeration efficiency at WWTPs has some potential for reducing emission of GHGs. However, the trade-off between efficient aeration and N_2O emission must be carefully monitored due to the high GWP of N_2O gas. Unlike the direct N_2O and CH_4 emissions, which are not easy to measure due to the complexity of gas measurements, especially at open WWTPs (Yoshida *et al.* 2014), the emission factor (EF) for electricity can more easily be estimated.

Other research works reported that direct emissions, such as N_2O and CH_4 from bioreactors and sewers, are often a large portion of the WWTP CF (Gustavsson & Tumlin 2013; Lorenzo-Toja *et al.* 2016). The contributions of N_2O emission in the total WWTP CF were reported to be as high as 78% (Daelman *et al.* 2013) and 60% (Rodriguez-Caballero *et al.* 2015) in a full-scale biological nutrient removal WWTP. On the other hand, Aboobakar *et al.* (2013) reported that N_2O emission added only 13% to the CF associated with the energy requirements. Those differences can be attributed to specific plant configurations and operational conditions. Moreover, the lack of standardization of the methodology for CF calculations makes comparison of results between objects difficult.

Differences between the contributions of indirect and direct CO_{2e} emissions reported in the literature revealed the importance of evaluating the impact of various parameters and operational strategies on the total CF of WWTPs. It remains to be explained how the assumptions made can affect the results and which measures are efficient in mitigating GHG emissions while applying a comprehensive approach.

This study aims to estimate the CF of two WWTPs located in northern Poland and compare the obtained results in order to evaluate the effect of different operational strategies and assumed EFs on the total CF. The total CF is reported in various benchmarks and new pathways to reduce the CF, such as sludge treatment and handling as well as energy efficiency, are discussed. After performing sensitivity analysis, it is possible to find the most effective contributors to CF and define prospective scenarios to reduce the GHG emissions.

MATERIALS AND METHODS

Characteristics of the studied WWTPs

Two municipal biological nutrient removal (BNR) WWTPs located in northern Poland were chosen for the CF analysis in this study. A major reason for the plants' selection was a

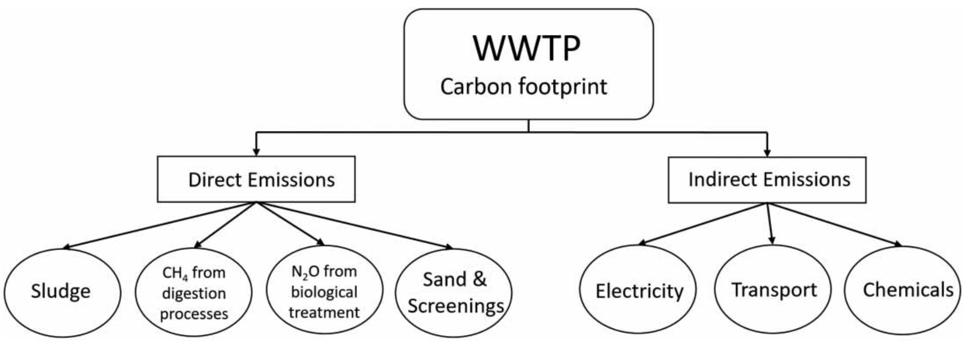

Figure 1 | Direct and indirect emissions discharged from WWTPs.

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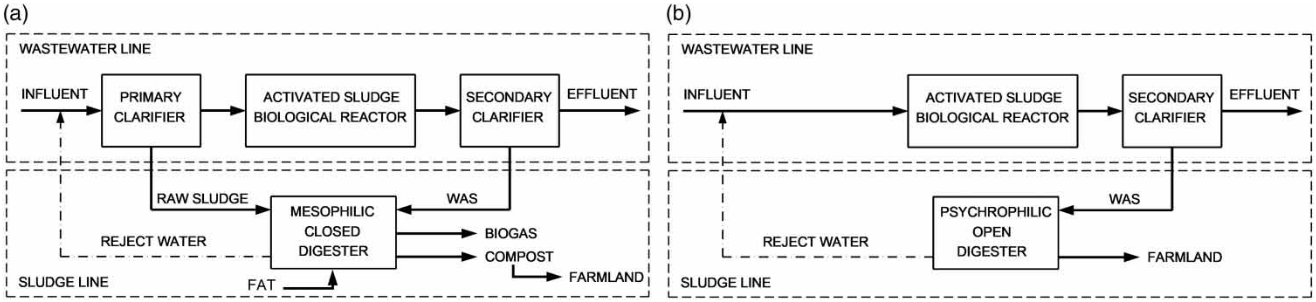

