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Streamlined Life Cycle CO_2 Emission Assessment of Sewage Treatment in Taiwan

(Penyelarasan Kitaran Hidup Penilaian Pembebasan CO_2 Perawatan Kumbahan di Taiwan)

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ABSTRACT

Sewage treatment is an important issue in a country for public health and environmental protection. The treatment process not only consumes energy but also emits CO_2. In this research, the idea of streamlined life cycle assessment was applied. The CO_2 emission from sewage treatment was assessed from direct energy consumption of four major sewage treatment plants in Taiwan. The results showed that the CO_2 emission at in-plant sewage treatment stage takes more than 95% of total CO_2 emission for most plants. The results suggested that CO_2 emission of sewage treatment can be calculated from energy consumption at in-plant sewage treatment stage to simplify the calculation. The CO_2 emission of sewage treatment was then assessed from sewage plants in Taiwan using in-plant electricity consumption. The unit CO_2 emission of sewage treatment in Taiwan is 0.216 kg-CO_2/m^3. This database will be an important reference for water resource research and future government environmental policies.

Keywords: CO_2 emission; life cycle assessment (LCA); sewage treatment

ABSTRAK

Rawatan kumbahan merupakan isu yang penting dalam negara untuk kesihatan umum dan perlindungan alam sekitar. Proses rawatan ini tidak hanya menggunakan tenaga tetapi juga membebaskan CO_2. Dalam kajian ini, idea kitaran hidup yang diselaraskan telah diaplikasikan. Pembebasan CO_2 daripada rawatan kumbahan telah dinilai daripada penggunaan tenaga langsung daripada empat pusat rawatan kumbahan yang utama di Taiwan. Keputusan menunjukkan bahawa pembebasan CO_2 di peringkat dalam pusat rawatan kumbahan merangkumi 95% daripada jumlah pembebasan CO_2 di kebanyakan pusat. Keputusan mencadangkan bahawa pembebasan CO_2 daripada rawatan kumbahan dapat dikira daripada penggunaan tenaga di peringkat dalam rawatan kumbahan untuk memudahkan pengiraan. Pembebasan CO_2 daripada rawatan kumbahan kemudiannya dinilai daripada pusat kumbahan melalui penggunaan elektrik dalam pusat. Unit pembebasan CO_2 daripada rawatan kumbahan di Taiwan adalah 0.216 kg-CO_2/m^3. Pangkalan data ini akan menjadi rujukan penting untuk kajian sumber air dan polisi alam sekitar kerajaan pada masa hadapan.

Kata kunci: Kitaran hidup yang dilaraskan; pembebasan CO_2; rawatan kumbahan

INTRODUCTION

Clean water is very important in our life. However, the sewage we produce in our life not only consumes water resources but also pollutes the environment. It is very important to treat sewage before it is discharged to the nature to avoid contamination of water resources. The rivers in Taiwan are seriously polluted. One of the important solutions for river pollution is to build public sewers and sewage plants to treat household wastewater. The development of public sewer systems has become an indicator for environmental protection and public health advancement in a country. In the public sewer system, the wastewater produced in the buildings drained into sewers requires treatment in the sewage treatment plant to meet the sanitation standards before being discharged to the water cycle in nature. The sewage treatment process consumes energy and produce CO_2. Recently, due to global warming, energy consumption and CO_2 emission of sewage treatment plants has become the research focus in developed countries. In the United States, 3% of the total electricity consumption comes from water and sewage treatment plants (Burton 1996). In Japan, 0.9% of the total electricity consumption comes from water plants (Ministry of Health, Labour and Welfare 2009) and 0.7% comes from sewage treatment plants (Japan Sewage Works Association 2008). As sewage water system becomes widespread, the energy consumption from sewage treatment systems will increase. Hence, researches related to energy consumption from sewage treatment plants become more and more important.

In 2011, among the total of 2933.9 km rivers in Taiwan, 62.59% were not or slightly polluted, while 37.41% were lightly, medium or seriously polluted. The polluted rivers will affect the quality of life and the recycling of water resources. The sewage produced in the household, commercial and medical buildings contain high amount of suspended solid, grease and fecal coliform bacteria and should go through sedimentation, aeration and disinfection processes to meet the sanitation standards before being discharged to the river. According to CPAMI (2011) report, 3,366,256 households were sewage treated.

