

# Sewage Sludge as a Biomass Resource for the Production of Energy: Overview and Assessment of the Various Options<sup>†</sup>

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Treatment of municipal wastewater results worldwide in the production of large amounts of sewage sludge. The major part of the dry matter content of this sludge consists of nontoxic organic compounds, in general a combination of primary sludge and secondary (microbiological) sludge. The sludge also contains a substantial amount of inorganic material and a small amount of toxic components. There are many sludge-management options in which production of energy (heat, electricity, or biofuel) is one of the key treatment steps. The most important options are anaerobic digestion, co-digestion, incineration in combination with energy recovery, co-incineration in coal-fired power plants, co-incineration in combination with organic waste focused on energy recovery, use as an energy source in the production of cement or building materials, pyrolysis, gasification, supercritical (wet) oxidation, hydrolysis at high temperature, production of hydrogen, acetone, butanol, or ethanol, and direct generation of electrical energy by means of specific micro-organisms. Incineration and co-incineration with energy recovery and use of sewage sludge in the production of Portland cement are applied on a large scale. In these processes, the toxic organics are destructed and the heavy metals are immobilized in the ash or cement. The energy efficiency of these processes strongly depends upon the dewatering and drying step. It is expected that these applications will strongly increase in the future. Supercritical wet oxidation is a promising innovative technology but is still in the development stage. With the exception of biogas production, the other biological methods to produce energy are still in the initial research phase. Production of biogas from sewage sludge is already applied worldwide on small, medium, and large scales. With this process, a substantial experience exists and it is expected that this application is getting more and more attention. Besides the increasing focus on the recovery and reuse of energy, inorganics, and phosphorous, there is also an increasing focus to solve completely the problem of the toxic organics and inorganic compounds in sludge. In the assessment and selection of options for energy recovery by means of biological methods, this aspect has to be taken into account.

## Introduction

During the last 2 decades, developments in municipal wastewater treatment strategies are characterized by a continuous effort to improve the quality of the effluent by upgrading existing treatment plants and designing and implementation of new more effective treatment plants. This effort simultaneously proceeded with an enforcement of the industry and households to reduce or eliminate the discharge of toxic pollutants into the sewer. Parallel to the improvement of the effluent quality, an increasing awareness of the problems associated with the sewage sludge produced in the wastewater treatment process is observed. These problems are a continuous increase in sludge production, the high costs of sludge treatment, and the risks that sewage sludge may have on the environment and human health. The latter is not surprising because the nature of the present wastewater treatment systems is such that toxic pollutants are concentrated in the sludge, together with a large fraction of pathogens. Because of this increasing awareness regarding risks for the environment and human health, the original application of the sludge as a fertilizer in agricultural systems has become

increasingly under pressure.<sup>1,2</sup> This is also caused by the increasing insight into the possible adverse effect of these toxic pollutants and pathogens. Parallel to this development, also, the government policy and regulations regarding the application of sludge in agriculture have changed considerably.<sup>3</sup> However, policy and legislation regarding sludge application and sludge management in general are heavily dependent upon local, national, and regional conditions. The costs of sewage sludge treatment often represent more than 50% of the total wastewater treatment costs.

Municipal wastewater treatment can be considered as a continuous activity also in the future. It is organizationally, technically, and economically hardly possible to prevent or strongly reduce the amount of municipal wastewater. Also, the presence of toxic pollutants in municipal wastewater can not be avoided because a large part of these toxics originates from diffuse sources. This means that also the quality of the sewage sludge and the produced amount of sewage sludge, estimated at about 50 g of dry matter per person per day, will not change significantly in the future. Sewage sludge will remain a permanent waste problem that requires an appropriate solution.

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Looking into the future, it can be expected that sludge management and research into innovative treatment methods will focus on three aspects: recovery and reuse of valuable products from sludge, a complete solution of the sludge problem, especially regarding the toxics, and acceptable costs. In this respect, it can be expected that the recovery of sustainable energy from sewage sludge will become more and more of interest.<sup>4</sup>

The aim of this paper, which is based on a literature review, is to discuss the various options to recover energy from sewage sludge and to assess qualitatively these options with respect to the development stage, potential of energy recovery, and expected future developments. In this evaluation, also, the effect of the presence of toxic organic and inorganic components in the sludge is assessed.

