SUSTAINABLE AND INTEGRATED SEWAGE AND ORGANIC WASTE HANDLING WITH GLOBAL WARMING IMPACT, A CASE STUDY OF ÅLAND AND ENERGY RECOVERY BY SCWO OR ANAEROBIC DIGESTION

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ABSTRACT
Organic waste exists both as sewage sludge from wastewater treatment and as municipal organic waste from for instance households. Sustainable handling of municipal organic waste and sewage sludge has as an important goal to recycle resources without supply of harmful substances to humans or the environment. Another important goal is to avoid to deposit waste and sludge on landfill. Deposition of incinerable material on landfill has been prohibited in Sweden and in year 2005 there will be a ban on deposition of all organic material on landfill. Incineration and SCWO, Super Critical Water Oxidation, are methods that eliminates all organic content and the potential energy of the organic material can be utilised. SCWO occurs in water at high pressure and temperature, and an organic content higher than 3 %. The energy can be recovered as steam or hot water. Sludge incineration requires that the sludge have to be dried to 40 % dry substance. The energy produced from the incineration is consumed by the drying process and there is therefore no net energy recovery from sludge incineration. With use of SCWO, energy can be recovered also from sewage sludge and organic waste with too low dry substance for incineration. Anaerobic digestion eliminates half of the organic content and half of the energy can be utilised as methane gas. Increasing the energy recovery from sewage sludge and organic waste decreases the need of fossil fuel and makes the society more sustainable. Less need for fossil fuels decreases the environmental impact of global warming caused by emission of greenhouse gases. A case study with evaluations of the energy gain using SCWO compared with anaerobic digestion is made on basis of a study of emissions of greenhouse gases and other air pollutants in Åland. At anaerobic digestion phosphorus is realised to the supernatant, which can be prevented by using more precipitation agents. Since SCWO gives no supernatant lower amount of precipitation agents can be used, if anaerobic digestion is substituted with SCWO. Handling of sludge and organic waste can be integrated by use of food waste disposers and transporting the organic waste to the wastewater treatment plant in the sewer net.

KEYWORDS
Sewage sludge, Organic waste, Super Critical Water Oxidation, Anaerobic digestion, Energy recovery, Global warming, Åland

INTRODUCTION

Organic waste exists both as sewage sludge from wastewater treatment and as municipal organic waste from for instance households. Sustainable handling of municipal organic waste and sewage sludge have as an important goal to recycle resources without supply of harmful substances to humans or the environment (Levlin 1999, Hultman and Levlin, 1997). Another important goal is to avoid to deposit waste and sludge on landfill. In Sweden a tax of 250 SEK/ton on all deposited solid waste was introduced year 2000 (SFS 1999:673). Deposition of incinerable waste has been prohibited and in year 2005 there will be a ban on deposition of all organic material on landfill (SFS 2001:512). Incineration (ATV, 1997) and SCWO, Super Critical Water Oxidation, are methods that eliminate all organic content and the potential energy of the organic material can be utilised.

Increasing the energy recovery from sewage sludge and organic waste decreases the need of fossil fuel and makes the society more sustainable. Less need for fossil fuels decreases the environmental impact of global warming caused by emission of greenhouse gases such as carbon dioxide, methane and nitrous oxide. Carbon dioxide produced from burning fossil fuel increases the carbon dioxide content in the atmosphere giving impact of global warming. Table 1 shows Global Warming Potentials (GWPs) for methane and nitrous oxide relative to carbon dioxide. GWPs are an index for estimating relative global warming contribution due to atmospheric emission of a kg of a particular greenhouse gas compared to emission of a kg of carbon dioxide. GWPs calculated for different time horizons show the effects of atmospheric life times of the different gases. Although methane and nitrous oxide have higher GWP than carbon dioxide, the emissions of carbon dioxide is so much larger that the global warming potential from carbon dioxide is higher than the global warming potentials from methane and nitrous oxide. For most nations such as Sweden, the contributions from different emissions to GWP are 80 % from carbon dioxide, 10 % from methane and 10 % from nitrous oxide. Most of the emission sources such as road traffic, sea traffic, electricity and heat are emission from burning fossil fuel such as oil.

Table 1. Direct Global Warming Potentials (GWPs) for methane and nitrous oxide relative to carbon dioxide (IPCC**,** 2001 page 47).

