Evaluation of methods for sewage sludge utilization: The Greek perspective

Kantza Eleni

SID: 3302100009

SCHOOL OF SCIENCE & TECHNOLOGY

A thesis submitted for the degree of

Master of Science (MSc) in Energy Systems

SEPTEMBER 2011

THESSALONIKI – GREECE
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Supervisor: Assoc. Prof. A. Zabaniotou

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DISCLAIMER

This dissertation is submitted in part candidacy for the degree of Master of Science in Energy Systems, from the School of Science and Technology of the International Hellenic University, Thessaloniki, Greece. The views expressed in the dissertation are those of the author entirely and no endorsement of these views is implied by the said University or its staff. This work has not been submitted either in whole or in part, for any other degree at this or any other university.

Signed: ...............................................
Name: Eleni Kantza
Date: 20 October 2011
“Don’t waste waste – it is a resource”
ABSTRACT

This thesis aims to contribute to the field of wastewater sustainable management by evaluating the methods for sewage sludge utilization, while identifying the emerging ones.

In the introduction, the initial data for sludge management in Greece and on international level are presented, while in the second chapter the European and Greek legislation regarding the utilization of sludge is analyzed. The most up to date literature review concerning sewage sludge treatment and disposal methods is presented in chapter three. Finally, the emerging technologies for sludge management are identified as well as the decision making tools are described.

The methodology followed is: firstly, the SWOT analysis of each sludge treatment technology is presented while being evaluated by certain qualitative criteria. The selected treatment option is analyzed further on economic as well as on energy efficiency basis. The study concludes by discussing the future role that pyrolysis process may have for the integrated treatment of sludge in Greece.

At this point I would like to say a few words about the people who helped me during the preparation of my dissertation.

First of all, I would like to thank Mrs A. Zabaniotou, Associate Professor in Department of Chemical Engineering AUTH, for the assignment of the thesis and her valuable supervision. With her wide level of knowledge and the willingness to address my problems helped greatly in the completion of this study.

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Eleni Kantza
14 October 2011
## CONTENTS

**ABSTRACT** ..................................................................................................................................... i

**CONTENTS** ................................................................................................................................ ....ii

**INDEX** ........................................................................................................................................... v

**ABBREVIATIONS** ............................................................................................................................vii

1 **INTRODUCTION** .................................................................................................................................1
  1.1 **THE PROBLEM OF WASTEWATER MANAGEMENT AND THE AVAILABLE SOLUTIONS** .................................2
  1.2 **AIM OF THE STUDY** ...............................................................................................................................3
  1.3 **SCOPE AND LIMITATIONS OF THE STUDY** ...........................................................................................3
  1.4 **SIGNIFICANCE OF THE STUDY** ................................................................................................................3

2 **SLUDGE MANAGEMENT POLICY & LEGISLATION** .............................................................................6
  2.1 **SUSTAINABLE SLUDGE MANAGEMENT** ..............................................................................................5
  2.2 **LEGISLATION** ....................................................................................................................................... 6
    2.2.1 **EUROPEAN DIRECTIVES OF SLUDGE MANAGEMENT** ........................................................................6
    2.2.2 **EUROPEAN LEGISLATION OVERVIEW** ..............................................................................................7
    2.2.3 **LEGISLATIVE FRAMEWORK OF SLUDGE MANAGEMENT AND DISPOSAL IN GREECE** .........................10
    2.2.4 **GREEK LEGISLATION OVERVIEW** ................................................................................................10
  2.3 **PRINCIPLES FOR SUSTAINABLE DEVELOPMENT** ..................................................................................11
  2.4 **THE “POLLUTER PAYS” PRINCIPLE** .....................................................................................................12

3 **LITERATURE REVIEW** .................................................................................................................................15
  3.1 **DEFINITION OF SEWAGE SLUDGE** ........................................................................................................15
  3.2 **SEWAGE SLUDGE CHARACTERISTICS** ..................................................................................................15
  3.3 **SLUDGE TREATMENT AND DISPOSAL IN PRACTICE** ..........................................................................18
    3.3.1 **CURRENT AND FUTURE LEVELS OF SLUDGE PRODUCTION AND DISPOSAL IN EU** .......................19
  3.4 **CURRENT RISKS TO HUMAN HEALTH AND THE ENVIRONMENT** .........................................................20
  3.5 **BENEFICIAL USES OF SEWAGE SLUDGE** ...........................................................................................21
    3.5.1 **SLUDGE TO ENERGY** .......................................................................................................................23
    3.5.2 **BIOGAS FROM SEWAGE SLUDGE TREATMENT** ...............................................................................24
6.1.1 Anaerobic Digestion ............................................................................................................................60
6.1.2 Incineration ........................................................................................................................................63
6.1.3 Pyrolysis ..............................................................................................................................................65
6.1.4 Gasification ..........................................................................................................................................67
6.1.5 Wet Oxidation .....................................................................................................................................69

6.2 Qualitative Evaluation Results ..............................................................................................................72

6.3 Further Study of the Selected Technology .............................................................................................72

6.3.1 Economic Evaluation of Sludge Pyrolysis ..........................................................................................73
  6.3.1.1 Energy consumption for drying .........................................................................................76
  6.3.1.2 Energy consumption for pyrolysis .....................................................................................77

6.3.2 Energy Efficiency ................................................................................................................................79

6.4 Discussion .............................................................................................................................................80

6.4.1 Impediments to Development of Pyrolysis Technology .................................................................80

6.4.2 Potential Deployment and Areas for Further Development ............................................................80

7 Conclusions & Recommendations ...........................................................................................................83

7.1 Conclusions ...........................................................................................................................................83

7.2 Recommendations ................................................................................................................................85

REFERENCES ....................................................................................................................................................86

APPENDIX .....................................................................................................................................................95
INDEX

LIST OF TABLES

Table 2.1: National standards compared with those of EU ................................................................. 9
Table 2.2: Tax for waste landfill in European countries, (data November 2006) ..................................... 10
Table 3.1: Typical chemical composition and properties of untreated/digested sludge ..................... 17
Table 3.2: Illustration of different major options for sludge handling .................................................. 19
Table 3.3: Estimates of annual sewage sludge production and disposal routes, 2010 and 2020 .......... 20
Table 3.4: Principles governing sludge co-incineration process .......................................................... 28
Table 3.5: Largest biogas plants in Greece ............................................................................................ 29
Table 4.1: Typical contents of combustible components of a gas resulting from the gasification of sewage sludge ........................................................................................................... 45
Table 5.1: Evaluation criteria’s for selecting the appropriate technology .............................................. 58
Table 6.1: SWOT analysis of anaerobic digestion ................................................................................. 62
Table 6.2: SWOT analysis of incineration ............................................................................................. 64
Table 6.3: SWOT analysis of pyrolysis .................................................................................................. 66
Table 6.4: SWOT analysis of gasification ............................................................................................. 68
Table 6.5: SWOT analysis of wet oxidation .......................................................................................... 70
Table 6.6: SWOT analysis comparative table ....................................................................................... 71
Table 6.7: Qualitative evaluation of the selected technologies ............................................................... 72
Table 6.8: Sludge pyrolysis products .................................................................................................... 75
Table 6.9: Economic value of bio-oil ..................................................................................................... 79

LIST OF FIGURES

Figure 2.1: Hierarchy Pyramid of European policy for sludge treatment ............................................ 5
Figure 3.1: Typical stages in the conventional treatment of wastewater ................................................ 16
Figure 3.2: Sludge2energy ....................................................................................................................... 24
Figure 3.3: Biogas utilization and required upgrading .......................................................................... 26
Figure 3.4: Largest WWTPs in Greece .................................................................................................. 30
Figure 3.5: Panoramic view of Psyttalia WWTP .................................................................................... 31
Figure 3.6: Need for ISSM .................................................................................................................... 32
Figure 3.7: Sustainability indicators ..................................................................................................... 33
Figure 4.1: Panoramic view of Pyrolysis plant of Burgau ................................................................. 44
LIST OF DIAGRAMS