Figure 2 | General concept of wastewater and sludge lines in (a) Slupsk, (b) Starogard WWTPs.

difference in the technologies in both wastewater treatment and sludge lines that makes a good background for comparisons. Figure 2 shows a general concept of wastewater treatment and sludge treatment in the studied facilities. The basic annual characteristics of wastewater influent are given in Table 1. For the Slupsk WWTP, data from the year 2013 were used Zaborowska *et al.* (2017), and for the Starogard WWTP, data collected in 2016 were applied. First, the Slupsk WWTP (Figure 2(a)) is a large facility (250,000 PE) with an average influent flow rate of approximately 24,000 m^3/d. That plant benefits from on-site electricity production through a combined heat and power (CHP) system. Biogas is produced from mesophilic anaerobic digestion of primary and waste activated sludge (WAS) as well as external organic material for co-digestion. In the studied period, the total annual feedstock contained approximately 4,670 Mg of dry matter and 3,600 Mg of organic matter. In those values, the external substrate (fat) had a share of 10% and 11%, respectively. The heat demand of the digester was provided from biogas-driven CHP engines. The recovered heat satisfied the annual heat demand of the digesters (2,700 MWh vs 3,570 MWh recovered).

The other studied plant (Figure 2(b)) is a medium-size facility in Starogard (60,000 PE) treating wastewater in the amount of approximately 8,400 m^3/d (annual average). In the Starogard WWTP, all the required energy is purchased from the grid since psychrophilic digestion of WAS is performed in an open chamber. These two WWTPs apply different standards for their effluent characteristics. The limits for total nitrogen and phosphorus concentrations for the Starogard WWTP (medium plant) are 15 mgN/L and 2 mgP/L, respectively, while the Slupsk WWTP (large plant) has stricter standards, i.e. 10 mg N/L and 1 mg P/L. Another difference is the sludge treatment strategy. The Slupsk WWTP converts the digested sludge to compost which is then distributed to farmlands (14,900 Mg/year), but the Starogard WWTP distributes the stabilized sludge directly to farmlands (8,500 Mg/year). In both cases, chemicals are used for sludge thickening/dewatering (polymers) and periodically to support phosphorus removal (ferric sulphate).

Table 1 | Basic annual average characteristics of wastewater influent including COD (chemical oxygen demand), TN (total nitrogen) and TP (total phosphorus) concentrations

		Mean concentration ± SD*	
Constituent	**Unit**	**Slupsk WWTP**	**Starogard WWTP**
COD	mg COD/L	1,133 ± 256	784 ± 216
TN	mg N/L	82 ± 13	80 ± 14
TP	mg P/L	12 ± 3	8 ± 3

*SD – standard deviation.

Analysis tool

The tool for calculating the CF of WWTPs was an MS Excel spreadsheet (CFCT 2014), developed in the project entitled 'Calculation of the CF from Swedish WWTPs' (SVU 12-120) (Gustavsson & Tumlin 2013). In this spreadsheet, the input data were divided into nine categories which are shown in Table 2. The detailed results are based on summing up the emissions expressed in CO_{2e} units and finding the total annual CF of the plant in ton CO_{2e}/year. The results can be analysed for each case study to observe which elements of the WWTPs have major contributions to the total CF. For a comparison of the plants, the specific CF values were expressed in kg CO_{2e} per population equivalent (PE), volume of influent wastewater (m^3) and removed load of nitrogen (kg N removed), respectively.