Gas		Lifetime (years)	Global Warming Potential (Time Horizon in years)		
			20 yrs	100 yrs	500 yrs
Carbon dioxide	CO_2		1	1	1
Methane	CH_4	12.0	62	23	7
Nitrous oxide	N_2O	114	275	296	156

A CASE STUDY OF SEWAGE AND WASTE HANDLING ON ÅLAND

Total emissions from Åland

A case study with calculations on amount of sewage, sludge, produced biogas, greenhouse gas emissions, energy gain etc. has been made in a study of emissions of greenhouse gases and other air pollutants in Åland (Levlin, 2003). Emission of greenhouse gases from sewage and waste handling in Åland is estimated to 0.8 Mg CO_2–equivalents per capita, which is 4 % of the total emissions of greenhouse gases (see table 2). The Åland islands lies in the Baltic Sea between Sweden and Finland and the main emissions are from the sea traffic, which are the ferries going between Sweden and Finland.

Table 2. Global warming potential GWP, in Mg CO_2–equivalents, from emission of greenhouse gases in Åland, distributed on different greenhouse gases and emission sources (Levlin, 2003).

	Carbon dioxide CO_2	Methane CH_4		Nitrous oxide N_2O		Total GWP		Per Capita
	Mg/year	Mg/year	GWP	Mg/year	GWP			
Sewage and waste	4 658	609	8 146	8.02	2 375	20 754	4 %	0.80
Electricity and heat	84 056	11.7	268	4.51	1 334	85 685	18 %	3.29
Road trafic	49 501	13.4	307	7.67	2 269	52 078	11 %	2.00
Agriculture	—	625	14 368	68.0	20 128	53 527	7 %	1.33
Other oil burning	18 900	0.21	5	0.43	126	19 031	4 %	0.73
Sea trafic	268 710	3.60	82.8	7.20	2 132	270 925	56 %	10.42
Total	425 826 90 %	1263	29 047 5 %	94.8	28 069 5 %	482 942		18.57

Emissions from sewage handling

Lotsbroverket, the WWTP of Mariehamn, the capital of Åland, treated 1.95 million m^3 sewage water in year 2001 with 423 Mg BOD_7, Biological Oxygen Demand. COD, Chemical Oxygen Demand, is 2 times BOD (Gray, 1999), which gives 845 Mg COD. COD is 1.8 g oxygen/g biomass, which gives 529 Mg DS, Dry Substance, organic content biomass. TOC, Total Organic Carbon, is about 40 % of COD, giving 339 Mg TOC, which can be converted to 1242 Mg CO_2 (TOC x 44/12). The energy content is 3.48 kWh/kg COD (Kepp and Solheim, 2000) which gives 2.78 GWh. At degradation of the biomass gases such as carbon dioxide is produced and in anaerobic conditions also methane. The biomass is degraded aerobically in the activated sludge process and anaerobically in the sludge digestion chambers. The WWTP produced 649 Mg sludge (23192 m^3, DS 2.8 %). With 30 % inorganic content and 41 % degree of digestion gives 520 Mg biomass or 936 Mg COD. Burning biogas gives carbon dioxide equivalent to the amount produced by aerobic degradation. Of 557 Mg DS sludge biomass 189 Mg biogas is produced can be the digestion chambers, which by burning can be converted to 562 Mg carbon dioxide and 1.33 GWh energy. The produced amount of biogas was 219 106 m^3, whitch with an energy value of 6 kWh/m^3 gives 1.31 GWh energy. The remaining biomass in the digested sludge can at further degradation be converted to 635 Mg carbon dioxide and has a potential energy content of 1.92 GWh. Since the digested sludge is composted, the energy content in the digested sludge is not utilised. A part of the produced biogas was used in a diesel engine for producing 0.178 GWh of electricity. A diesel engine has about 30 % efficiency, which means that methane equivalent to 0.59 GWh (100 000 m^3) was used for producing electricity. The remaining biogas was flared. An other large sludge producer is the potato chips factory, which produced 394 Mg digested sludge equivalent to 580 Mg sludge before digestion. There are also some smaller treatment works in smaller villages around Åland. The total amount of sludge produced in Åland can thereby be estimated to about 1400 Mg before digestion. The inorganic content of the sludge before digestion is about 20 % DS, giving 1120 Mg DS biomass. Table 3 shows the calculations of BOD, COD, TOC, CO_2, CH_4 and energy from 1400 Mg DS sludge. The energy content in the sludge after digestion is the potential energy that can be recovered. 1200 Mg DS sludge was digested (41 % degree of digestion) thus reducing the amount of sludge to 1000 Mg after digestion.