Diagram 3.1: Typical metal content in wastewater sludge ................................................................. 18
Diagram 4.1: Process flowchart of the sludge processing steps ......................................................... 37
Diagram 4.2: Flow-diagram of sludge incineration process ............................................................... 40
Diagram 4.3: Pyrolysis’s products according to temperature ............................................................. 42
Diagram 4.4: Flow-diagram of pyrolysis process .............................................................................. 43
Diagram 4.5: Flow-diagram of gasification process .......................................................................... 46
Diagram 4.6: Flow-diagram of wet oxidation process ...................................................................... 49
<table>
<thead>
<tr>
<th>Abbreviation</th>
<th>Full Form</th>
</tr>
</thead>
<tbody>
<tr>
<td>AD</td>
<td>Anaerobic Digestion</td>
</tr>
<tr>
<td>BAT</td>
<td>Best Available Technology</td>
</tr>
<tr>
<td>COD</td>
<td>Chemical Oxygen Demand</td>
</tr>
<tr>
<td>CHP</td>
<td>Combined Heat and Power</td>
</tr>
<tr>
<td>DS</td>
<td>Dried Sludge</td>
</tr>
<tr>
<td>GG</td>
<td>Government Gazette</td>
</tr>
<tr>
<td>GHG</td>
<td>Green House Gas</td>
</tr>
<tr>
<td>GWP</td>
<td>Global Warming Potential</td>
</tr>
<tr>
<td>ISSM</td>
<td>Integrated Sewage Sludge Management</td>
</tr>
<tr>
<td>JMD</td>
<td>Joint Ministerial Decision</td>
</tr>
<tr>
<td>MSW</td>
<td>Municipal Solid Waste</td>
</tr>
<tr>
<td>NCG</td>
<td>Non – Condensable Gas</td>
</tr>
<tr>
<td>NG</td>
<td>Natural Gas</td>
</tr>
<tr>
<td>PPP</td>
<td>Polluter Pays Principle</td>
</tr>
<tr>
<td>SCWO</td>
<td>Supercritical Water Oxidation</td>
</tr>
<tr>
<td>SMP</td>
<td>Sewage Management Plant</td>
</tr>
<tr>
<td>SP</td>
<td>Strategic Planning</td>
</tr>
<tr>
<td>STF</td>
<td>Sludge – to – fuel</td>
</tr>
<tr>
<td>TS</td>
<td>Total Solids</td>
</tr>
<tr>
<td>VFA</td>
<td>Volatile Fatty Acids</td>
</tr>
<tr>
<td>VS</td>
<td>Volatile Solids</td>
</tr>
<tr>
<td>WID</td>
<td>Waste Incineration Directive</td>
</tr>
<tr>
<td>WO</td>
<td>Wet Oxidation</td>
</tr>
<tr>
<td>WWTP</td>
<td>Wastewater Treatment Plant</td>
</tr>
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</table>
1 Introduction
1.1 The problem of wastewater management and the available solutions

In recent years, with the application of Directive 91/271/EC, many Wastewater Treatment Plants (WWTP) were constructed in Europe. During operation of WWTP, significant amount of sludge (mud) is produced, which requires environmentally safe management and disposal. Although WWTPs were constructed in order to address the problem of wastewater management and to protect public health and environment, a new problem was created related to processing sewage sludge.

Sewage sludge contains many valuable components such as nutrients and organic matter and has high calorific value, making it suitable for a wide range of uses. But at the same time, sewage sludge is a pollutant’s carrier because it contains heavy metals, synthetic organic and pathogenic micro-organisms. The methods of disposal of sewage sludge have significant environmental impacts such as air emissions, threat to public health and the possibility of contamination of soil and water resources, requiring therefore appropriate treatment and careful management [1].

Sewage sludge will remain a product the quality of which is not strictly controllable. Hence, it may has no secure long-term outlet and usually entails processing, transport and disposal costs of about half the total cost of operating the sewage works. Sludge is thus often regarded as the major problem of water pollution control [2].

In recent years, sewage sludge has become an international topic. In the case of the EU, interstate co-ordinated research and scientific committees are focused on various common problems [3]. This activity reflects the growing realization that while world’s sludge production is on a relentless growth curve, environmental quality requirements for sludge are becoming increasingly stringent, disposal outlets are decreasing and yet economic pressures still require low-cost solutions to sludge disposal problems [2].
1.2 Aim of the study

This thesis intends to contribute to the field of sewage sludge sustainable management by conducting an analysis of current sewage sludge treatment technologies in Greece, while aims to identify the emerging ones.

1.3 Scope and limitations of the study

The study addresses three aspects:

a) Assessment of sewage sludge exploitation technologies by SWOT analysis

b) Economic evaluation of the selected technology

c) Energy efficiency conduction of the selected technology

However, the study has some limitations:

- Much of the information available on these technologies is based on sales and publicity material provided by the technology suppliers or interest groups and not in BAT.
- The information available is often incomplete and based on widely varying assumptions, so comparisons between different technologies on a consistent and common basis are impossible.
- It is usually difficult to subject the information to critical and impartial scrutiny, since the information is often sketchy, assumptions unclear and the design basis unknown.
- The scarcity of quality data is at least partly due to the scarcity of operating plants.

1.4 Significance of the study

The study aims to understand the technical development trends of the sewage sludge sector in Greece and also aims to identify the driving forces that actually lead to future development. It is important to understand the development trends while planning for future sewage sludge management. It is not only the technology that influences sludge management system for a region, but also other parameters like sludge regulations, policy or socio-economical matters that influence the overall waste management system.
2 Sludge management policy & legislation
2.1 Sustainable sludge management

Sewage sludge is related with economic, environmental and social aspects and the definition of “sustainable development” given by World Commission for Environment and Development is defined as “meeting the needs of the present global population, without compromising the ability of future generations to meet their own needs” [4]. Therefore, sustainable development also depends on the efficient management system of the sludge. New ways of thinking and modern technology gives us the opportunity to make less valued sludge to valuable energy generation and resource recovery option. Even though sludge management system was adopted due to the health and hygienic point of view, over the time the context has changed into positive ways. High consumption of the resources and irresponsible sludge production lead current generation to an uncertain and adverse future. As a result, current global climate change forces society to think about more sustainable ways of using resources and managing the sludge, pounding people to develop new technology for sustainable solution. Efficient way of development with least natural resources is important to ensure future generation’s well-being [5].

The priorities in the hierarchy of sewage sludge management in Europe are depicted in Figure 2.1.

![Hierarchy Pyramid of European policy for sludge treatment](image)

**Figure 2.1:** Hierarchy Pyramid of European policy for sludge treatment, [5]

The energy recovery occupies one of the positions in the pyramid of European policy for wastewater management. Higher in the hierarchy pyramid are fitted objectives such as reducing production, wastewater reduction and reuse. Nevertheless, the energy recovery is
one of the key management options in Europe not only for the fraction of wastewater that cannot be reused or recycled, but for all the waste [6].

2.2 Legislation

The wide range of analyzed and proposed solutions for municipal sewage-sludge utilization, face serious legal constraints determining the choice. Legislation, Greek and EU, usually sets the required quality characteristics of sewage sludge for each method of disposal. Therefore, the various systems of sewage treatment in conjunction with existing legislation, determine the management options of sludge [4].

2.2.1 European directives of sludge management

The analysis of the existing legislation concerning the handling, disposal and recycling of sludge shows that the specifications and limitations focus primarily on the end use of sludge in agriculture, both on national and European level. Other uses or methods of sludge disposal fall into more general provisions related to waste management.

The European Directives on byproducts from Sewage Treatment Plant are:

- **1986/278/EC**: On environmental protection and in particular of the soil in the use of sewage sludge in agriculture
- **1989/369/EC**: On the prevention of air pollution from new municipal waste incineration plants
- **1991/271/EC**: For the treatment of municipal wastewater
- **1991/676/EC**: For the protection of water from nitrate pollution from agricultural uses
- **1999/31/EC**: Landfill waste
- **2000/76/EC**: For waste incineration
- **2001/118/EC**: About the European Waste Catalogue
- **2003/33/EC**: Establishing criteria and procedures for acceptance of wastes at landfills according to Article 16, Paragraph 2 of Directive 1999/31/EC
2.2.2 European legislation overview

While several Directives have an effect on sludge management (such as 1991/31/EC on the landfill) those that are considered most important are 86/278/EC and 91/271/EC. More specifically, the requirements set by the 86/278/EC are critical for the treatment of the produced sludge in Member-State.

The sludge coming out from a WWTP is very useful from an agronomic point of view. For its application, the nutritional needs of plants must be taken into account, without detriment the quality of the soil or the surface and ground water. Indeed, some heavy metals found in sewage may become toxic to crops and humans. The sludge can be used in agriculture provided that each Member State will have adopted legislative instruments regulating the use of sludge.

The Directive 86/278/EC lays down limit values for concentration of heavy metals in soil and sludge and limit values for amounts of heavy metals that can be brought into the ground on an annual basis. Therefore, the use of sludge is prohibited if the concentration of one or more heavy metals in the soil exceeds the limit values from Annex IA of the Directive. Member States are obliged in such situations to take appropriate measures to ensure that these limits will not be exceeded due to the use of sludge.

Before being applied to agriculture, the sludge must be treated. Member States have the opportunity to approve the use of untreated sludge, if it is injected into the ground.

According the Article 7 of the Directive, the use of sludge is prohibited:

- In grassland or forage crops if the grassland is to be grazed or the forage crops to be harvested before a certain period has elapsed. This period, which is set by Member States, shall be less than three weeks.
- Soli in which fruits and vegetables crops are growing, with the exception of fruit trees
- Ground intended for the cultivation of fruit and vegetable crops which are normally in direct contact with the soil and normally eaten raw, for a period of 10 months preceding the harvest of the crops and during the harvest itself.