Data collection and evaluation

The CF analysis was based on a wide range of annual routine operating data as listed in Table 2. Daily average samples of wastewater were collected and analysed in accredited laboratories meeting the Polish standards following

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Table 2 | Input parameter categories introduced to the CF tool (CFCT 2014)

Input parameter	Type of data	Input parameter	Type of data
Influent wastewater		*Biogas*	
Flow	Annual average	Produced biogas	Annual average
COD, BOD, N, P concentrations		CH_4 content	Annual average
		Biogas loss emissions	Based on EFs
Wastewater treatment		Flared biogas	Annual average
Direct CH_4 emissions	Based on EFs	Directly emitted biogas	Annual average
Direct N_2O emissions		Type of biogas utilization	Constant
External organic material	Annual average		
		Transports	
Chemicals		Sludge	Annual average
Type and amount	Annual average	Screening and sand	Annual average
Transportation	Estimation	Delivery frequency	Estimation
Energy		*Sludge*	
Electricity consumption	Annual average	Duration of storage	Constant
Purchased electricity	Annual average	Amount of dewatered sludge	Annual average
Renewable energies share	Constant	TS and VS contents	Annual average
Internally produced electricity	Annual average	Total N, P and C	Annual average
Total heat use	Annual average	Type of management	Constant
Internally produced heat	Annual average		
		Waste handling	
Recipient		Amount of screening	Annual average
Effluent characteristics	Annual average	Amount of sand	Annual average
Sea or lake	Constant	Waste utilization	Constant

Standard Methods (APHA 2005). Then the annual data were calculated and introduced to the CF calculation tool. Missing data were estimated based on the values found in the literature. Some of the data such as direct emissions were highly uncertain and calculated based on the EFs available in the literature. For N_2O, the EFs were expressed in kg N_2O per kg N denitrified, with respect to the minimum, average and maximum values. A broad range of N_2O emissions for different types of wastewater treatment configurations was found in the literature. Therefore, the total CF of each studied plant was calculated based on various EFs found in the literature and the effect of sensitivity analysis was demonstrated.

Assumptions for calculations

Table 3 provides the main EFs used in the CF analysis as default values incorporated in the calculation tool (CFCT 2014). The biogas loss category contains the EFs assuming that biogas is partially lost during biogas production in the closed anaerobic digesters and not fully combusted during conversion to useful energy carriers in the CHP units. The emission of GHGs from an open psychrophilic digestion chamber (used for storage) was calculated by assuming the period of sludge storage before further use (90 days in the Starogard WWTP) and included in the sludge management category. For the energy consumption, the EF for the electricity produced mainly from coal (and purchased by the WWTPs from the grid) was assumed to be 0.8 kg CO_{2e}/kWh as reported by NCEM (2017). The reference point for the N_2O EF was assumed to be 0.0157 kg N_2O/kg $N_{denitrified}$ (Foley *et al.* 2010).

In this study, sludge management refers to the fate of sludge after anaerobic digestion (inside and outside of the WWTP). For digested and dewatered sludge management strategies, five different scenarios, including farmland, incineration, landfill, fertilizer and composting, were assumed for each case study. The effects of each possible scenario were

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Table 3 | EFs used in the CF analysis (CFCT 2014)

Category	EF	Value	Unit	Reference
GWP	CH_4 GWP	28	kg CO_{2e}/kg CH_4	IPCC (2013)
	N_2O GWP	265	kg CO_{2e}/kg N_2O	IPCC (2013)
Biogas loss	Biogas slip	2.8	%	Göthe (2013)
	N_2O from biogas	0.004	g N_2O/kg_{burned} CH_4	Brown et al. (2010)
	CH_4 from biogas	0.034	kg CH_4/kg_{burned} CH_4	Doka (2003)
Composting	N_2O emissions	2	% of total N-loss	Kirkeby et al. (2005)
	CH_4 emissions	0.75	% of total C	Kirkeby et al. (2005)
	Indirect N_2O emissions	0.0157	kg N_2O/kg NH_3	IPCC (2006)
	Substituted production of chemical fertilizer	2.9	kg CO_{2e}/$kg_{fertilizer}$	Yara (2013)
Recipient	Effluent wastewater sea or lake	0.003	kg N_2O/kg $N_{effluent}$	Foley et al. (2008)

calculated based on the assumed EFs. In the fertilizer scenario, a preceding process of sludge drying was considered with the related direct and indirect GHG emissions. In the case of sludge composting, different sub-scenarios can be considered indicating the ultimate use of compost, such as landfill, farmland or soil production. It was assumed that the compost would be distributed to farmlands for further usage. As a result of substituting a synthetic fertilizer in the farmland scenario, a negative emission was calculated (a CF credit).