Table 3. Calculation of COD, BOD, TOC, CO_2, CH_4 and energy from 1400 Mg DS sludge.

	Sludge Mg DS	Inorganic Mg	Organic Mg	COD Mg	BOD Mg	TOC Mg	CO_2 Mg	CH_4 m^3	Energy MWh
Formula		20 %	Sludge - inorg.	1.8xOrg .	$\frac{COD}{2}$	0.4xCOD	$\frac{44xTOC}{12}$	900 x TOC	3.48 x COD
Total sludge	1400	280	1120	2016	1008	806	2957		7 016
Digested	–399		–399	–718	–359	–287	–1053	258 422	2 498
After digestion	1001	280	721	1298	649	520	1904		4 518

Table 4 shows emissions of greenhouse gases and some other air pollutants from incineration of biogas from sludge digestion, and emissions from deposition of digested sludge (Mg/year) year 2001 calculated on a total amount of sludge on 1400 Mg DS before digestion. CH_4, N_2O, NO_X, CO, SO_2 and NMVOC (Non Methane Volatile Organic Carbons) from biogas incineration have been calculated with emission factors from fuel oil incineration received from SCB, Statistics Sweden. The emission was calculated from the amount of CO_2 by dividing the factors with 3.15 (3.15 kg CO_2 is produced per kg oil). Emission of gases from stored or deposited sludge has calculated with emission factors by RVF Utveckling (2002), which gives a contribution of 2262 Mg CO_2-equivalents. RVF Utveckling measured gas emissions and calculated the methane emission to 3.13 kg/Mg DS and the nitrous oxide emission to 5 kg/Mg DS. However, composting the sludge will reduce the methane and nitrous oxide emission from the digested sludge.

Table 4. Emissions of greenhouse gases and some other air pollutants from incineration of biogas from sludge digestion, and emissions from deposition of digested sludge (Mg/year) year 2001 calculated on a total amount of sludge on 1400 Mg DS before digestion (Levlin, 2003).

	Greenhouse gases				Other air pollutants			
	CO_2	CH_4	N_2O	GWP	NO_X	CO	SO_2	NMVOC
Biogas incineration	1053	0.012	0.024	1061	0.60	0.60	0.36	0.036
From digested sludge	1904	4.382	7.000	4166	—	—	—	—
Total	2957	4.394	7.024	5227	0.60	0.60	0.36	0.036

Emissions from waste handling

The emission from waste handling Åland was estimated by calculating emissions from Svinryggen, the largest landfill on Åland, which serves 60 % of the population. For the calculation a computer program LandGEM, Landfill Gas Emission Model was used, which can be received from EPA, USA Environmental Protection Agency (http://www.epa.gov/ttncatc1/dir1/landgem.zip). Gas containing 50 % methane and 50 % carbon dioxide is produced for 20 to 30 years after deposition by degradation of cellulose in the waste. The degradation of cellulose is a very slow process, since the cellulose is protected by lignin, which first has to be degraded. To calculate the emissions for year 2001, all amount of waste that has been deposited since opening of the landfill in year 1960 has to be used as input to the program. The amount of deposited waste was largest in year 1992 with 10 600 Mg. Since then the amount of deposited waste has decreased to 4366 Mg year 1999, 4250 Mg year 2000 and 2557 Mg year 2001. The LandGEM calculated the emissions for year 2001 from the landfill to 363 Mg methane (543 500 m^3) and 995 Mg carbon dioxide (543 500 m^3). To get an estimation of emission of all waste deposit on Åland the figures has to be multiplied with 1.66, giving 1658 Mg carbon dioxide and 605 Mg methane.