Member States shall ensure that up-to-date records are kept, which register:

- The quantities of sludge produced and the quantities supply for use in agriculture
The composition and properties of the sludge in relation to the parameters referred in Annex II A

The type of treatment carried out

The names and addresses of the recipients of the sludge and the location where the sludge is to be used

Member States may adopt more stringent measures than those laid down in Directive 86/278/EC. Every four years must prepare a consolidated report on the use of sludge in agriculture, giving the quantities used, the criteria used and problems encountered. The report is sent to the Commission, which shall publish the content.

The Commission in its recent report (2003) considers that it is difficult under certain circumstances, to draw definite conclusions, since several Member States have not presented reports, while some of them are incomplete. It is believed however that the Directive correctly was activated as regard permissible concentrations of heavy metals in sewage sludge utilized in agriculture, since levels are generally lower than the limits set out in Annex B of the Directive [1].

According to EU report, the national legislations of several States are stringent than the requirements of 86/278. Thus, the concentration limits of heavy metals in sludge are lower than the limits of the Directive in five Member States (Belgium, Denmark, Finland, Netherlands and Sweden). In contrast, six States (Greece, Ireland, Italy, Luxembourg, Portugal and Spain) have adopted the same limits for concentrations of heavy metals of Annex I B of Directive 86/278/EC [1].

Note that in France, Italy and Luxembourg, the legislation includes limits for pathogenic organisms. Also, in several countries, including Austria, Belgium, Denmark, France, Germany and Sweden there are limits for organic compounds. For both these cases, the Directive 86/278/EC does not include limits. Concerning the new Member States, Estonia, Lithuania and Poland, legislation is comparable or tighter than 86/278/EC. Among the other new members, use and disposal of sludge fall into more general regulations, regarding waste and environment protection [1].
So far, however, national legislations do not have significant differences regarding the rest requirements of 86/278 for the use of sludge. More specifically [1]:

- Regarding the type of sludge, legislation in Belgium, Denmark, Italy and Netherlands is applied equally to the sludge of municipal and industrial waste.
- As far as sludge process obligation is concerned, in France, Ireland, Luxemburg and Sweden the use of untreated sludge is permitted under certain conditions, while in Denmark, Finland, Germany, Italy, Netherlands and Spain it’s prohibited.
- About the information requirements, there are significant differences in EU, although Denmark is required to analyze the content of organic compounds at least once per year. So far, there is no reference to any existing national legislation of the certification of products or services.

It should however be noted that in Britain and Sweden have been signed agreements that include standards for the use of sludge in agriculture, more stringent than their national legislations, concerning the pollution levels in sludge or its treatment. The analysis of the requirements of national legislations allows the classification of the EU members according to the severity compared with the 86/278/EC. The results are shown in Table 2.1 [1]:

<table>
<thead>
<tr>
<th>National Standards</th>
<th>European Country</th>
</tr>
</thead>
<tbody>
<tr>
<td>much more stringent</td>
<td>Denmark, Finland, Sweden, Netherlands</td>
</tr>
<tr>
<td>more stringent</td>
<td>Austria, Belgium, France, Germany, Poland</td>
</tr>
<tr>
<td>equal</td>
<td>Greece, Ireland, Italy, Luxemburg, Portugal, Spain, Britain, Estonia, Lithuania</td>
</tr>
</tbody>
</table>

Directive 2000/76/EC [7] puts in detail the conditions and requirements which have to meet a wastewater thermal treatment plant. With reference to this Directive, most of European countries have taken decisions aimed at the dramatic reduction of the amount of sewage sludge going to landfills while giving special incentives for energy exploitation of non-recyclable waste. Particularly striking examples are Denmark, Belgium and Switzerland, which have virtually banned deposition in landfills of organic waste while imposing additional tax per ton of waste in case of landfill (Table 2.2) [4], [8].
<table>
<thead>
<tr>
<th>Country</th>
<th>Landfill tax</th>
</tr>
</thead>
<tbody>
<tr>
<td>Austria</td>
<td>87€/ton</td>
</tr>
<tr>
<td>Belgium</td>
<td>64€/ton</td>
</tr>
<tr>
<td>Denmark</td>
<td>51€/ton</td>
</tr>
<tr>
<td>Italy</td>
<td>10-25€/ton</td>
</tr>
<tr>
<td>Netherlands</td>
<td>85€/ton</td>
</tr>
<tr>
<td>Sweden</td>
<td>40€/ton</td>
</tr>
</tbody>
</table>

2.2.3 Legislative framework of sludge management and disposal in Greece

List of directives on sludge:

- **JMD 80568/4225/1991**: the use of waste sludge in agriculture (GG 6641/91, 07.08.1991)
- **L. 1650/86**: for the protection of the environment
- **JMD 82805/2224/23**: to prevent air pollution from waste incineration (GG 699/93)
- **JMD 114218/97**: training framework standards and general programs for solid waste management (G.G. 1016/1097)
- **JMD 29407/3508/2002**: measures and conditions for the landfill (G.G. 1572/02)
- **JMD 50910/2727/2003**: measures and conditions for solid waste management,
  National and Regional Design Manager (G.G. 1909/03)

2.2.4 Greek legislation overview

JMD 114218/1997 is set out for sludge management. Specifically are prescribed the following:

- Thickening
- Biological digestion
- Dehydration and drying
- Combustion
- Co-composting

Regarding the disposal of sludge from municipal wastewater treatment plants, only the disposal in agriculture is specified, referring to JMD 80568/4225/1991.
By JMD 50910/2727/2003, the European Waste Code is being part of the Greek legislation according to which “waste from sewage cleaning” and “septic tank” are included in Chapter 20: Municipal Waste. By the same JMD is determined the National Planning Management of non-hazardous waste including sludge from wastewater treatment.

The main target of National Planning of sludge from wastewater treatment is to achieve a high recovery rate with a corresponding decrease in the rate of disposal. The actions that will enable the use of sludge are [1]:

- Direct use in agriculture applications, in accordance with the limitations of JMD 80568/4225/1991
- Reintegration into the environment, provided that the sludge will be stabilized or has been co-treated with other non-hazardous biodegradable waste, such as the organic fraction of municipal solid waste
- Drying the sludge and using it as fuel

According to the above, there is an urgent need for a complete change in the way of addressing the issue at national level, in order to adopt new methods directly to solve the problem. The challenge for the decision-makers is to balance the preferred policy of using sewage sludge with regard to sustainable development and with quality standards that are achievable and affordable.

### 2.3 Principles for sustainable development

The WWT industry is a business activity of vital importance to human well-being as it provides products that cover society’s basic needs. To ensure that current as well as future requirements of society are met, WWT enterprises need to be able to operate within a predictable legal and institutional framework, which enhances entrepreneurship, ensures environmental protection and strengthen social cohesion [9].

The above requisites are in line with the principles of sustainable development, as defined by the European Union, which aims at the balanced improvement of business performance in all three of its pillars: Economy, Environment and Society [9].
For this purpose, the member companies of the Greek WWT Enterprises must adopt the present Code of Principles for Sustainable Development and must strive for the continuous improvement of their performance in the economic, environmental and social areas of activity by [9]:

1. Incorporating sustainable development considerations within member companies decision making processes.
2. Implementing principles and practices of business ethics as well as sound systems of corporate governance.
3. Fulfilling consistently institutionalized obligations and providing credible and systematic reporting and information to all those who are affected by or could affect the activities of these companies.
4. Adopting the development and implementation of proper and scientifically based methods in sewage sludge treatment for the effective protection of the environment and the conservation of biodiversity.
5. Investing in natural, technological, financial and human resources aiming at the development and continuous improvement of effectiveness and efficiency in depth of time.
6. Striving for the continuous improvement of performance in the area of occupational health and safety.
7. Providing regular reporting for monitoring progress in the economic, environmental and social performance of the extractive sector, with special emphasis on health and safety.
8. Contributing as “active corporate citizens” in the social, economic, cultural and institutional development of the local communities in which they are active.

2.4 The “polluter pays” principle

The Polluter Pays Principle (PPP) is an environmental policy principle which requires that the costs of pollution borne those who cause it. In its original emergence the Polluter Pays Principle aims at determining how the costs of pollution prevention and control must be allocated: the polluter must pay [10].
Its immediate goal is that of internalizing the environmental externalities of economic activities, so that the prices of goods and services fully reflect the costs of production. There are four versions of the PPP: economically, it promotes efficiency; legally, it promotes justice; it promotes harmonization of international environmental policies; it defines how to allocate costs within a State [10].

The normative scope of the PPP has evolved over time to include also accidental pollution prevention, control and clean-up costs, in what is referred to as extended Polluter Pays Principle [10].

The PPP is normally implemented through two different policy approaches: command-and-control and market-based. Command-and-control approaches include performance and technology standards. Market-based instruments include pollution taxes, tradable pollution permits and product labelling. The elimination of subsidies is also an important part of the application of the PPP [10].