Sensitivity analysis

For evaluating the data, it was necessary to classify them to focus more on the highly influential parameters with respect to carbon emissions. In the first step, the three categories with the highest contributions to the total CF were selected for more detailed analysis. The methodology applied in the sensitivity analysis assumed variations of the pre-selected quantitative input parameters: (i) from the minimum to the maximum value reported in the literature; or (ii) by ±10% in relation to the default (reference) value. A response of the variations on the total CF was then analysed. For those input data which are qualitative, such as sludge handling, different prospective scenarios were introduced and compared using the calculation tool.

RESULTS AND DISCUSSION

Total CF

Results of the analysis performed for both studied plants are shown in Figure 3. For the Slupsk WWTP, direct emissions from the wastewater treatment had the highest share (62%) in the total CO_{2e} emission, followed by the energy consumption (23%) and the biogas loss category (17%). The biogas production under anaerobic mesophilic conditions (in the closed digester) had a positive effect, which was considered in the energy consumption category (reduction in the CF related to electric energy purchased from the grid). Distribution of the composted sludge in the farmlands reduced the total CF by 8%. The negative value (the CF credit) in the sludge management category

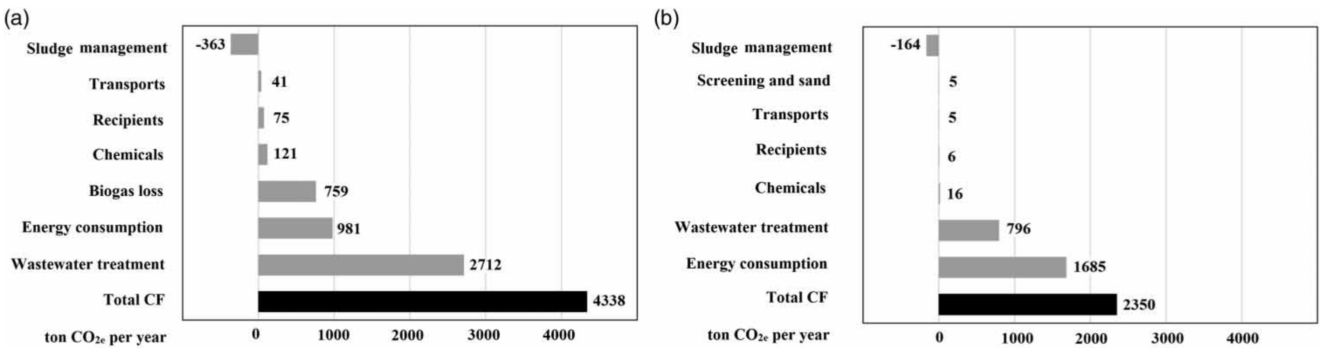

Figure 3 | Different components' share in the total CF in (a) Slupsk and (b) Starogard WWTPs.

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resulted from the avoided emissions of GHGs through substituting synthetic fertilizer production. In contrast, the Starogard WWTP produced most of the CO_{2e} emissions (71%) through the indirect way by supplying all the energy demand from the grid. Other significant CF contributors in the plant belonged to the wastewater section (34%), whereas the other categories had a small impact on the total CF. The distribution of the sludge stabilized under psychrophilic conditions (in the open chamber) to farmland helped to reduce the total CF by 7%. As the main result achieved from the analysis for both studied WWTPs, sludge management, electricity consumption and direct emissions from wastewater treatment were found to be the most influential and sensitive parameters affecting the total annual CF. Therefore, the results from these components are separately discussed in the following sub-sections.