### Composition of Sewage Sludge

To assess the options for energy recovery from sewage sludge, it is necessary to look at the composition of the sludge. As a very rough guide, this composition is characterised by six groups of components: (1) nontoxic organic carbon compounds (approximately 60% on a dry basis), for a large part from biological origin, (2) nitrogen- and phosphorous-containing components, (3) toxic inorganic and organic pollutants, i.e., (a) heavy metals, such as Zn, Pb, Cu, Cr, Ni, Cd, Hg, and As (concentrations vary from more than 1000 ppm to less than 1 ppm) and (b) polychlorinated biphenyls (PCBs), polycyclic aromatic hydrocarbons (PAHs), dioxins, pesticides, linear-alkyl-sulfonates, nonyl-phenols, polybrominated fire retardants, etc., (4) pathogens and other microbiological pollutants, (5) inorganic compounds, such as silicates, aluminates, and calcium- and magnesium-containing compounds, and (6) water, varying from a few percentages to more than 95%.

The fundamental problem of sewage sludge is that all of these compounds are present in one mixture. Organic carbon-, phosphorous-, and nitrogen-containing compounds can be considered as valuable compounds. This often holds for the inorganic compounds as well. Sustainable treatment involves the recovery and useful reuse of the valuable components and the minimisation of the possible adverse impact of sewage sludge or residues from sewage sludge treatment on the environment and humans. For reasons of transport, disposal, or efficient treatment, it is also often required to remove the water. The amount of nitrogen-containing components in the sludge is small compared to the amount of these components present in the wastewater. The amount of phosphorous in the sludge depends upon the type of wastewater treatment process. It is possible to concentrate almost all of the available phosphorous in the sludge. However, also, a direct recovery of phosphorous from the waterline is possible.

### Options for Energy Recovery from Sewage Sludge

Very briefly, the various options for the recovery of energy from sewage sludge, in fact, from the organic compounds in the sludge, can be subdivided into nine groups: (1) anaerobic digestion of sewage sludge, (2) production of biofuels from sewage sludge, (3) direct production of electricity from sewage sludge in microbial fuel cells, (4) incineration of sewage sludge with energy recovery, (5) co-incineration of sewage sludge in coal-fired power plants, (6) gasification and pyrolysis of sewage

sludge, (7) use of sludge as an energy and raw material source in the production of Portland cement and building materials, (8) supercritical wet oxidation of sewage sludge, and (9) hydrothermal treatment of sewage sludge.

Several of these treatment options are already applied in practice; others are still in the research phase. In the next few paragraphs, the various options are further discussed and assessed.

### Anaerobic Digestion of Sewage Sludge

The anaerobic digestion process consists of three steps: a hydrolysis step in which organic compounds, such as polysaccharides, proteins, and fat, are hydrolyzed by extracellular enzymes, an acidification step in which the products of the hydrolysis are converted into hydrogen, formate, acetate, and higher molecular-weight volatile fatty acids, and a third step in which biogas, a mixture of methane and carbon dioxide, is produced from hydrogen, formate, and acetate. The high-molecular-weight volatile fatty acids first have to break down to hydrogen, formate, and acetate before further conversion to methane and carbon dioxide is possible. The complete methanogenic conversion occurs by mixed microbiological communities, yielding methane as the sole reduced organic compound. The entire process can take place in one reactor or in a two-step reactor, one for the hydrolysis and acidification and one for the biogas production. The biogas can be used as an energy source for the production of electricity and/or heat.

Anaerobic digestion is used to stabilize the sewage sludge and convert part of the volatile compounds into biogas. The biogas can be applied as an energy resource either at the wastewater treatment plant itself or elsewhere. Currently, anaerobic digestion of sewage sludge is mainly applied at large- and medium-sized wastewater treatment plants. However, also, a growing interest is observed in the application of anaerobic treatment in small-sized plants.