COMPARISION OF TREATMENT TECHNOLOGY ON BASIS OF ENERGY RECOVERY

Energy utilisation of organic matter in sludge

Super Critical Water Oxidation, SCWO (Gidner et al., 2000) occurs in water of a supercritical phase at a temperature above 374 °C, a pressure higher than 22 Mpa and an organic content higher than 3 %. Anaerobic digestion eliminates half of the organic content and half of the energy can be utilised as methane gas. Sludge incineration requires that the sludge has to be dried to more than 40 % dry substance. The energy produced from the incineration is thereby consumed by the drying and there is therefore no net energy recovery from sludge incineration. With use of SCWO, energy can be recovered also from sewage sludge and organic waste with too low dry substance for incineration. However, sludge incineration reduces emission from undigested sludge of methane and nitrous oxide, which has a larger GWP than carbon dioxide. The impact of global warming from methane and nitrous oxide emissions from undigested sludge, is larger than the impact of global warming from carbon dioxide produced by incineration of the sludge.

At anaerobic digestion phosphorus is realised to the supernatant, which can be prevented by using more precipitation agents. At the wastewater treatment plant of east lake Shinji in the Shimane prefecture, Japan, phosphorus recycling with the supernatant was so large that the supernatant was 70 % of phosphorus load of the plant (Ueno and Fujii, 2001). Phosphorus release is larger at biological phosphorus removal there a large part of the phosphorus in the excess sludge is biological bounded (Wild et al, 1996). Reduction of iron (III) to iron (II) in the digestion requires that the amount of iron precipitation agent must be higher, if the sludge is digested.

$$3FePO_4 + 3e^- \rightarrow 3Fe(PO_4)_2 + PO_4^{2-}$$

Since SCWO gives no reduction lower amount of precipitation agents can be used, if anaerobic digestion is substituted with SCWO. Foaming problems of digestion chambers caused by recycling of foaming bacteria with the digester supernatant (Hultman and Levlin, 2003), can also be eliminated by substituting anaerobic digestion with SCWO. SCWO can be used to oxidise digested sludge as well as undigested. If SCWO is used to oxidise undigested sludge the amount of energy produced will be higher and all energy content in the sludge biomass will be recovered as heat above 374 °C. The heat from the SCWO can be used in district heating systems, which will reduce the need for fuel and thus reduce the emission of greenhouse gases for burning fuel for district heating.

Chemical precipitation versus biological phosphorus removal

To increase the energy recovery and thereby substituting fossil fuel to decrease the impact of global warming, wastewater treatment with chemical precipitation can be better alternative than biological phosphorus removal. In a LCA, Life Cycle Assessment, of different wastewater treatment process by Ødegaard (1995), the environmental impact showed to be mainly an effect of the consumed and produced energy. Comparision between a plant with chemical precipitation and a plant with biological phosphorus removal (see table 5), both with biological denitrification, shows that with biological phosphorus removal the energy consumption is higher and the biogas production smaller. Energy consumption was energy in used chemical, for aeration of the biological basins and for transport, and energy produced as gas from digestion of the sludge. The largest energy consumption was for aeration, which in the cases that included nitrogen reduction, the consumed amount of energy was larger than the energy produced as biogas. In the case with the energy production much larger than the consumption the LCA showed a reduced environmental impact due the produced energy, reduced environmental impact of energy that otherwise has to be produced in other ways.

Table 5. Energy demand and energy production (Wh/m^3 wastewater) for a plant with chemical pre-precipitation compared to a plant with biological phosphorus removal both with biological nitrogen removal through post denitrification (Ødegaard, 1995).

Energy demand:	Chemicals	Aeration	Biogas(el)	Sludge transport	Difference
Chemical plant	-30 Wh/m^3	-150 Wh/m^3	+ 210 Wh/m^3	-19 Wh/m^3	+11 Wh/m^3
Biological plant	-8 Wh/m^3	-213 Wh/m^3	+115 Wh/m^3	-13 Wh/m^3	-119 Wh/m^3
Difference	27 %	142 %	55 %	68 %	

The gain of biogas was higher and the need of electricity for the air blowers in the activated sludge process was lower for a plant with chemical precipitation than for a plant with biological phosphorus removal. At chemical precipitation more biological material is removed with the primary sludge and less is degraded aerobically with oxygen in the activated sludge process. With chemical precipitation a larger part of the organic material in incoming wastewater will be precipitated as sludge, 310 g SS/m^3 compared to 200 g SS/m^3 for biological phosphorus removal, thus increasing the biogas production. With biological phosphorus removal more of the organic material will be degraded to carbon dioxide and water in the activated sludge process. This requires a larger oxygen demand in the activated sludge process thus increasing the energy needed for aeration. The amount produced of carbon dioxide and the impact of global warming from the sewage depends on the total amount of biodegradable organics in the sewage. However the impact of global warming can be reduced if a larger part of the organic material is transferred to the sludge and utilised for energy production and reducing consumption of fossil fuel.