Sludge management

One of the parameters which can help reduce the CF of WWTPs is the proper way of dewatered sludge management, regardless of the preceding sludge treatment (stabilization) method. The sensitivity analysis showed that for both case studies, sludge management scenarios could make major changes in the total CF. Five different scenarios were defined and their influence on the CF is shown in Table 4 by assuming each possible scenario in the CF analysis tool. The results shown in bold are based on the sludge management method which was applied at the time when the data were reported. The Starogard WWTP distributes the dewatered sludge in farmlands and such a management strategy was found to be the best scenario in terms of CF production. The other possible methodology is converting the anaerobically stabilized sludge to compost (for further usage as fertilizer on farmlands) as it is at the Slupsk WWTP. The results of this analysis showed that it was the second-best option for the Slupsk WWTP in terms of CF production. Therefore, both WWTPs apply appropriate sludge management strategies (farmland or farmland after composting) which can partially recover the carbon emissions (around 7%–8% for both WWTPs). In the alternative process of synthetic fertilizer production, annual CF reduction as high as 363 and 164 ton CO_{2e} was estimated in the Slupsk and the Starogard WWTP, respectively. The worst scenario predicted conversion of dewatered sludge to fertilizer after drying, due to the high energy consumption needed for drying the sludge.

Table 4 | Effect of different sludge management scenarios on the CF

	Total CF (ton CO_{2e}/year)		Relative change in the total CF	
Sludge management	**Slupsk**	**Starogard**	**Slupsk**	**Starogard**
Farmland	3,966	**2,350**	−9%	**0**
Farmland after composting	**4,338**	2,794	**0**	19%
Incineration	4,714	2,612	9%	11%
Landfill	5,104	2,748	18%	17%
Fertilizer (after drying)	7,724	3,677	78%	56%

Electricity consumption

The data on energy consumption of WWTPs are typically readily available. The EFs in this section depend on the country's electricity source. Marginal emissions from electricity production in Europe are reported in the range of 0.75 to 0.90 $kgCO_{2e}$/kWh, while the EF (mainly in Scandinavian countries) for the average and future scenarios are approximately 0.45 and 0.35 $kgCO_{2e}$/kWh, respectively (Gustavsson & Tumlin 2013; Larsen 2015). Against that background, the EF for electricity production in Poland (0.80 $kgCO_{2e}$/kWh (NCEM 2017)) is high due to the domination of coal power plants.

The available data on electricity consumption were reliable (registered by electricity meters) and considerably influenced the indirect emissions of WWTPs. The Slupsk WWTP consumed annually approximately 4,100 MWh of electric energy. Only 30% of the total demand was purchased from the grid. Approximately 2,800 MWh was converted from biogas by the CHP engines, which accounted for 70% of the total demand and contributed to significant cost savings. Moreover, the recovered heat satisfied the annual heat demand of the digesters (2,700 MWh vs 3,570 MWh recovered). On the other hand, following the assumptions given in Table 3, the additional CF related to biogas loss was estimated at 17%. However, this emission (759 ton CO_{2e}) was balanced by reduction in the off-site emission from the industrial coal power plant (960 ton CO_{2e}). Moreover, the amount of reduced CF due to the energy recovery from biogas was estimated at 2,354 ton CO_{2e} per year. This value is more than three times higher than the additional CF from biogas loss during the production and combustion stages. Therefore, it is highly recommended for WWTPs to recover energy from biogas.

The results showed that the energy consumption category could possibly have the highest share in the total

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CF if the WWTP would not use a renewable energy source. A 71% share of the total CF belonged to the energy consumption category in the Starogard WWTP. This plant consumed approximately 2,000 MWh per year, of which 100% was purchased from the grid. Although the electricity consumption of the Starogard WWTP was 70% smaller than that of the Slupsk WWTP (the amount of wastewater treated in Slupsk is approximately three times bigger), the Starogard WWTP had a larger CF in the energy category. The Starogard and Slupsk WWTPs produced 1,685 and 981 ton CO_{2e}/year, respectively, as indirect GHG emissions through the energy section. These results confirm that one of the effective methods of reducing the CF is to increase the energy efficiency of WWTPs. Implementation of the mesophilic anaerobic digestion process along with on-site energy recovery from biogas via CHP engines is a possible solution for the Starogard WWTP. Such a strategy could result in a major reduction in the total GHG emissions. This reduction was estimated at 33% assuming 70% of the energy demand was covered by the energy recovered from biogas.