The vast majority of the anaerobic processes applied in practice are mesophilic. The sludge retention time in the anaerobic digester amounts to approximately 20 days. Biogas production strongly depends upon the type of sludge and also the operating conditions of the digester. The gas production from a mixture of primary and secondary (biological) sludge roughly amounts to 1 m<sup>3</sup> of biogas/kg of organic solids biodegraded. It is also possible to digest sludge thermophilically at a temperature of about 55 °C. In comparison to mesophilic digestion, thermophilic treatment has some advantages, such as a somewhat higher biogas production, a higher destruction degree of pathogens, and a larger reduction in the amount of organic solids. Also, the retention time of the sludge in the reactor can be reduced.

With the standard digestion technologies, only approximately 20–30% of the organic matter is mineralized. A substantial increase of biogas production can be obtained by applying a proper physical, chemical, thermal, mechanical, or biological pretreatment step, such as hydrothermal heating, microwave heating, ultrasonic treatment, use of ozone, use of enzymes, use of liquid jets, treatment (hydrolysis) with sodium hydroxide, application of high-performance pulse techniques, or wet oxidation.<sup>5–9</sup> The potential of the various pretreatment processes to increase the anaerobic biodegradation rate and to produce a much larger amount of biogas is substantial. Also the smaller

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residual amount of the dewatered sludge, which has to be disposed in a controlled landfill or treated additionally, is an advantage. With regard to the assessment of the feasibility of a pretreatment method, the extra biogas production, the total energy balance, the final amount of sludge, and the costs have to be taken into account and analyzed.

Toxic organic compounds are only partly removed in the anaerobic digestion process. Besides the residual toxic organics, the digested sludge still contains the heavy metals, soluble phosphates, and inorganics. To obtain a complete solution, a further treatment is necessary, for example, by dewatering the digested sludge, incineration of the sludge cake, and treatment of the supernatant. However, it has to be realized that after recovery of the biogas the energy content of the residual fraction is low, which means that incineration of this fraction with the aim to recover energy has become less attractive.

### Production of Biofuels from Sewage Sludge

Numerous papers are available regarding biological conversion processes that can be used to produce liquid or gaseous energy carriers from biomass. A clear overview of the various conversion processes is given by Claassen et al.<sup>10</sup> A general process scheme of a microbiological conversion process focused on the production of energy carriers consists of three main steps. The first step is a pretreatment step that is often necessary to make the substrate accessible to the biological conversion step, the fermentation step. In general, biomass components, such as sugar and starch, are easily bioavailable. However, plant materials, especially plant cell-wall components, often contain large amounts of lignocellulose. This lignocellulose consists of a complex of three major polymers: cellulose, hemicellulose, and lignin. To make the polysaccharides in a lignocellulose complex bioavailable to microorganisms, a pretreatment process is necessary. Possible pretreatment systems are steam treatment, acid or alkaline hydrolysis, treatment with enzymes, ultrasonic treatment, wet oxidation, high-temperature treatment, solvent extraction, reduction in particle size, extrusion, application of ozone, or a combination of one of these methods. In the fermentation step, the biological conversion takes place. Often, it will be necessary, to obtain optimal process conditions, to split up this step in two treatment steps integrated with each other. After the fermentation step, a post-treatment step is necessary. What type of energy carrier is produced strongly depends upon the types of microorganisms and the applied process conditions. Dependent upon the type of microorganisms, energy carriers, such as methane, ethanol, acetone, butanol, or hydrogen, can be produced. For sewage sludge, by far, most information is available on the production of biogas (methane) from sewage sludge. As already mentioned in the previous

paragraph, this process is applied worldwide on large, medium, and small scales.

As far as known, there are hardly any studies on the production of ethanol, butanol, or acetone from sewage sludge. One reason can be that production of ethanol, butanol, or acetone from sewage sludge is less attractive because of the complex separation system that is necessary to separate these components selectively. A few studies have been focused on the production of hydrogen from sewage sludge.<sup>11,12</sup> However, the results are not very promising up to now, and taking into account the simple way to produce methane and the huge experience with methane production processes, it will be doubtful whether hydrogen production from sewage sludge will become much more attractive than the production of methane in the short term.