These households covered 57.98% of total households in Taiwan. The annual sewage treatment volume was 1,051,340,000 m^3. There were 224 sewage plants being planned and 56 had been constructed. In recent years, due to the difficulty to obtain large lands, small scale of sewage plants within the same drainage area have been planned and constructed to solve the land acquisition problems. The above information shows that the public sewage systems in Taiwan are continuously constructed. In this research, we investigated and analyzed energy consumption of sewage plants during sewage treatment. The energy consumption and CO_2 emission data is established to provide reference for future water resource research and government environmental policies.

METHODS

In this research, the production line direct energy consumption statistics was used to calculate the energy consumption and CO_2 emission from the sewage treatment (Chang 2002). This is the most direct and reliable method to calculate CO_2 emission. First, the energy consumption was investigated. Since the basic component of fossil fuels is carbon and CO_2 is produced after the combustion of fossil fuels, CO_2 emission can be calculated from energy consumption. The unit CO_2 emission of fossil fuels was calculated using the method developed by Intergovernmental Panel on Climate Change (Houghton et al. 1997). This method is the most common method used to calculate CO_2 emission internationally.

Life cycle assessment (LCA) is a method to calculate various environmental loads. A complete and detailed life cycle assessment is very complicated and difficult to put into practice. To resolve these problems, we modify and simplify the analysis steps and data to a streamlined life cycle. The streamlined life cycle assessment reduces the human and material resources used in the complete and detailed life cycle assessment and makes the information easy to process (Todd & Curran 1999). The streamlined life cycle assessment was used to investigate CO_2 emission at different stages of sewage treatment. In general, sewage treatment includes the physical methods such as sedimentation, flotation, sieving, gritting, grinding and mixing. These methods were to remove solids in the sewage and known as the primary treatment. The secondary treatment was to use biological methods such as sludge activation, trickling filtration, oxidation, anaerobic biological method and rotating biological disk method to remove more organic substances (Emmerson et al.1995; Henze & Ødegaard 1995). The most common method used in Taiwan was the sludge activation method. This method can remove more than 90% BOD and SS and the discharged water following treatment was clear and low in pollutant. The sewage plants under construction and being planned for the future in Taiwan are to achieve the secondary treatment. The sewage treatment processes were as follows:

THE COLLECTION AND TRANSPORTATION OF WASTEWATER

Wastewater produced by households and offices were collected in the sewers. The inflow of sewage to sewage treatment plants can be forced by gravitation, pumping in treatment plants or pumping in the relay station.

SEWAGE TREATMENT

Following transported to wastewater treatment plants, the SS, BOD, grease and fecal coliform bacteria contained in the wastewater is much higher than the discharge standard. Therefore, the sewage needs to go through sedimentation, aeration and disinfection processes to meet the sanitation standards. During the sewage treatment process, additives such as coagulants, disinfectants and deodorants were added to purify water.

PURIFIED SEWAGE DISCHARGE

The purified sewage should meet the discharge standards before it was discharged to river or ocean by gravitation or other methods.

SLUDGE TREATMENT

The sludge left following sewage treatment contains high amount of pollutants and should not be recycled. The sludge was usually sent to a sludge incinerator for incineration or sludge landfills for bury treatment.

The sewage treatment process from transportation to aeration, sedimentation and disinfection requires various machinery operation and chemical additives. In this research, we investigated the electricity consumption, chemical addition and sewage treatment in several representative sewage plants to calculate the unit energy consumption and CO_2 emission. In addition, the sludge produced following sewage treatment and energy consumption from the transportation of sludge was calculated. From the sewage plants production data analysis, we can estimate CO_2 emission calculation. In addition, methane was produced from the biodegradation of sludge. Methane is also a greenhouse gas and can be used for electricity production. Therefore, in this research, methane production is also estimated for better environmental protection (Environmental Protection Administration 2005).