At the international level, the Kyoto Protocol is an example of application of the PPP: parties that have obligations to reduce their greenhouse gas emissions must bear the costs of reducing (prevention and control) such polluting emissions [10].
3 Literature Review
3.1 Definition of sewage sludge

Sewage sludge is regarded as the residue produced by the wastewater treatment process. Wastewater is a combination of the liquid- or water-carried wastes removed from residential, institutional, commercial and industrial establishments, together with ground water, surface water and storm water, as may be present [11]. Liquids are being discharged to aqueous environment while solids are removed for further treatment and final disposal. The constituents removed during wastewater treatment include grit, screenings and sludge [12]. Of the constituents removed by effluent treatment, sludge is by far the largest in volume, therefore its handling methods and disposal techniques is a matter of great concern. Without a reliable disposal method for the sludge, the actual concept of water protection will fail [13].

The amount of sludge produced is affected in a limited scale by the treatment efficiency while the sludge quality is strongly dependent on the original pollution load of the treated effluent and also, on the technical and design features of the waste water treatment process [13].

3.2 Sewage sludge characteristics

Sludge, originating from the treatment process of waste water, is the residue generated during the primary (physical and/or chemical), the secondary (biological) and the tertiary (additional to secondary, often nutrient removal) treatment (Figure 3.1). The sources of solids in a treatment plant vary according to the type of plant and its method operation. Obviously, in order to treat and dispose of the sludge that is produced in a wastewater plant effectively, it is crucial to know the characteristics of the sludge that will be processed. A typical chemical composition and properties of untreated and digested sludge is reported in Table 3.1 [12].
As a very rough guide, sewage sludge composition is characterised by six groups of components [14]:

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.
   i. 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)
   ii. 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
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.
Table 3.1: Typical chemical composition and properties of untreated/digested sludge, [13]

<table>
<thead>
<tr>
<th>Item/ untreated sludge</th>
<th>Range</th>
<th>Typical</th>
</tr>
</thead>
<tbody>
<tr>
<td>Total dry solids (TS), %</td>
<td>2.0-8.0</td>
<td>5.0</td>
</tr>
<tr>
<td>Volatile solids (% of TS)</td>
<td>60-80</td>
<td>65</td>
</tr>
<tr>
<td>Grease and fats (% of TS)</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Ether soluble</td>
<td>6-30</td>
<td>-</td>
</tr>
<tr>
<td>Ether extract</td>
<td>7-35</td>
<td>-</td>
</tr>
<tr>
<td>Protein (% of TS)</td>
<td>20-30</td>
<td>25</td>
</tr>
<tr>
<td>Nitrogen (N, % of TS)</td>
<td>1.5-4</td>
<td>2.5</td>
</tr>
<tr>
<td>Phosphorous (P2O5, % of TS)</td>
<td>0.8-2.8</td>
<td>1.6</td>
</tr>
<tr>
<td>Potash (K2O, % of TS)</td>
<td>0-1</td>
<td>0.4</td>
</tr>
<tr>
<td>Cellulose (% of TS)</td>
<td>8.0-15.0</td>
<td>10.0</td>
</tr>
<tr>
<td>Iron (not as sulfide)</td>
<td>2.0-4.0</td>
<td>2.5</td>
</tr>
<tr>
<td>Silica (SiO2, % of TS)</td>
<td>15.0-20.0</td>
<td>-</td>
</tr>
<tr>
<td>Alkalinity (mg/l as CaCO3)</td>
<td>500-1500</td>
<td>600</td>
</tr>
<tr>
<td>Organic acids (mg/l as Hac)</td>
<td>200-2000</td>
<td>500</td>
</tr>
<tr>
<td>Energy content</td>
<td>10,000-12,500</td>
<td>11,000</td>
</tr>
<tr>
<td>pH</td>
<td>5.0-8.0</td>
<td>6.0</td>
</tr>
</tbody>
</table>

Based on the physical–chemical processes that are involved in activated wastewater sludge treatment, sludge tends to accumulate heavy metals existing in the wastewater [15]. Heavy metals such as zinc (Zn), copper (Cu), nickel (Ni), cadmium (Cd), lead (Pb), mercury (Hg) and chromium (Cr) are principal elements restricting the use of sludge for agricultural purposes [15]. Their potential accumulation in human tissues and biomagnifications through the food-chain create both human health and environmental concerns [16]. Concentrations of heavy metals in sewage sludge may vary widely, depending on the sludge origins. Typical metal concentrations are indicated in Diagram 3.1 [15].
3.3 Sludge treatment and disposal in practice

Improving sewage sludge management is a key objective for the development of an integrated strategy for treating domestic wastewater. In fact, treatment and disposal of sewage sludge from wastewater treatment plants (WWTPs) accounts for up to 60%, of the total cost of wastewater treatment [17]. Decreasing available land space, coupled with increasingly stringent regulations governing the design and operation of new landfills (i.e. EU Landfill Directive 99/31) have caused the cost of siting, building, and operating new landfills to rise sharply. The increasingly restrictive targets for the continuous reduction of biodegradable waste sent to landfills make land application a disposal alternative to be considered for the final destination of sewage sludge. Sewage sludge has been utilized in agricultural applications for several years as it represents an alternative source of nutrients for plant growth and is an efficient soil conditioner [18]. However, land application of sewage sludge is restricted to prevent health risks to humans and livestock due to potentially toxic components, i.e. heavy metals, pathogens, and persistent organic pollutants and to the high amounts of soluble salts, which may negatively affect the soil properties.

The various options available for sludge handling are presented in Table 3.2 [19]. The decision-makers should combine in the optimum way the following alternatives, in relation to sludge handling, bearing in mind all the technical, economic and environmental data.
Table 3.2: Illustration of different major options for sludge handling, [19]

<table>
<thead>
<tr>
<th>Option</th>
<th>Purpose</th>
<th>Application in sludge handling</th>
</tr>
</thead>
<tbody>
<tr>
<td>No use</td>
<td>Stop use of an unwanted substance due to detrimental and irreversible effects to the environment</td>
<td>Effective control of industrial discharges, use of environmentally friendly consumer products etc to facilitate sludge use in agriculture and use of sludge products</td>
</tr>
<tr>
<td>Reuse</td>
<td>Decrease of the amount reaching the environment and of extraction of mineral resources by reusing the compound</td>
<td>Internal reuse of materials (as reuse of precipitation chemicals) and external reuse (as reuse of phosphorous as fertilizer)</td>
</tr>
<tr>
<td>Convert</td>
<td>Conversion of a substance from an obnoxious form to a form, acceptable for further transport by air, or water or in solid form</td>
<td>Conversion of organics to methane gas (for further use as energy source), solubilization of sludge components for product recovery, conversion of sludge into compost, etc.</td>
</tr>
<tr>
<td>Contain</td>
<td>To contain the residues with as low leaching ability as possible</td>
<td>Separate containment of toxic substances in the sludge, inclusion or stabilization of ashes from sludge incineration, etc.</td>
</tr>
<tr>
<td>Disperse</td>
<td>Dispersion into environment without negative impact</td>
<td>Effective dispersion of sludge in agricultural use, effective dispersion of untreated flue gases in sludge incineration</td>
</tr>
</tbody>
</table>

3.3.1 Current and future levels of sludge production and disposal in EU

The total quantities (i.e. production) of sludge in the EU27 are currently estimated at 11.5 million tons (dry solids) and it is expected to rise just less than 13.0 million tons in 2020, as shown in the Table on the next page [20].

Overall, the proportion of treated sludge recycled to agriculture across the EU will remain more or less the same; from 42% in 2010 to 44% in 2020 (see the Table 3.3). The share used in incineration will rise slightly, while the share going to landfills will be halved [20].

While the analysis considers that the use of sludge on land in the EU15 will not change dramatically over the next 5 years, the use of sludge on agricultural land will increase in the EU12, in particular in some Member States where it is currently little practiced. The predominant reason may be that national, regional and local legislation may impose some restrictions here [20].
Many of the factors that will influence future levels of sludge production and of sludge use on land are uncertain. The analysis identified among the key uncertainties the following factors: the development of treatment technologies for sludge; public perceptions of sludge recycling to land; future demand and supply of mineral fertilisers; and future risk assessments related to sludge (as well as public and political reactions to their results) [20].

### 3.4 Current risks to human health and the environment

The presence of human pathogens in sewage sludge has led to a considerable amount of research to assess the health risks associated with the land applications of sludge. Significant environment or health risks linked to the use of sewage sludge on land in the EU have not been widely demonstrated by observations or risk assessments in scientific literature since the directive has taken effect, although there continue to be authoritative studies that
identify and assess concerns. It is difficult to establish if the lack of evidence for adverse effects is because the provisions of the Directive are sufficient or is due to more stringent national requirements in some Member States [20].