In general, it can be concluded from the previous that up to now the research into the production of liquid or gaseous fuels other than methane (biogas) from sewage is not very promising. When the simple way to produce methane from sewage sludge, the experience with the biogas production process, and the application of biogas for the production of electricity and thermal energy are taken into account, it is doubtful that the production of the mentioned other liquid and gaseous fuels from sewage sludge will become in the future a serious alternative for biogas production. Another alternative might be the production of these biofuels from a mixture of sewage sludge and other residues from biological origins, such as food wastes or biomass. However, it is somewhat doubtful whether this combination will be attractive, taking into account the presence of toxic components and inorganic compounds in the sludge, which very likely may influence negatively the quality of the residue and the further processing of this residue.

Worldwide, a lot of research effort is spent on developing innovative biological conversion processes of biomass and improving existing biological conversion processes of biomass. The focus of this research is to improve the technical performance and decrease the total costs of biological conversion processes, also including costs of pretreatment and post-treatment. A better overall performance is possible by improvement of the pretreatment, focused on a better accessibility of the substrate component for microbiological conversion, application of new types of microorganisms, such as hyperthermophilic microorganisms or genetically modified microorganisms, improved reactor concepts, and better process control. Maybe the results of this research will also become of interest for the treatment of sewage sludge in the future.

### Direct Production of Electricity from Sewage Sludge in Microbial Fuel Cells

Microbial fuel cells can be used to produce directly electricity from a wastewater stream, such as municipal wastewater containing biodegradable organic compounds. In Figure 1, a schematical presentation of a microbial fuel cell is given. Basically, a microbial fuel cell consists of an anode chamber and a cathode chamber separated from each other by a cation-exchange membrane.<sup>13</sup> In the anode chamber, organic com-

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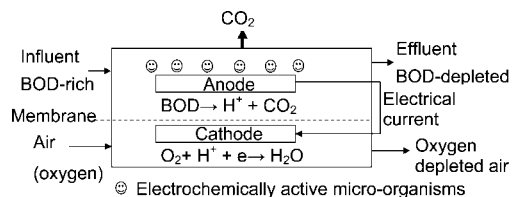
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**Figure 1.** Microbial fuel cell.

pounds, such as carbohydrates, present in the wastewater are oxidized by specific microorganisms.

The electrons produced in this oxidation process are transferred to the anode and then transported via an electrical wire to a cathode in the cathode chamber. In the cathode chamber, oxygen is reduced. Protons produced in the anode area can react with hydroxide ions produced in the reduction process of oxygen in the cathode area. Often the anode and cathode areas are separated from each other by a cation-exchange membrane. The electron transfer from the bacteria to the anode can occur either directly by bacteria attached to the anode surface (for example, bacteria of the family *Geobacteraceae* have this property) or indirectly by the use of so-called electron shuttles (mediators). Besides two-chamber microbial fuel cells, also single-chamber cells exist. The voltage of a biofuel cell is normally in the order of several hundred millivolts. Power densities in the order of 50–100 W/m<sup>3</sup> reactor have been reported.<sup>14</sup> The performance of a microbial fuel cell depends upon many process and system parameters, such as pH, temperature, type of substrate, type of bacteria, type of electrodes, internal resistance, etc.<sup>15</sup>

Research into microbial fuel cells is strongly increasing and becoming a real hype. The focus is primarily on the type of cell, the way to solve the specific bottlenecks that are responsible for the low efficiency of the process, and the various potential waste streams that can be used as feed for these fuel cells.

It has been demonstrated that the principle of a microbial fuel cell can be applied to municipal wastewater (primary effluent).<sup>13</sup> The microbial fuel cell used in the described experiments was a so-called single-chamber microbial fuel cell. The efficiency with respect to the production of electrical energy was, however, less than 12%. The possibility for the application of a microbial fuel cell on sludge has been investigated by Dentel et al.<sup>16</sup> In their study, they used a single-chamber reactor with a volume of a few liters filled with sewage sludge. The reactor was provided with graphite foil electrodes, which were placed in an aerated (aerobic) zone at the top and in an anaerobic sludge zone at the bottom. It was observed that an electrical current of about 60  $\mu$ A maximum could be obtained and a potential of several hundreds of millivolts. Although the first results are promising, there will still be a long way to go to make this process suitable for large-scale treatment of sewage sludge. There are several reasons for that. Not all of the organic material in sewage sludge is biodegradable and present in a form that is bioavailable for the production of electricity. It is possible to increase the fraction of organic material that is bioavailable by physical, chemical, or microbiological pretreatment of sludge. In that respect, the experience obtained with pretreatment systems to increase the total amount of biogas in the anaerobic