At present, the share of renewable energy in electricity production in Poland is estimated at 13% (from wind, biomass, water) (CSO 2017). The sensitivity analysis showed that if the share of renewable energies increased by 10%, the annual CF would decrease by 96 ton CO_{2e} in the Slupsk WWTP and 163 ton CO_{2e} in the Starogard WWTP. These values account for 2% and 7% reduction of the total CF for each WWTP, respectively. Therefore, investing in green energies on both the plant scale and the country scale can substantially decrease the CF of WWTPs.

Direct N_2O emissions

There are several literature reviews on N_2O EFs for full-scale BNR WWTPs. Andrews *et al.* (2009) examined 10 country-specific national inventory reports. Six of them used the Intergovernmental Panel on Climate Change (IPCC) default procedures (Table 5).

The EF in the other four developed countries, those being Denmark, Japan, USA and UK, has been reported as high as 0.0024, 0.004, 0.0015 and 0.002 $kgN_2O/kgN_{denitrified}$, respectively (GWRC 2011). Some other studies performed laboratory-scale experimental studies. For example, Kampschreur *et al.* (2008) performed both online monitoring and discrete sampling over a nitrification/denitrification sludge wastewater treatment process and the EFs were 2.3% and 4% of the total nitrogen load, respectively. Another option is to estimate the N_2O emission rates from empirical models (e.g. Baresel *et al.* 2016; Marques *et al.* 2016). Different EFs reported in the literature are collected in Table 5 and split into ranges of low, middle and high values.

Table 5 | Effect of direct N_2O emissions on the CF for different N_2O EFs

Range	N_2O EF ($kgN_2O/kg\ N_{denitrified}$)	Calculated total CF of WWTP (CO_{2e}/PE)		Reference
		Slupsk	Starogard	
Low	0.00022	9.9	29.2	de Haas *et al.* (2014)
	0.0003	9.9	29.2	Foley *et al.* (2010)
	0.0032	11.3	31	IPCC (2006)
	0.005	12.2	32.1	IPCC (2006)
Mid	0.01	14.6	35.2	IPCC (1997)
	0.012	15.6	36.5	Townsend-Small *et al.* (2011)
	0.0157	**17.3**	**38.8**	Foley *et al.* (2010)
	0.016	17.5	39	de Haas *et al.* (2014)
High	0.03	24.2	47.7	de Haas *et al.* (2014)
	0.0471	32.5	58.3	Foley *et al.* (2010)

Table 5 presents the results for the specific CF (calculated per PE with respect to different ranges of N_2O EFs). The bold results are assumed as the reference values used in this study (the default values in the analysis tool). As shown in Table 5, only the N_2O EF can make substantial differences in the final total CF results in the WWTPs. With respect to the reference value, the relative changes in the WWTPs' total CF could be as high as 88% and 50%, respectively, while applying various fixed EFs. In GHG modelling studies, uncertainty in the modelled N_2O emissions was also identified as the primary contributor to uncertainty in predicting GHG emissions (Mannina *et al.* 2016).