RESULTS

In this research four sewage treatment plants including Neihu, Pali, Anping and Kaohsiung were selected for investigation. These four sewage treatment plants handle 74.3% of total sewage treatment households in Taiwan. In addition, the public sewer system in new Taipei, Kaohsiung and Tainan city is still under construction. Several wastewater stoppage stations were constructed to divert waste water into these four sewage treatment plants for water treatment. The wastewater stoppage area covers more than 500,000 households. Therefore, the four sewage treatment plants selected have covered most sewage treatment households in Taiwan. Based on the above life cycle assessment, we convert energy consumption at different stages of sewage treatment into CO_2 emission (Table 1). The calculated unit CO_2 emission for sewage treatment is 0.174 kg-CO_2/m^3. Among four sewage plants, Pali plant has the lowest CO_2 emission of 0.131 kg-CO_2/m^3 while Neihu plant has the highest CO_2 emission of 1.032 kg-CO_2/m^3 which is almost 7.9 times of the value of Pali plant. This indicates that sewage treatment plant at different locations have huge CO_2 emission difference. Table 1 also shows that secondary treatment plants have higher CO_2 emission than primary treatment plants. If we analyze the percentage of CO_2 emission at different stages of sewage treatment, the CO_2 emission at in-plant sewage treatment stage takes more than 95% of total CO_2 emission for three sewage treatment plants (except for Pali). The CO_2 emission at chemical addition stage, sludge transportation and treatment stages only take less than 1% of total CO_2 emission. On the other hand, Pali plant has many pumping, stoppage and relift stations which require a lot of energy for operation. Therefore, the CO_2 emission at sewage collection and transportation stage takes about 69% of total CO_2 emission while the CO_2 emission at in-plant sewage treatment stage only takes 27%.

Analyzing CO_2 emission at different stages in the life cycle of sewage treatment is a very labor-intensive work. In this research, only four sewage treatment plants were selected for analysis. The CO_2 emission analysis showed that for most plants (except Pali) the in-plant sewage treatment stage has the highest CO_2 emission. It is suggested that CO_2 emission can be evaluated using electricity consumption at in-plant treatment stage. The energy consumption at sewage collection, chemical addition and sludge transportation stages can be ignored to simplify the CO_2 emission calculation. In the future, operation statistics such as total treatment volume and in-plant electricity consumption can be used for unit CO_2 emission calculation. However, Pali plant treats more than 30% of sewage in Taiwan and the importance of energy consumption other than in-plant electricity consumption should not be ignored. For Pali plant, the electricity consumption at pumping, stoppage and relift stations should be considered along with in-plant electricity consumption to calculate CO_2 emission.

Discussion

Using the aforementioned streamlined principles, the CO_2 unit emission from sewage treatment plants in Taiwan was estimated. The usage of electricity in 43 sewage plants was estimated from the cost of electricity stated in a report (Construction and Planning Agency Ministry of the Interior 2011). These sewage plants include primary, secondary and tertiary treatment plants located across Taiwan and cover most of the sewage plants in Taiwan. In this research, the unit electricity consumption and CO_2 emission from sewage treatment was calculated from the cost of electricity and summarized in Table 2. The data showed that the unit electricity consumption was 0.1 kWh/m^3 and the unit CO_2 emission was 0.068 kg-CO_2/m^3 for Pali sewage plant. The calculation was only half the amount of what we calculated in investigation results. The huge difference in estimated electricity consumption in Pali sewage plant was likely due to the overlook of high electricity consumption during the sewage collection and transportation stages. Consequently, for Pali sewage plant, the CO_2 emission data calculated from investigation results was used for comparison. For the rest of the sewage plants, the total CO_2 emission was estimated from CO_2 emission of in-plant electricity consumption in

TABLE 1. CO_2 emission of sewage treatment

Plant name		Neihu	Pali	Anping	Kaohsiung
The annual volume of sewage treated (CMY)		13,734,234	330,352,600	21,782,021	294,171,460
CO_2 emission[*2] (kg-CO_2/m^3)	Collection & transportation	0.0002 (0.02%)	0.0904 (68.95%)	0.0071 (3.36%)	0.0071 (3.98%)
	In-plant treatment	1.0166 (98.48%)	0.0357 (27.23%)	0.2021 (95.69%)	0.1700 (95.34%)
	Chemical addition	0.0071 (0.69%)	0.0043 (3.28%)	0.0004 (0.19%)	-[*1]
	Sludge transportation	0.0070 (0.68%)	0.0005 (0.38%)	0.0010 (0.4%)	0.0005 (0.28%)
	Sludge digestion	0.0014 (0.14%)	0.0002 (0.15%)	0.0006 (0.28%)	0.0007 (0.39%)
Unit CO_2 emission (kg-CO_2/m^3)		1.032	0.131	0.211	0.178
Average sewage treatment unit CO_2 emission		0.174 kg-CO_2/m^3			

Note:*1.Part of chemical additives is produced in the plant and cannot be calculated
2. Conversion factor for electricity to CO_2 emission is 0.676 kg-CO_2/kWh