Epidemiological and risk assessment studies on the risks to health from microbial pathogens in sewage sludge for workers and populations in the vicinity of sludge operations have not generally found the risks to be significantly greater than background risks [21]. Overall the health risks from indirect exposure to pathogens have also been found to be low, with no clearly identified public infections from the use of food grown on land where sludge was applied in accordance with the provisions in the Directive [22].

Environmental issues related to the recycling of sewage sludge on land include the risk of nutrient leaching, impacts on soil biodiversity and greenhouse gas emissions. Methane and nitrous oxide, both potent greenhouse gases, are both produced after sludge and other bio-wastes and recycled into agricultural land. Procedures and means to minimise their uncontrolled production and emission during treatment and recycling are necessary. In assessments of the global warming potential (GWP) of different treatment, recycling or disposal routes, efficient treatment and recycling to agricultural land can usually be demonstrated to have a lower GWP than other processes. There are some local circumstances, such as the location of the land or the nature of the sludge, in which the overall environmental impacts, either in terms of greenhouse gas emissions alone or in conjunction with other environmental factors, result in assessments that suggest non-agricultural routes may be more beneficial [20].

3.5 Beneficial uses of sewage sludge

Disposing sewage sludge to landfills is considered a beneficial use only when such disposal includes methane gas recovery for fuel. However, methane operations are relatively rare. Alternative beneficial uses are receiving greater attention because of a decline in available landfill space and an interest in conserving nutrients, and utilizing soil conditioning properties and other recoverable qualities of sewage sludge. Thus, land application for soil conditioning and fertilization is the primary beneficial use of sludge [23].
Sludge applications to agricultural lands utilize recyclable components of wastewater in the production of crops. Sludge recycling and reuse programs not only create savings for local and state governments through lower disposal costs and sales of sludge-derived products, but they also add nutrients and improve soil characteristics [24]. Biosolids provide the essential plant nutrients, moisture content, and organic matter necessary to improve a soil’s physical condition and render it more productive. Biosolids contain all the elements essential for the growth of higher plants, and since nitrogen and phosphorus are the most abundant major plant nutrients in biosolids, they can be used effectively as a supplemental source for fertilizer manufacturers. Biosolids also contain most of the essential plant micronutrients, with the possible exception of potassium [25].

As with land application of other organic materials, such as hay and animal manures, sewage sludge addition improves the physical properties of soils. This, in turn, exerts a beneficial influence on water penetration, soil porosity, bulk density, strength, and aggregate stability [26].

**SLUDGE APPLICATION TO CROPS IN SPAIN**

The effects of sewage sludge application to crops is an issue of public scrutiny, but consider that in Spain’s Andalusia region, cherry wine produced with sludge continues to outsell the wine produced using conventional fertilizers in taste tests, even when the wine grown in sludge was identified prior to tasting [27].

Dewatered treated sludges have also been used successfully for producing building materials, such as concrete and bituminous mixes, and also as a road subsoil additive utilizing chemical fixation processes [28]. Final residuals of incineration or other thermal process have also been used to generate road sub base material or concrete aggregate [29]. Pulverized sludge ash and dewatered sludge/clay slurries have been used successfully in lightweight concrete applications without influencing the product’s bulk properties [30]. Sludge based concrete has been deemed suitable for load-bearing walls, pavements, and sewers [31].

Sludge has also been used in cement manufacturing. This industry is highly energy intensive; however the large energy costs of creating clinker at 1500°C can be offset by utilizing sewage
Sludge as a low-cost and readily available supplemental energy source. The technique is discussed below thoroughly.

Sludge enriched by heavy metal content has been incorporated into the production of biobricks. In this approach, incinerator sludge ash is used as a clay substitute during the manufacture of bricks. The process improves the ceramic properties and product strength of the resulting construction materials [32]. Biobricks do not release metals during firing or weathering [33]. Benefits of biobrick technologies also include volume reduction and substantial savings on water and fuel consumption as well as treatment costs.

A technique called “sludge-to-fuel” (STF) involves a process that converts sludge organic matter into an incinerable oil using a solvent, atmospheric pressures, and temperatures in the range of 200-300°C [34] or, alternatively, high pressures in the range of 10 MPa combined with high temperatures [35]. One system uses a hydrothermal reactor to convert mechanically dewatered sludge to oil, char, carbon dioxide, and wastewater. The char, making up 10% of the product, is sent to a landfill, while the gaseous emissions are treated and released to the atmosphere. The produced oil has approximately 90% of the heating value of diesel fuel and can be sold to offsite users or refineries [36].

3.5.1 Sludge to Energy

Sewage sludge contains 10 times the energy needed to treat it, and it is technically feasible to recover energy from sludge. As renewable energy, it can be directly used for wastewater treatment, reducing the facility’s dependency on conventional electricity. The greater the quantity of energy produced by the industry, the more the industry can help reduce emissions of greenhouse gases. The following figure shows the source to produce energy in different process steps [37].

Converting sludge to energy is feasible and desirable, from a treatment perspective. The challenge is finding a process that meets social, economic and environmental objectives, as well as being affordable and cost effective. For instance, chemical use may be required in certain processes, but it may not always be the best option in terms of health protection and life cycle impacts (energy use and emissions during production and transportation) [37].

### 3.5.2 Biogas from sewage sludge treatment

Biogas is produced by the fermentation of organic matter including manure, sewage sludge, and municipal solid waste, under anaerobic (having no oxygen) conditions. As produced by digestion, biogas is a clean and environmentally friendly fuel, although it contains only about 55–65% of CH4. Other constituents include 30–40% of CO2, fractions of water vapour, traces of H2S and H2, and possibly other contaminants (e.g. siloxanes) [39].

Without further treatment, it can only be used at the place of production. There is a great need to increase the energy content of the biogas, thus making it transportable over larger distances if economically and energy sensible. Ultimately, the compression and use of gas cylinders or introduction into the gas network are targets. This enrichment and enhanced potential of use can only be achieved after removing the CO2 and contaminants [39].
The heating value of biogas is determined by the CH\textsubscript{4} content, with the higher heating value being the energy released when 1Nm\textsuperscript{3} of biogas is combusted and the water vapour formed within combustion is condensed. The lower heating value omits the vapour condensation [39].

The methane number describes the gas resistance to knocking when used in a combustion engine. Methane has per definition a methane number of 100 and H\textsubscript{2} a methane number of 0. CO\textsubscript{2} increases the methane number because it is a non-combustible gas with a high knocking resistance. Upgraded biogas, therefore, has a methane number in excess of 100 [39].

3.5.2.1 Biogas utilization

Gas is an excellent fuel for a large number of applications and can ultimately also be used as feedstock for the production of chemicals. Biogas can more or less be used in all applications that were developed for natural gas [39].

There are four basic ways of biogas utilization, production of heat and steam, electricity generation/co-generation, use as vehicle fuel, and (possibly) production of chemicals. These utilizations are governed by national frameworks like the tax system, subsidies, green energy certificates and increased feed-in tariffs for electricity, availability of heat or gas grids [39].

The annual potential of biogas production in Europe is estimated in excess of 200 billions m\textsuperscript{3}. Worldwide, biogas is mainly used in combined heat and power (CHP) applications, whereas various EU countries have embarked on programs to use a growing portion of the biogas in the transport sector, especially attractive in view of the steady increase of the cost of fossil fuels. The various utilization pathways are illustrated in Fig. 3.3 [39].
3.5.3 Sewage sludge as alternative fuel in cement plants

In order to reduce the energy demands/costs and meet the environmental requirements, cement industry co-incineration of sewage sludge is considered as an acceptable option further and further by the decision-makers in the EU [40]. The firing of sludge in a cement plant will vanish it, while at the same time energy is produced. Therefore all negative effects associated with its presence are removed. When fired – combusted – the gaseous emissions can be monitored accurately in real time and continuously [44].

The input fuel sludge can be analyzed frequently for its properties. The high cement kiln temperature (1450 °C) and the rapid cooling of gases hinders the formation of dioxins/furans, where as any heavy metals present in the sludge, are frapped in the liquid fraction of the raw materials at the kiln’s sintering zone. The high sludge volatile matter enforces a better pet – coke ignition and any ash residue that is produced is embodied in the kiln’s clinker product (the heavy metal is present there). The ash constituents are similar to those of clinker produced without sludge firing and the ash serves as a 28day strength improver of cement [40].

Being a biomass fuel it helps the cement plant reduce its CO₂ conventional fuel emissions as well as the country’s and global in general CO₂ emissions. Using a suitable fuel, helps in
saving reserves of conventional fuels and is accepted as a renewable fuel energy source. It is fact that its life cycle is much smaller to any other disposal method [40].

The alkaline kiln environment removes any traces of HCl and or HF produced during firing and the low primary air used in third generation burners creating a low flame temperature hinders the thermal conversion of sludge nitrogen to NOx. Last but not least the use of sludge as a substitute fuel results in reducing the export currency required for conventional fuels. If however the levels of Mercury (Hg) and Thallium (TI) are high a good monitoring of those volatile heavy metals should be established. To avoid such a possibility, although the mercury level in the sludge fuel can reach 16mg/kg, the cement industry aims to fire sludge with a maximum mercury content of 0,5 mg/kg [42].