digestion process of the sludge is very helpful. Sludge contains a lot of colloidal particles and polymer substances that tend to adsorb to all types of surfaces and can plug the internal structure of the microbial fuel cell. Furthermore, it is also important to suppress conventional microbiological oxidation processes of sludge material in the reactor. It also has to be realized that sludge contains toxic organics and inorganic compounds and also a substantial amount of nontoxic inorganics. It is not clear yet what happens with the toxic organics. This means that the sludge problem can not be solved completely by the application of microbial fuel cells only. A further post-treatment of the residual waste stream will be necessary. How far the direct production of electricity from sewage sludge will become attractive depends upon not only the microbial electricity production process itself but also the effect of this process on the residual sludge amount and sludge composition.

### Incineration of Sewage Sludge with Energy Recovery

Incineration of sewage sludge is aimed at a complete oxidation at high temperature of the organic sludge compounds also including the toxic organic compounds.<sup>17,18</sup> The process can either be applied to mechanically dewatered sludge or dried sludge. Potential environmental problems related to sludge incineration are the emissions of pollutants with the exhaust gases to the atmosphere and with the quality of the ashes. However, there is a lot of standard technology available to abate the gaseous emissions very efficiently, so that the stringent air-quality standards can be met. Also, the ash quality, especially with respect to heavy metals in the ash, is not a real environmental problem. Because of the high temperatures applied in the incineration process and the composition of the inorganic compounds in the sludge, the heavy metals are very well-immobilized and resistant to leaching. This ash has to be disposed of or can be used as a source for the production of building materials. Because, in general, the incineration process deals with large quantities of polluted exhaust gases, the costs of an efficient and adequate gas treatment system are very high. This is the main reason that sludge incineration is rather expensive. The energy produced in the incineration process can be used for the drying of the mechanically dewatered sludge cake prior to the incineration process or can be used for the production of electricity. Currently, sludge incineration processes are increasingly focused on the recovery of energy from the sludge in the form of heat (steam) or electricity.<sup>18,19</sup> The amount of energy that can be obtained strongly depends upon the water content of the sludge and the modification and performance of the incineration, mechanical dewatering, and drying processes. Incineration of sludge is applied worldwide, currently, more and more in combination with energy recovery. The process is mainly applied on a large scale.

### Co-incineration of Sewage Sludge in Coal-Fired Power Plants

To avoid the high costs of a stand-alone incineration plant for sludge and also to improve the energy recovery efficiency,

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possibilities have been investigated to incinerate dried sludge in a coal-fired power plant.<sup>20</sup> In that case, beneficial use can be made from existing coal combustion installations and existing exhaust gas treatment systems. Because the amount of incinerated sludge is small compared to the amount of coal, the effect of the incineration of the sludge on the air and ash qualities can be neglected.

The energy recovery from the incineration of the sludge can often strongly be increased by improvement of the dewatering and drying processes of the sludge and probably also by the use of the low-caloric waste heat from the exhaust gases of the power plant. Also, the use of the polluted drying gas in the incineration process can contribute to a better total process performance. Co-incineration of sewage sludge in coal-fired power plants is applied in practice. Also, other co-incineration processes, for example, in combination with municipal waste, are applied in practice.

### Pyrolysis and Gasification of Sewage Sludge

Pyrolysis is a thermal treatment process in which the sludge (or biomass) is heated under pressure to a temperature of 350–500 °C in the absence of oxygen.<sup>21</sup> In this process, the sludge is converted into char, ash, pyrolysis oils, water vapor, and combustible gases. Part of the solid and/or gaseous products of the pyrolysis process are incinerated and used as heating energy in the pyrolysis process. Dependent upon the equipment used and the applied operating conditions, several modifications of this process exist. Gasification involves the breakdown of dried sludge (or biomass) in an ash and in combustible gases at temperatures usually about 1000 °C in an atmosphere with a reduced amount of oxygen.<sup>22</sup> Also, thermal treatment techniques exist that combine the specific aspects of both pyrolysis and gasification. A lot of research is going on regarding the pyrolysis and gasification of biomass. However, research on the pyrolysis and gasification of sewage sludge is very limited.