TABLE 2. Evaluation of unit CO_2 emission of sewage plants in Taiwan

Treatment level	Sewage plant	Sewage treated volume (m^3)	In-plant electricity consumption*1 (kWh)	Unit electricity consumption (kWh/m^3)	Unit CO_2 emission ($kg\text{-}CO_2/m^3$)	Corrected unit CO_2 emission*2*3 ($kg\text{-}CO_2/m^3$)
Primary	Pali	272,139,391	27,346,752	0.100	0.068	0.131*2
	Kaohsiung	290,380,479	71,925,815	0.248	0.167	0.176
Secondary	Daping Village	12,468	39,246	3.148	2.128	2.234
	Qingtian	58,916	125,210	2.125	1.437	1.508
	Donglin	89,565	136,365	1.523	1.029	1.081
	Jiayi	186,364	181,889	0.976	0.660	0.693
	Neilu	195,280	220,232	1.128	0.762	0.800
	Ronghu	219,729	204,799	0.932	0.630	0.662
	Wulai	381,853	364,498	0.955	0.645	0.678
	Zhitan	411,975	471,773	1.145	0.774	0.813
	Zhongzheng	427,730	504,553	1.180	0.797	0.837
	Kending	443,597	569,622	1.284	0.868	0.911
	Liuying	496,057	681,922	1.375	0.929	0.976
	Taihu	511,957	306,242	0.598	0.404	0.425
	Jiayi	814,981	1,239,246	1.521	1.028	1.079
	Jincheng	880,184	369,439	0.420	0.284	0.298
	Taichung	1,145,712	1,419,013	1.239	0.837	0.879
	Huweiliao	2,284,707	683,416	0.299	0.202	0.212
	Douliou	3,942,892	1,198,981	0.304	0.206	0.216
	Linkou	5,210,833	2,308,777	0.443	0.300	0.314
	Liukuaicuo	5,309,096	3,407,856	0.642	0.434	0.456
	Yilan	5,553,681	2,743,059	0.494	0.334	0.351
	Fengshan river	6,800,316	6,169,553	0.907	0.613	0.644
	Futien	19,096,402	4,556,940	0.239	0.161	0.169
	Anping	37,898,178	8,512,309	0.225	0.152	0.159
	Neihu	39,379,368	37,952,355	0.964	0.652	0.684
	Dihua	158,776,886	53,750,021	0.339	0.229	0.240
Tertiary	Houwo	3,457	33,505	9.692	6.552	6.879
	Tianwo	5,326	27,566	5.176	3.499	3.674
	Fushing	6,814	29,524	4.333	2.929	3.075
	Fuao	9,999	39,097	3.910	2.643	2.775
	Lishan	16,074	62,457	3.886	2.627	2.758
	Qingshui	16,185	37,118	2.293	1.550	1.628
	Magang	17,804	43,057	2.418	1.635	1.717
	Huanshan	56,465	114,619	2.030	1.372	1.441
	Jieshou	60,469	188,162	3.112	2.104	2.209
	Nanwan	272,521	427,481	1.569	1.060	1.113
	Pinglin	326,160	599,970	1.839	1.243	1.306
	Luodong	547,958	723,238	1.320	0.892	0.937
	Danshui	1,110,219	2,244,315	2.022	1.367	1.435
	Dashu	1,135,187	1,754,557	1.546	1.045	1.097
	Linkou	2,027,188	1,766,882	0.872	0.589	0.619
	Liudu	4,118,816	4,396,347	1.067	0.722	0.758
	Total	862,779,239	239,877,778	Sewage weighted	0.188	**0.216**

*1. Electricity consumption was estimated from the cost of electricity and might be different from the actual electricity consumption
*2. For all plants except Pali, the corrected unit CO_2 emission was calculated from in-plant electricity consumption multiplied by 1.05 correction factor. For Pali sewage plant, the data reported in investigation results was used
*3. Conversion factor for electricity to CO_2 emission is 0.676 $kg\text{-}CO_2/kWh$

2009 multiplied by correction factor 1.05. The correction factor comes from the aforementioned result that for three sewage plants (except Pali) the CO_2 emission at in-plant sewage treatment stage takes more than 95% of total CO_2 emission in the life cycle assessment of sewage treatment. The corrected nationwide unit CO_2 emission from sewage treatment is 0.216 kg-CO_2/m^3.