Specific CF emission factors

The final result of the CF of each WWTP can be compared with respect to the plant size (expressed in PE), influent flowrate, and effluent TN concentrations. As is shown in Table 6, although the Slupsk WWTP has a larger absolute CF, the relative EFs are lower in comparison with the Starogard WWTP. The Slupsk WWTP is thus operated in a more sustainable way. The most frequent specific CF reported in the literature is based on kg CO_{2e} per m^3 treated wastewater. Li *et al.* (2017) reported the CF for WWTPs with resource recovery ranges from 0.1 to 2.4 kg CO_{2e}/m^3. This is a relatively wide range and both studied WWTPs are within that range. Wang *et al.* (2016) reported the range 0.1 to 0.96 kg CO_{2e}/m^3 for case studies located in

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Table 6 | Total annual CO_{2e} emission and EFs for the studied WWTPs

CF expressed in:	Slupsk WWTP	Starogard WWTP	Literature data	Reference
ton CO_{2e}/year	4,338	2,350	2,445	Koutsou et al. (2018)
kg CO_{2e}/PE	17.2	38.8	7–108	Gustavsson & Tumlin (2013)
			61–161	Mamais et al. (2015)
kg $CO_{2e}/m^3_{wastewater}$	0.5	0.8	0.1–2.4	Li et al. (2017)
			0.1–0.96	Wang et al. (2016)
			0.18–1.18	Mannina et al. (2019)
			2.21	Koutsou et al. (2018)
			0.33	Vourdoubas (2018)
ton CO_{2e}/ton $N_{removed}$	6.9	11.5	6.5–12.6	Delre et al. (2019)

different countries. The EFs were affected by different effluent discharge permit limitations and different EFs for electricity. For instance, for the plant with the minimum reported CF (0.1 kg CO_{2e}/m^3), which is significantly smaller than the Slupsk and Starogard WWTPs, the EF used was 0.36 kg CO_{2e}/kWh. That value is less than half of the one assumed in the present study. Mannina et al. (2019) developed a new model for CF estimation in WWTPs. The range of EFs reported in that study was 0.18 to 1.18 kg CO_{2e}/m^3 considering both direct and indirect emissions. The results with the relatively high EFs were attributed to high indirect emissions (for scenarios with high electricity consumption). Moreover, high direct emissions attributed to the high TN concentrations of the influent increased the contribution of the N_2O emissions. Vourdoubas (2018) reported a CF (related only to electricity) as high as 0.33 kg CO_{2e}/m^3. This portion of the CF for the Slupsk and Starogard WWTPs was 0.11 and 0.56 kg CO_{2e}/m^3, respectively. Those differences result primarily from the different energy sources applied in the studied cases.

The comparative analysis with the literature data showed that the estimated total CF for both WWTPs fall within the reported ranges. In comparison with the data reported in the literature, the Slupsk WWTP has a relatively low CF due to the high on-site energy recovery at this plant. Moreover, the farmland distribution of sludge affected the total CF positively in both WWTPs. In contrast, much reported data in studies in the literature assumes the landfill scenario (Koutsou et al. 2018; Delre et al. 2019). Table 6 shows the results along with the literature data. The variety of different operational strategies can change the final EFs considerably. Hence, the comparison among the emission factors reported for WWTPs is not a straightforward task.

CONCLUSIONS

The evaluation of the effect of different operational strategies and calculation assumptions on the total CF of the studied municipal BNR WWTPs revealed the following:

- Wastewater treatment, energy consumption and sludge management are the most influential categories affecting the total CF of the WWTPs.
- The energy consumption category could possibly have the highest share in the total CF (71% in the studied case) if the WWTP covered the total energy demand from non-renewable sources.
- Digestion of sewage sludges under mesophilic conditions and prevention of biogas losses at each stage of production and use are highly recommended.
- A reduction of over 30% in the total CF could be achieved while applying energy recovery from biogas by CHP plants.
- Farmland distribution of sludge was found to be the most appropriate strategy for sludge management and could create a CF credit (8% of the total CF) as a result of substituting a synthetic fertilizer.
- Reliable full-scale measurements of N_2O emissions from wastewater treatment are recommended due to high uncertainty in CF estimation based on fixed EFs. While applying the lowest and the highest N_2O EFs reported in the literature, the total CF would change significantly.

ACKNOWLEDGEMENT

This work was financially supported by the Regional Fund for Environmental Protection and Water Management in Gdansk, Poland, in the Pomeranian R&D Projects, grant no. WFOS/D/201/3/2018.

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First received 9 July 2018; accepted in revised form 21 June 2019. Available online 28 June 2019

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