**Sludge use from cement sector in Netherlands and Spain, [43]**

The Netherlands and Spain are just two examples of countries where the cement industry is providing a solution for sewage sludge.

Since March 2000, the ENCI cement plant located in Maastricht (Netherlands) has been working together with the Limburg Purification Board, receiving pre-treated sewage sludge from their sewage water treatment plants (following further treatment in the Board’s own thermal sludge dryers). Today, 80.000 tonnes of dried sewage sludge are co-processed annually in a kiln with a capacity of 865.000 tonnes of clinker per year.

In 2005, the cement sector in Catalonia (Spain) reached an agreement with the Catalan administration, trade unions and the local councils, to launch a trial to monitor the environmental behaviour of thermally dried sewage sludge from the Barcelona area as an alternative fuel in cement plants. The aim is to use more than 60.000 tonnes of dried sewage sludge every year as a petcoke substitute, providing a solution for the high amount of sewage sludge which cannot be used in agriculture.

3.5.3.1 Impact on health and environment

Co-combustion of sewage sludge in cement industry does not have a negative impact on the health and safety of its workers or surrounding neighborhood [44].
However, the contrary is possible, when poor planning results in projects where cement kilns have higher emissions, or where alternative fuels are not put to their highest value use. Five guiding principles are intended to help avoid the latter scenarios. The principles, reproduced in Table 3.4, provide a comprehensive yet concise summary of the key considerations for co-incineration project [45].

**Table 3.4: Principles governing sludge co-incineration process, [46]**

<table>
<thead>
<tr>
<th>Principle</th>
<th>Description</th>
</tr>
</thead>
</table>
| co-processing respects the waste hierarchy | -waste should be used in cement kilns if and only if there are not more ecologically and economically better ways of recovery  
-co-processing should be considered an integrated part of waste management  
-co-processing is in line with international environmental agreements |
| additional emissions and negative impacts on human health must be avoided | -negative effects of pollution on the environment and human health must be prevented or kept at a minimum  
-air emissions from cement kilns burning alternative fuels cannot be statistically higher than those of cement kilns burning traditional fuels |
| the quality of the cement must remain unchanged | -the product (clinker, cement, concrete) must not be used as a sink for heavy metals  
-the product must not have any negative impacts on the environment (e.g., leaching)  
-the quality of the product must allow for end-of-life recovery |
| companies that co-process must be qualified | -have good environmental and safety compliance records  
-have personnel, processes, and systems in place committed to protecting the environment, health, and safety  
-assure compliance with all laws and regulations  
-be capable of controlling inputs to the production process  
-maintain good relations with public and other actors in local, national and international waste management schemes |
| implementation of co-processing must consider national circumstances | -country specific requirements must be reflected in regulations  
-stepwise implementation allows for build-up of necessary management and handling capacity  
-co-processing should be accompanied with other changes in waste management processes in the country |
3.6 Current situation of sewage sludge in Greece

In recent years in our country in effort of reducing water pollution and implementing Directive 271/91/EK has built many wastewater treatment plants that reach the 212 WWTPs. These facilities cover a population inventory of about 85% of equivalent population [47].

The most frequent method of sludge treatment is the aerobic stabilization, which corresponds to 80% of the treatment works. In larger installations such as in Athens and Thessaloniki, it is used anaerobic digestion and energy generation from biogas [47].

Given the recent development of modern anaerobic degradation units of organic substances (waste), the implementation of biogas recovery and utilization systems in Greece is relatively limited. By the end of 1997, were issued 7 permits for electricity production using biogas facilities from the Development Ministry. The largest biogas plants in Greece are presented in the following table, while the number in brackets corresponds to their exact location on the following map [48].

<table>
<thead>
<tr>
<th>Raw material</th>
<th>Location</th>
<th>Biogas production m³/day</th>
<th>Electrical output MW</th>
</tr>
</thead>
<tbody>
<tr>
<td>Landfill gas</td>
<td>{1} A. Liosia, Attica</td>
<td>184000</td>
<td>14</td>
</tr>
<tr>
<td>Landfill gas</td>
<td>{2} Tagarades, Thessaloniki</td>
<td>1200</td>
<td>0,24</td>
</tr>
<tr>
<td>Biological sludge treatment</td>
<td>{3} Psyttallia, Attica</td>
<td>60000</td>
<td>7,37</td>
</tr>
<tr>
<td>Biological sludge treatment</td>
<td>{4} Iraklio, Crete</td>
<td>2460</td>
<td>0,18</td>
</tr>
<tr>
<td>Biological sludge treatment</td>
<td>{5} Volos</td>
<td>2800</td>
<td>0,23</td>
</tr>
</tbody>
</table>

Table 3.5: Largest biogas plants in Greece, [48]
3.6.1 Psyttalia WWTP

The Psyttalia WWTP is the main wastewater treatment plant in the greater Athens area, receiving an average wastewater flow of approximately 730,000 m³/d. The Psyttalia WWTP capacity is 5.600.000 p.e., being one of the biggest WWTPs in Europe and worldwide [49].

Pretreated wastewater is piped to Psyttalia Island, by means of submerged pipes, so as to undergo primary treatment, producing primary sludge. Primarily treated wastewater further undergoes advanced secondary biological treatment, using activated sludge processes, achieving both organic load removal and a considerable reduction of nitrogen load in the biological stage. The Psyttalia WWTP final effluent is being received by the Saronic Gulf through gradual deep disposal by means of a system of submerged outfall pipes. By then wastewater treatment has achieved suspended solids and organic load reduction by about 93%. Part of the effluent undergoes filtration and disinfection so as to be reused as process water for the facilities on Psyttalia Island [49].
The sludge drying unit final product (120 – 150 t/day with approximately 92% dry matter) is a renewable source of energy and it is being utilized as secondary fuel in cement factories and power stations. Sludge mixture anaerobic digestion produces biogas, consisting of approximately 61-65% methane (CH$_4$) and 34-38% carbon dioxide [49].

Biogas produced at Psyttalia WWTP is a renewable source of energy and it is being utilized as the fuel in two CHP plants, totaling 11.4 MWe. Additionally a 12.9 MWe CHP plant using natural gas operates at Psyttalia, supporting the operation of the sludge thermal drying unit. The CHP plant system provides a considerable part of the heat needs of Psyttalia WWTP (for sludge digestion and drying) as well as its electric power needs, whereas surplus power is being sold to the National Power Grid Manager [49].

### 3.7 Integrated sewage sludge management

A plausible solution to wastewater management would be an integrated approach which would include collective management of sewage sludge and implementation of the 3R (Reduce, Reuse and Recycle) policies and strategies. Figure 3.6 highlights the need for integrated sewage sludge management (ISSM) [50].
Integrated sewage sludge management (ISSM) refers to a strategic initiative for the sustained management of the sewage sludge through the use of comprehensive integrated format generated through sustained preventive and consultive approach to the complementary use of a variety of practices to handle sewage sludge in a safe and effective manner [50].

ISSM is a frame of reference for designing and implementing new waste management systems and for analysing and optimizing existing systems [50].

ISSM is based on the concept that all aspect of the sludge management systems (technical and non-technical) should be analysed together, since they are in fact interrelated and developments in one area frequently affect practices or activities in another area [50].
ISSM proposes to take a comprehensive approach across all types of sewage sludge streams and involves the use of a range of different options. The selection of the most appropriate sludge management systems and sustainable technologies are also needed to deliver an optimum and sustainable ISSM system. In combination with economic and social considerations, this approach would help sludge managers to design more sustainable sewage sludge management systems [50].

3.8 Criteria for the optimum sewage sludge management solution

Selection of a particular sludge treatment technology should not be based primarily on technical insight, but should also integrate the human and environmental activities that surround it. In this study, the selection of the optimum sewage sludge treatment and management solution was stemmed from the three dimensional view of sustainability, based on the mother of all definitions of sustainability as established by the Brundtland Commission (Figure 3.7) [51].

![Figure 3.7: Sustainability indicators, [51]](image)

3.8.1 Environmental criteria

Initially, the environmental impact of each treatment and disposal option was evaluated and compared to each other. Such assessment was performed by examining the following parameters [52]:

• The qualitative and quantitative determination of sewage sludge from each of the major WWTP
• The availability of the receiving bodies
• The required sludge treatment before disposal
• The local infrastructure required for transport and storing of the by products
• The rights and obligations of the sludge ‘producer’ and end-user.

As soon as these parameters have been determined, all the alternative management solutions should be presented to the end users of sewage sludge for their approval.

3.8.2 Financial criteria

Obtaining and classifying international up-to-date economic data on the most widely used technologies for sewage treatment is crucial. Experience shows that decision-makers pay particular attention to the financial feasibility of the suggested technological solutions. In developing countries, financial feasibility often rates above the environmental benefits. The technologies that fulfilled the environmental criteria were categorized according to the capital cost, maintenance and operational cost and the possibility of generating income on an annual basis [52].