In 2009, the total volume of sewage treatment of 4 sewage plants (Anping, Neihu, Pali and Kaohsiung) we investigated took 74% of nationwide sewage treatment indicating the importance of these 4 sewage treatments plants. Comparing the corrected unit CO_2 emission from sewage treatment estimated from electricity consumption in 2009 data and unit CO_2 emission from the investigation results, the amount for Kaohsiung sewage plants in these two years are rather close as well as the annual volume of sewage treatment in these two years. Therefore, the corrected unit CO_2 emission estimated from 2009 data is credible. For Neihu and Anping sewage plants, compared with investigation results, the unit CO_2 emission estimated from 2009 data was decreased by 34% and 25% while the volume of sewage treatment was increased to 2.87 and 1.74 fold. It was shown that as the volume of sewage treated increases, the unit energy consumption of sewage treatment decreases for the reason that under normal operation, the energy consumption of sewage treatment machines at high load and low load does not differ dramatically. Therefore, the volume of sewage treated in a sewage plant should be close to its designed volume to achieve the highest energy efficiency. Compared with the total national electricity consumption in 2009, the electricity consumption comes from sewage treatment takes 0.12%. This percentage is relatively small compared to the United States and Japan. In future, as the sewage pipeline and the volume sewage treated increase, the consumption of electricity will increase.

In this research, the unit CO_2 emission for sewage treatment was calculated according to the sewage treatment level. Among the 43 sewage plants we investigated, two of them were primary plants with an average unit CO_2 emission of 0.154 kg-CO_2/m^3, twenty-five of them were secondary plants with an average unit CO_2 emission of 0.313 kg-CO_2/m^3 and sixteen of them were tertiary plants with an average unit CO_2 emission of 0.911 kg-CO_2/m^3. The results showed that the more advanced the sewage treatment, the higher the unit energy consumption and CO_2 emission. In future, the newly added sewage plants are designed for secondary or more

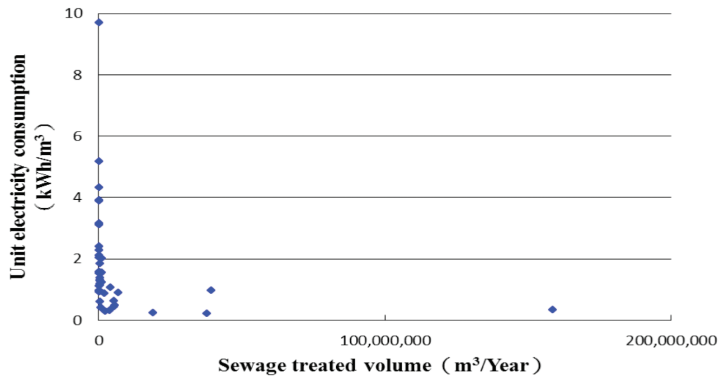

FIGURE 1. Volume of sewage treatment and unit electricity consumption for sewage plants (secondary and tertiary sewage plants)

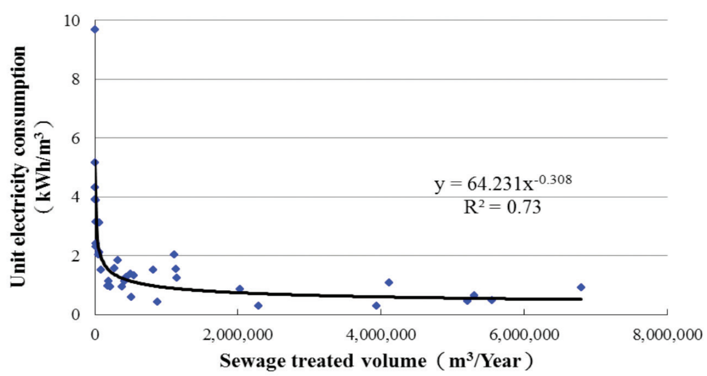

FIGURE 2. Volume of sewage treatment and unit electricity consumption for sewage plants (treat less than 10 million tons of sewage annually)

advanced sewage treatments. Therefore, the unit energy consumption and CO_2 emission for sewage treatment in Taiwan will be higher in the future. The annual volume of sewage treatment versus unit electricity consumption for secondary and tertiary sewage plants (41 plants) were analyzed and showed that the higher the volume of sewage treated the more efficient the energy use was. On the other hand, the unit electricity consumption increases as the volume of sewage treated decreases (Figure 1). We further analyzed the relationship of sewage treatment volume and unit electricity consumption for small scale sewage plants that treat less than 10 million tons of sewage annually. The analysis showed that the unit electricity consumption is an exponential function of treated sewage volume. At low volume of sewage treatment, the unit electricity consumption will increase dramatically (Figure 2). Therefore, the volume of sewage treatment in a sewage plant should be closer to its designed capacity to achieve the best efficiency of machine operation.