DISCUSSION

The case study from Åland can be used to compare anaerobic digestion with a potential use of SCWO. Utilisation of the biogas for energy production decreases the contribution of sewage treatment to global warming by reducing emissions from burning the fuel that otherwise would have been required. Since the emission from burning fuel will be about the same as from burning biogas the gain in global warming potential will be equal to the emission from burning the biofuel, that is 1061 Mg CO_2-equivalents, the emission from sewage will decrease from 5227 to 4166 Mg CO_2-equivalents. If the digested sludge is oxidised with SCWO the energy of the remaining biomass can be utilised and thereby through fuel saving will the emissions of greenhouse gases from the digested sludge be eliminated. The district heating system of Mariehamn burned 6116 Mg heavy oil in year 2001 giving 71 GWh heat energy (Levlin, 2003). If the biogas from the WWTP was used for heat production it would give 1.31 GWh heat energy and save 178 Mg oil. If the digested sludge was oxidised with SCWO it will give additional 1.92 GWh heat energy and save further 202 Mg oil. If the anaerobic digestion is substituted with SCWO it will give 3.23 GWh heat energy and save 380 Mg oil. This is however only 6 % of the fuel needed for the district heating system. If all sludge on Åland is transported to Mariehamn and used by SCWO for district heating it will give 7 GWh heat energy and save 939 Mg oil, 15 % of the fuel need. In this case due to the decrease of greenhouse gas emissions from the fuel saving, there will be no contribution to the global warming potential from the sewage handling. A proposal has been made to improve wastewater treatment by building sewer pipelines from villages on North Åland to transport wastewater to Mariehamn.

If also organic waste is used for heat production through SCWO further amount of fuels for district heating can be saved. The energy gain and thereby the fuel saving from oxidising organic waste will be higher than from oxidising the sludge. In 2001 the amount of household waste on Åland was 2985 Mg and the amount of organic waste was 3034 Mg. In 2001 at the Åland landfill Svinryggen, 343 Mg organic waste was deposited, which if it had been digested with 40 % degradation would have give 128 000 m^3 biogas (0,77 GWh energy) equivalent to 65 Mg oil. Of the household waste 1163 Mg was incinerated in Uppsala, Sweden and 1822 Mg was deposited. Of the organic waste was 128 Mg recycled, 2521 composted and 385 Mg deposited. If the SCWO facility is situated at the WWTP, organic waste can also be transported by the sewer net. Handling of sludge and organic waste can be integrated by use of food waste disposers and thereby transporting the organic waste to the wastewater treatment plant in the sewer net (Karlberg and Norin, 1999). The increase in the amount of sludge produced in the wastewater treatment showed to be proportional to the addition of organic waste by he waste disposers. However the sewer net has to have the capability to transport a sewer with a higher amount of suspended solids.

Most of the greenhouse gas emission from the waste handling originates from waste deposited 20 to 30 years ago. Even if the waste in the further will be used for energy production the emissions from the deposited waste will continue. To reduce the risk of burning in the landfill and to reduce the impact on global warming, methane produced in a landfill shall be collected and utilised to produce energy or flared. Incineration of 1 kg methane produces 2.75 kg carbon dioxide. Since GWP of methane is 21 CO_2-equivalents, incineration of 1 kg methane reduces the GWP with 18.25 CO_2-equivalents.

CONCLUSIONS

The environmental impacts of wastewater treatment processes on global warming are mainly an effect of produced greenhouse gases such as carbon dioxide, which can be reduced by saving fossil fuel through energy recovery.

By maximising the amount of organic material of the wastewater that is transferred to the sludge and utilized for energy recovery, the impact of global warming from sewage handling can be minimised.

With use of Super Critical Water Oxidation SCWO all the potential energy of the organic material or biogas production half of potential energy of the organic material, can be recovered from sewage sludge and organic waste and by utilisation of the energy there will be less contribution to the global warming potential from the sewage handling.

A large need of energy for district heating makes utilisation of the heat energy produced by SCWO of sludge and organic waste possible.

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