Pyrolysis and gasification of sewage sludge have some potential advantages compared to incineration. One advantage is that the conversion of the combustible gases of both systems into electrical power can be achieved more efficiently. In addition, valuable gases can be produced as basic chemicals or as fuel. Also, it is not necessary to treat large amounts of waste gases. However, because of the presence of toxic organic pollutants in the sewage sludge, the treatment process of the gases can be more complicated. In general, the process performance of pyrolysis and gasification is much more complicated than incineration.

There is one successful application of the pyrolysis/gasification process that is applied in practice to produce oil from sewage sludge that can be used as a fuel.<sup>23</sup> In this process, which consists of a large number of unit operations, dried sludge pellets are heated in the absence of oxygen in a gas generator to a temperature of approximately 450 °C. The organic compounds are converted into char, oil, and noncondensable gases. These gases are brought into contact with the char and converted into

straight-chain hydrocarbons, which are then condensed into an oil. The char is used as an energy source to provide the energy for the gas reactor or can be used as a fertilizer. The quality of the oil, important for the application of the product, can be controlled by using catalysts and by application of the right process conditions.

On the basis of existing information, it is not clear whether pyrolysis and gasification will play an important role in the future management of the sludge problem.

### Integrated Use of Sewage Sludge as an Energy and Material Source for the Production of Construction Material

In sewage sludge, both the organic carbon-containing compounds and the inorganic compounds represent valuable materials. There are several possibilities to use these compounds simultaneously in a beneficial way. A lot of effort has been put into the manufacturing of valuable products by thermal solidification of the inorganic sludge compounds, especially in Japan. The starting point in this production process is either incinerator ash, obtained after combustion of sludge, or dried sludge. The solidification process occurs at high temperatures, up to 1000 °C. The temperatures are high enough to destroy the toxic organics. Waste heat is available for the drying process. Dependent upon the specific process modifications and the applied operating conditions, various types of products can be made, such as artificial light-weight aggregates, slags, and bricks. A lot of experience exists with these processes, mainly in Japan.<sup>24,25</sup> In general, the energy efficiency in the production process is not very high. The costs are also high. Currently, the practical application is very limited.

Another beneficial way to use both the inorganic and organic compounds of the sludge is the use of sludge in the production of Portland cement.<sup>26</sup> In this process, which is also applied in practice, either ash or dried sludge can be used. Toxic organic pollutants in the sludge are completely oxidized, and because of the high process temperature, heavy metals are immobilized in the cement. In general, the amounts of ash or dried sludge that are used as raw materials are only a few percentages of the total amount of the raw materials used. Specific requirements set to the sludge quality for use in the production of Portland cement are a sufficiently low concentration of phosphate and mercury in the sludge.

### Supercritical Wet Oxidation of Sewage Sludge

Supercritical wet oxidation occurs at temperatures and pressures above the supercritical point of water (374.2 °C and 22.1 MPa). Supercritical water has special properties, such as a superior ability to dissolve oxygen and organic compounds. However, it has a low solubility for mineral compounds, such as sodium chloride. With supercritical oxidation, the organic compounds are completely oxidized. Nitrogen, present in nitrogen-containing compounds, such as ammonia and amino acids, is converted into nitrogen gas. Also toxic organic compounds are completely oxidized. The oxidation rate at supercritical conditions is much higher than at subcritical conditions. The required retention time for the oxidation of

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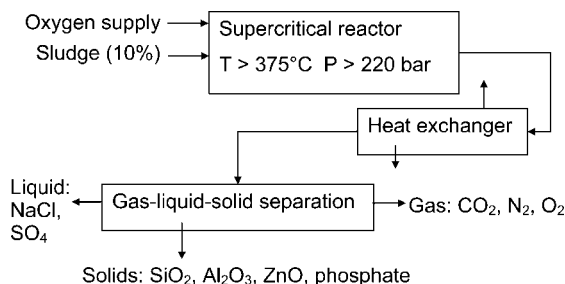
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**Figure 2.** Supercritical oxidation of sewage sludge.