CONCLUSION

In this research, the energy consumptions and sewage treatment volume of major sewage plants in Taiwan were investigated and converted to CO_2 emission. The unit CO_2 emission for sewage treatment is calculated to be 0.216 kg-CO_2/m^3. Among four major sewage treatment plants investigated for CO_2 emission. Pali sewage plant (primary) has the lowest CO_2 emission, 0.131 kg-CO_2/m^3, while Neihu sewage plant (secondary) has the highest CO_2 emission, 1.032 kg-CO_2/m^3. This showed that different sewage treatment plants have huge energy consumption difference. From the life cycle analysis, for most sewage plants (except Pali plant), the CO_2 emission at in-plant sewage treatment stage takes more than 95% of total CO_2 emission in the life cycle analysis of sewage treatment. Therefore, it was suggested that the total CO_2 emission of sewage treatment can be calculated from in-plant electricity consumption and ignore energy consumptions at sewage collection and transportation, chemical addition, and sludge treatment stages to simplify the calculation. The CO_2 emission in the sewage treatment life cycle can be estimated from annual electricity consumption multiplied by a correction factor 1.05.

The research showed that the unit CO_2 emission for primary sewage treatment plants is 0.154 kg-CO_2/m^3, the unit CO_2 emission for secondary sewage treatment plants is 0.313 kg-CO_2/m^3, and for tertiary plants is 0.911 kg-CO_2/m^3. It was found that the higher the treatment level, the more the unit CO_2 emission. It was shown that the unit energy consumption decreases as the treatment volume increases. Therefore, it was suggested that in the future plan, the sewage plant should be designed to treat the optimal volume of sewage accordingly. In addition, the installation of equipments and machineries in the sewage plants can be divided into stages and sections to avoid the situation that the machinery only operates at low efficiency due to low treatment volume. The results from this research can be combined with CO_2 emission information of piped water for water conservation and sewage reduction analysis for various buildings (Chang 2012). Along with CO_2 emission information at different stages of a building's life cycle, the results of this research can provide valuable information for future water resource research and government environmental policies.

REFERENCES

Burton, F.L. 1996. *Water and Sewage Industries: Characteristics and Energy Management Opportunities*. Los Altos: Electric Power Research Institute.

Chang, Y.S. 2012. The streamlined life cycle assessment of carbon dioxide eEmission of tap-water in Taiwan. *Journal of Architecture* 82: 55-67.

Chang, Y.S. 2002. *Life Cycle Assessment on the Reduction of Carbon Dioxide Emission of Buildings*. PhD thesis. Taiwan: National Cheng Kung University (Unpublished).

Construction and Planning Agency Ministry of the Interior (CPAMI). 2011. *The Report of Sewage Plants Energy Saving Project*. Taipei: CPAMI Taiwan.

Emmerson, R.H.C., Morse, G.K., Lester, J.N. & Edge, D.R. 1995. The life-cycle analysis of small-scale sewage treatment processes. *Water and Environment Journal* 9: 317-325.

Environmental Protection Administration. 2005. *Kitchen Waste Recycling Advocacy and Counseling Evaluation*. Taipei: EPA Taiwan.

Henze, M. & Ødegaard, H. 1995. Wastewater treatment process development in Central and Eastern Europe: Strategies for a stepwise development involving chemical and biological treatment. In *Remediation and Management of Degraded River Basins: With Emphasis on Central and Eastern Europe*. Berlin: Springer Verlag. pp. 357-383.

Houghton, J.T., Meira Filho, L.G., Lim, B., Treanton, K., Mamaty, I., Bonduki, Y., Griggs, D.J. & Callender, B.A. 1997. *Revised 1996 IPCC Guidelines for Greenhouse Gas Inventories*. United Kingdom: Intergovernmental Panel on Climate Change.

Japan Sewage Works Association. 2008. *Sewage Sludge Eenergy use Survey Report*. Japan: JSWA

Ministry of Health, Labour and Welfare. 2009. *Handbook of Environmental Measures in the Water Supply Business (Revised edition)*. Tokyo.

Todd, J.A. & Curran, M.A. 1999. *Streamlined Life-Cycle Assessment: A Final Report from the SETAC North America Streamlined LCA Workgroup*. SETAC. Pensacola.

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