3.8.3 Social criteria

When the optimum solutions call for a unified disposal route for the sludge produced in the major WWTPs, a wider consent is desirable. For that reason, public and stakeholders should be informed, impacts and measures taken must be presented, as well as the rights and obligations of stakeholders, in order to ensure social acceptance [52].
4 Sewage sludge treatment technologies
4.1 Description of sewage sludge treatment methods

Lately, various modern technologies have been introduced, offering an alternative trend to the sewage sludge disposal, especially with the decreasing availability and the increasing price of land for landfilling. These technologies can be grouped in the category of thermal utilization of sewage sludge; pyrolysis, gasification, wet oxidation are the main representatives of the above group. Thermal processes involve removing of the organic part of the sludge, leaving only the ash component for final disposal. Sewage sludge is a type of biomass fuel and, as mentioned previously and its calorific value is similar to coal [12]. The principal goal of thermal processing of sewage sludge is the utilization of the stored energy in sludge and the minimization of environmental impacts at the same time, in order to meet the increasingly stringent standards. It is well known that sludge contains high moisture contents. Therefore the majority of energy released during thermal processes is consumed to reduce the amount of moisture [53]. However these routes are generally considered to be self-sufficient in energy. The main problem concerning thermal processes includes the following [54]: (a) excessive energy necessary to reach high temperatures; (b) high capital costs; (c) need for extensive air pollution equipment.

It is worth emphasizing here that any thermal method for the disposal of sewage sludge is usually preceded by a process of partial (to obtain 85% dry matter) or total (>85% dry matter) drying. [55].

Presently, an extensive review of current literature will be carried out concerning anaerobic digestion, incineration, pyrolysis, gasification and wet oxidation.

4.1.1 Anaerobic Digestion

Anaerobic digestion is a widely used method for the treatment of sewage sludge. During the anaerobic digestion, the organic compounds such as carbohydrates, proteins, and fats are initially hydrolyzed and fermented by fermentative bacteria to volatile fatty acids (VFA) (e.g. acetate, propionate, butyrate, iso-butyrate, etc.), alcohols, H₂ and CO₂. The VFA as well as some alcohols are subsequently oxidized by syntrophic bacteria to acetate, H₂ and CO₂ and these are finally converted into biogas (methane and carbon dioxide) by methanogens [56]. A process flowchart of the sludge-processing steps is shown in Diagram 4.1.
Diagram 4.1: Process flowchart of the sludge processing steps

In comparison with other methods of wastewater treatment, such as landfilling, incineration and composting, anaerobic digestion has the advantages of: (a) reducing the amount of waste, (b) generating energy in the form of methane that can be used for production of heat and/or electricity and (c) resulting to a nutrient-containing final product that is suitable for application on the farmland as fertilizer or soil-improving agent. Thus, the anaerobic digestion process can be considered as a sustainable method for sewage sludge treatment and it is worthy of further study [57].

Anaerobic digesters are usually operated under mesophilic or thermophilic conditions at temperatures of 30–40 °C or 50–60 °C, respectively [58]. Most of the anaerobic digesters in Europe were started and operated in mesophilic manner [59]. However, recognizing the advantage of the thermophilic process that derives from higher metabolic activities of the thermophiles makes the shift to the thermophilic operational temperature attractive. Higher metabolic activities and substrate conversion rates of the thermophilic microorganisms are reflected by a higher methane production rate. The latter allows the shortening of the retention time of the waste/wastewater in the digester, treating larger volumes of sludge in existing capacities or building of new reactors with smaller volume [59]. Several cases of successful shift of sewage sludge treatment in full-scale digesters documented that the thermophilic operation could be stable and reliable [60].
Despite these advantages of AD, some limitations are inevitable, e.g. (i) only a partial decomposition of the organic fraction, (ii) the rather slow reaction rate and associated large volumes and high costs of the digesters, (iii) the vulnerability of the process to various inhibitors, (iv) the rather poor supernatant quality produced, (v) the presence of other biogas constituents such as carbon dioxide (CO₂), hydrogen sulphide (H₂S) and excess moisture, (vi) the possible presence of volatile siloxanes in the biogas that can cause serious damage in the energy users (generator, boiler) due to the formation of microcrystalline silica, and (vii) the increased concentration of heavy metals and various industrial “organics” in the residual sludge due to the significant reduction of the organic fraction during digestion, leaving the mineral and non-degradable fraction untouched [39].

The economy of a biogas plant is directly linked to the amount of biogas produced per unit of raw material treated. In practice, only half of the organic material is converted and therefore there is a large potential for increasing the biogas yield of sewage sludge. The optimization of the anaerobic digestion process strongly depends on the increase of the hydrolysis efficiency since the organic matter of sewage sludge mainly exists in particulate form and hydrolysis is the rate-limiting step of the whole process [61].

4.1.1.1 Energy balance

The energy consumption during the operation of an anaerobic digestion system covers the heating of the influent sludge, the pumping of the sludge, the stirring of the digesters and the heat losses through the piping and through the digester boundaries. It has been shown that the major part of the heat requirement of a full-scale plant for thermophilic sludge digestion concerns the heating of the influent sludge. On the other hand and depending on the outside temperature, the heat losses account only to 2–8% of the heat needed for the influent sludge heating [62]. The energy requirements for pumping and mixing are estimated to 1.8x10³ kJm⁻³ and 3.0x10² kJ (m³ d)⁻¹, respectively (information from Lundofte Wastewater Treatment Plant, Lyngby, Denmark).
4.1.2 Incineration

Incineration remains as the most attractive disposal method, currently in Europe. One should have in mind that legal limitations concerning landfilling and agricultural reuse as well as sea disposal is no longer an outlet. In that context, it should be expected that there will be an increase in the role of incineration in the long term [64]. The technology of incineration in terms of the process engineering, energy efficiency and compactness of plant has experienced great improvement lately. Modern fluidized bed incinerators have become more and more attractive both in terms of capital as well as operating costs, in comparison to the conventional multiple hearth type. A process flowchart of the sludge-processing steps is shown in Diagram 4.2. The advantages of incineration can be summarized as follows [65]:

a. Large reduction of sludge volume; researchers have concluded that the final sludge volume after incineration is approximately 10% of that after mechanical dewatering.

b. Thermal destruction of toxic organic compounds

c. The calorific value of sewage sludge is almost equal to that of brown coal; therefore incineration offers the possibility of recovering that energy content.

4.1.2 Incineration

The Lübeck Waste Treatment Facility is a mechanical biological treatment plant located near the city of Lübeck in Germany. The facility treats the entire municipality's waste stream utilizing a municipal waste treatment process consisting of mechanical sorting and anaerobic digestion. The facility has the ability to process up to 150,000 tpa of mixed waste. This facility was constructed in 2005 at Lübeck -Niemark and utilizes the Haase MBT process.

The anaerobic digestion plant produces biogas that in turn is used to generate renewable energy in a combined heat and power module.

The waste treatment facility also includes a separate composting facility for green waste.

**Anaerobic Digestion Waste Treatment Facility in Lübeck, Germany, [63]**
Nevertheless, incineration is in effect only a means of sludge minimization; it is not a means of complete disposal since 30% of the dry solids remain as an ash. The ash is classified as hazardous waste due to its content of heavy metals, and so incurs further expense for its disposal in special landfill sites. However, there are opportunities for utilizing ash, such as for construction materials, and when sludge is used as a fuel in cement production, the ash becomes an integral part of the product [64].

One of the major constraints in the widespread use of incineration is the public concern about possible harmful emissions. However, introducing new technologies for controlling gaseous emissions can minimize the adverse effects mentioned beforehand, while the reduction in the correspondent cost gives incineration considerable advantages in future as compared to other available disposal routes. The amount of sludge being incinerated in Denmark has already reached the percentage of 24% of the sludge produced, 20% in France, 15% in Belgium, 14% in Germany while in USA and Japan the percentage has increased to 25% and 55%, respectively [19].

Diagram 4.2: Flow-diagram of sludge incineration process
4.1.3 Pyrolysis

Pyrolysis is the process through which, organic substances are thermally decomposed in an oxygen-free atmosphere, at temperatures varying in the range of 300 and 900 °C. In other words, pyrolysis involves heating of sewage sludge in an inert atmosphere and the consequently release of organic matter and its potential recycling. This technique appears to be less pollutant than conventional methods (incineration), as it concentrates the heavy metals in a solid carbonaceous residue, so its leaching is not that crucial as that in ashes from incineration [67]. A process flowchart of the sludge-processing steps is shown in Diagram 4.4. The reactions that take place are thermal cracking and condensation reactions. Compared to incineration process, which is highly exothermic, pyrolysis is rather endothermic, on the order of 100 KJ Kg\(^{-1}\) [54].

\[
\text{Organic + Energy (poorO}_2\text{atmosphere)} \rightarrow CH_4 + CO + ... + \text{energy}
\]

The major fractions that are formed after thermal degradation of the sludge in an inert atmosphere or vacuum are the following [68]:

1. The gaseous fraction; this non-condensable gas (NCG) contains mainly hydrogen, methane, carbon monoxide, carbon dioxide, and several other gases in smaller concentrations.
2. The liquid fraction; this stream consists of a tar and/or oil, which contains substances such as acetic acid, acetone, and methanol.
3. The solid fraction that consists mainly of char, which is most of times pure carbon with small amounts of inert materials.