sewage sludge in a supercritical reactor is in the order of a few seconds to 1 min. This means that the required reactor size is relatively small. Energy recovery from this oxidation process can occur directly by heat exchange in the reactor or from the exit flow from the reactor. In comparison to sludge incineration, supercritical oxidation has the advantage that off gas treatment is very simple, so that the costs of off gas treatment can be neglected. It is also not necessary to dewater the sludge prior to the oxidation process. The inorganics present in the treated sludge can easily be removed from the water phase as ash.

An interesting study into the applicability of supercritical water oxidation for sewage sludge is given by Svanström et al.<sup>27</sup> A schematical presentation of a complete process based on this study is given in Figure 2. From their laboratory-scale research, system design, and simulation, it can be clearly concluded that supercritical wet oxidation has a high potential to solve the sludge problem in a sustainable way and appears to be also economically competitive with existing high-thermal sludge treatment systems.

However, large-scale practical experience is not available yet. Use of oxygen in the process, use of high-pressure piping, the need of high-pressure reactors, and potential corrosion problems if chlorides are present in the sludge might be bottlenecks in the acceptance and further development of this technology. In another study, it is clearly shown that phosphate can easily be recovered and also heavy metals can easily be removed from the ashes from a supercritical wet oxidation process.<sup>28</sup>

### Hydrothermal Treatment of Sewage Sludge

Hydrothermal treatment (or thermal hydrolysis) is a process in which the sludge is heated as an aqueous phase to temperatures (normally) varying between 120 and about 400 °C. The hydrothermal treatment process aims to disintegrate the sludge and results in a formation and accumulation of dissolved products. This makes it possible to recover and recycle useful resources from the sludge, such as volatile fatty acids, phosphorous compounds, organic compounds for enhanced anaerobic biogas production, and coagulants.<sup>29</sup> Dependent upon the primary aim, there are several modifications of the process. One modification is hydrolysis at a temperature of 200–400 °C (sub- or supercritical). Results obtained from laboratory-scale experiments showed that significant quantities of soluble chemical oxygen demand (COD) and volatile fatty acids can be ob-

tained.<sup>30</sup> For sludge with an initial COD of about 20 g/L, maximum concentrations of volatile fatty acids of about 4 g/L (as COD) were obtained at moderate treatment temperatures below 200 °C. It was also observed that the use of an oxidant, such as hydrogen peroxide, can have a positive effect on the production of volatile fatty acids, depending upon the treatment temperature, treatment time, type of sludge, and amount of oxidant.

The potential of hydrothermal treatment for the recovery of energy from sewage sludge strongly depends upon the process performance. Volatile fatty acids and other dissolved biodegradable organic compounds can be beneficially used as an energy or organic carbon source in the denitrification step of the wastewater treatment process and in the anaerobic digestion step. Heat necessary to increase the temperature of the sludge can easily be recovered and reused by application of heat exchangers. However, it is not clear what happens to the toxics, especially the toxic organics. To solve the sludge problem completely, an intensive post-treatment will be necessary.

### Discussion and Conclusions

Basically, it is possible to evaluate and compare the various energy recovery methods discussed in the previous paragraphs regarding the stage of development, technical and economic feasibility, environmental sustainability, and social acceptability. However, a problem is that the stage of development varies strongly and also the available information with respect to completeness varies strongly. Another problem is that specific local and regional circumstances can also influence the feasibility of a treatment method. A key question in this assessment is also whether it can be expected that an innovative method, which needs further research to be developed to a practical scale, will at the end be competitive with methods already applied in practice. In this respect, it also has to be taken into account that we can expect an improvement and further reduction in costs of the methods already applied in practice. In the following brief discussion and summary, these bottlenecks will be taken into account. The discussion and final conclusions are primarily based on the strong and weak points and the expected future competitiveness of the various methods.

From the previous, it will be clear that many options exist to produce energy from the organic compounds present in sewage sludge, sometimes also in combination with the production of valuable materials from the inorganics present in the sludge. Because the focus of a sludge treatment process is very often on a complete process that also offers a solution for the toxics present in the sludge, the fate of these toxics has to be taken into account in the evaluation of an energy recovery process. Furthermore, attention has to be given to the large amount of water in the sludge and to phosphorous components present in the sludge. Phosphorous can be considered as a scarce component. Recovery can therefore be useful. In the case of cement production from sludge, a too high of a phosphorous content can be a problem.

In fact, two groups of energy recovery processes can be distinguished: chemical/thermal processes and biological processes. If the temperature is high enough, the chemical/thermal processes result in a complete oxidation of the organics and also the toxic organics. Heavy metals are often immobilized in the inorganic matrix. The inorganic fraction can be used for

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the production of building materials. In principle, it is also possible to produce biologically a gaseous or liquid energy carrier or to produce directly electricity from sewage sludge. However, in these processes, a substantial part of the organic substances will not be converted into an energy carrier. Also, the toxic organic compounds are hardly biodegraded. Currently, only the production of biogas by anaerobic digestion is of interest. This process is already applied worldwide since decades ago. It is expected that in the short term the application of this process will increase strongly. However, also, with this process, only a relatively small part of the organics can be converted into biogas. A mechanical, physical, chemical, thermal, or microbiological pretreatment step can increase substantially the amount of organic material bioavailable for the conversion process and therefore also the conversion percentage. However, also, by a very intensive pretreatment process, there will be a relatively large amount of organics that will still not be converted. Furthermore, the residue contains, besides the residual fraction organics, also the inorganic compounds and almost all of the toxics. If the focus is on energy recovery, the efficiency of the process in terms of energy recovery can be negatively influenced by the pretreatment step.

In the previous discussion, a brief assessment of the various processes has been given. This assessment is mainly based on the current knowledge regarding weak points, strong points, and expected competitiveness with respect to existing methods already applied in practice.

What can we expect in the future? Worldwide, we see a tremendous effort to produce energy, energy carriers, or bioelectricity from biomass and biowastes. Regarding research on processes aimed to produce energy or other valuable products from sewage sludge by thermal methods, it is expected that more attention will be given to gasification, pyrolysis, and supercritical (wet) oxidation. Especially, the latter process, which is still in the development stage, has several very interesting potential advantages.

Besides the direct focus on the production process itself and the reactor performance, there is also a strong focus on the pretreatment of the sewage sludge. This is often a key factor in the transformation of solid or semisolid biowastes into an energy carrier or directly in an electrical current. The aim of this

pretreatment process is to make biomass and organic waste components bioavailable to the microorganisms. Experience and knowledge obtained in the research into production of energy from biomass can be beneficial for the further development of energy carriers and electricity from biowastes, such as sludge. Maybe this can also lead to a combined treatment process. However, for a successful breakthrough, it will always be necessary to find a definitive solution for the toxics in the sludge. Also, the increasing focus on the direct recovery of phosphorous from wastewater or sewage sludge is an issue of increasing interest. This aspect may negatively interfere with energy production from sewage sludge.

In the Introduction, it was stated that municipal wastewater treatment can be considered as a continuous activity, also in the future. However, there are several developments to make the municipal wastewater treatment process environmentally more sustainable. One of these approaches is decentralized sanitation. This approach results in a strong decrease in wastewater volumes that have to be treated. The other approach is to change the basic concept of centralized treatment of municipal wastewater. Currently, most treatment concepts include an aerobic microbiological conversion step in which a substantial part of the organic material is microbiologically oxidized to biomass, water, and carbon dioxide. The nitrogen-containing components in the wastewater, also representing an interesting valuable component, are also microbiologically oxidized to nitrogen gas. There is, however, an alternative approach to centralized treatment of municipal wastewater, which is primarily based on the application of physical/chemical treatment steps, such as flotation and membrane filtration. This approach is still in the development stage. In this concept, all of the organic material, also including the colloidal and suspended particles, present in the wastewater, is concentrated in a small volume. This volume can be considered as an energy source. This energy source represents almost 100% more energy than the amount of energy present in the sludge of conventional wastewater treatment plants. This means that in the future the significance of municipal wastewater and sewage sludge as a valuable energy source might increase.

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