It should be stated that the proportion of the three phases depends on temperature, reactor residence time, pressure, turbulence and also the characteristics of the effluent. Pyrolysis gas can be used as fuel, as well as the char, while pyrolysis oil can be used as raw material for chemical industries, even as fuel [13]. Many researchers have focused on how the different fractions are formed during pyrolysis, using primarily fixed beds, rotary reactors [68]. Experimental studies in sludge low-temperature pyrolysis in fluidized-bed reactors have come to very interesting conclusions, corresponding with product distribution of sewage sludge after it has undergone pyrolysis treatment [69]. With temperature varying between 300 and 600 °C and gas residence time varying from 1.5 to 3.5 s, three types of products are formed, the NCG, the oil and the char [68]. The maximum oil yield (30%) is achieved at the temperature of 525 °C and gas residence time 1.5 s. The oil yield increases with temperature, due to the fact that sludge is subject to more energy, stronger bonds break and thus an increase in larger compounds is observed. Increasing temperature above 525 °C as well as the residence time, oil yield decreases since secondary-cracking reactions occur and so the production of NCG is favored (see Diagram 4.3) [70].

Diagram 4.3: Pyrolysis’s products according to temperature, [70]
Pyrolysis generally takes place at lower temperatures than for incineration and gasification. The result is less volatilization of carbon and certain other pollutants such as heavy metals and dioxin precursors into the gaseous stream. Ultimately, the flue gases will need less treatment to meet the emission limits of WID. Any pollutant that is not volatilized will be retained in the pyrolysis residues and need to be dealt with in an environmentally acceptable manner [71].

While pyrolysis of sewage sludges for the production of oils has been of interest for some time, full scale implementation of the technology has been limited. Acceptance of the technology has been limited by the low economic value of the produced oil as well as the relative complexity of the processing equipment. The economic viability of pyrolysis may be improved if the yield of oil were enhanced or if value-added products such as adsorbents could be produced from the pyrolysis chars [72].

Diagram 4.4: Flow-diagram of pyrolysis process
4.1.4 Gasification

Gasification is the thermal process during which carbonaceous content of sewage sludge is converted to combustible gas and ash in a net reducing atmosphere. (Diagram 4.5) Moreover one could state that the optimum targets of sewage sludge gasification are the production of clean-combustible gas at high efficiency [75]. An example of a gas composition resulting from the gasification of sewage sludge is presented in Table 4.1. This includes only the main combustible components; the others, depending on the gasification medium, are oxygen, carbon dioxide, or nitrogen [13].

Pyrolysis Plant of Burgau, Germany, [73]

In 1983, Waste Gen UK supplied a Materials Energy and Recovery plant to Burgau, Germany. The plant is a unique combination of a pyrolysis plant and power generation plant and was designed to treat municipal solid waste (MSW). The plant currently processes around 34,000 tonnes of MSW a year from 120,000 residents.

Any solid by-products produced by the plant are disposed of in a nearby landfill. Gas, however, is typically used to generate energy. Approximately 22,473 ft³/tons MSW of syngas are produced annually. The heating value is 268-376 Btu/ft³, depending on the quality of the feedstock. Syngas is burned in a gas boiler to create steam which drives a 2.2 MW steam turbine for electricity production. This is enough electricity to power over 4000 residential homes. Any excess steam is piped to a next door greenhouse for heating.

Figure 4.1: Panoramic view of Pyrolysis plant of Burgau, [74]
Table 4.1: Typical contents of combustible components of a gas resulting from the gasification of sewage sludge, [13]

<table>
<thead>
<tr>
<th>Component</th>
<th>wt. % vol</th>
</tr>
</thead>
<tbody>
<tr>
<td>Carbon monoxide</td>
<td>6.28-10.77</td>
</tr>
<tr>
<td>Hydrogen</td>
<td>8.89-11.17</td>
</tr>
<tr>
<td>Methane</td>
<td>1.26-2.09</td>
</tr>
<tr>
<td>Ethane</td>
<td>0.15-0.27</td>
</tr>
<tr>
<td>Acetylene</td>
<td>0.62-0.95</td>
</tr>
</tbody>
</table>

Gasification is a series of complex sequential chemical and thermal sub-processes. The total process is actually energetically self-sustaining and usually in steady conditions no energy input is necessary. During the gasification process, sewage sludge undergoes a complex physical and chemical change, starting with the drying or removal of water contained as moisture. The dried sewage sludge is then pyrolysed or thermally decomposed. In the final step, the pyrolysis products, condensable and non-condensable vapors and char undergo gasification, where they are concurrently oxidized and then reduced to permanent gases at the reduction zone. In the drying zone, sewage sludge descends into the gasifier and moisture is evaporated using the heat generated in the zones below. The rate of drying depends on the surface area of the fuel, the recirculation velocity, the relative humidity of these gases and temperature differences between the feed and hot gases as well as internal diffusivity of moisture within the fuel. Characteristically, sludge with less than 15% moisture loses all moisture in this zone [76].
Diagram 4.5: Flow-diagram of gasification process

The heating value of the gas after gasification varies around a value of 4 MJ/m³. The gas obtained can be used to generate electricity or to produce heat for the drying of sewage sludge. An important aspect of the process of the gasification of sewage sludge is the production of hydrogen [77].
Almost all of the hydrogen produced today is by steam reforming of natural gas and for the
near term, this method of production will continue to dominate. Researchers at are
developing a wide range of advanced processes for producing hydrogen economically from
sustainable resources. At a time when industrial society is beginning to perceive the end of
the period of relatively inexpensive oil, and when the collective consciousness is beginning
to change in favor of the fight against the greenhouse effect the use of the biomass and
waste as energy sources, and/or the supply of hydrogen, constitutes a particularly attractive
alternative and is a major issue for the future. Researchers from UK and Turkey have investigated the hydrogen production potential from sewage sludge, by applying downdraft gasification technique. Wet sewage sludge can be assumed as one of the most common feedstock to manufacture hydrogen gas all over the world [76]. As mentioned in the literature, hydrogen can also be produced by thermal gasification of biomass such as forestry by-products, straw, municipal solid waste and sewage sludge. The processes involved in producing hydrogen from waste resemble the processes in production from fossil fuel. Under high temperatures, the waste breaks down to gas. The gas consists mainly of $\text{H}_2$, CO and methane ($\text{CH}_4$). Steam is then introduced to reform $\text{CH}_4$ to $\text{H}_2$ and CO. CO is then put through the shift process to attain a higher level of hydrogen. The by-product from this process is $\text{CO}_2$, but $\text{CO}_2$ from biomass is considered “neutral” with respect to greenhouse gas, as it does not increase the $\text{CO}_2$ concentration in the atmosphere. The mixed gas can also be used in fuel cells for electricity production [79].

Compared to conventional processes for production of electric energy from waste, integrated gasification fuel cell systems are preferable. Electrical efficiency over 30% is possible for these systems. This is not possible using traditional technology. Wet sewage sludge can be assumed as one of the most common feedstock to manufacture hydrogen gas all over the world [80].

### 4.1.5 Wet Oxidation

Wet oxidation (WO) can be used for the treatment of the organic compounds in wastewaters. WO is a destructive wastewater technology based on the oxidation of pollutants at high temperature and high pressure in the liquid phase. Molecular oxygen dissolved in the wastewater reacts with the organic and inorganic pollutants. The oxidizing power of WO is based on the high solubility of oxygen at these severe conditions and the high temperature that increases the reaction rates and production of free radicals. A process flowchart of the sludge-processing steps is shown in Diagram 4.6. The working conditions of the WO are temperatures of 125–300 °C and pressures of 0.5–20 MPa. Organic wastes are oxidized to carbon dioxide, water and intermediate oxidation products which are predominantly of low molecular weight like carboxylic acids, acetaldehydes and alcohols [81]. These intermediate products are synthetized via a free radical mechanism and show a
significant reduction in toxicity and chemical oxygen demand (COD). Insoluble organic matter is converted to simpler soluble organic compounds which are in turn oxidized and eventually converted to carbon dioxide and water, without emissions of NO\textsubscript{x}, SO\textsubscript{2}, HCl, dioxins, furans, fly ash, etc. [82]. Although the degree of oxidation depends on the process conditions, retention time and feed composition, in most operations low molecular weight compounds will accumulate as they tend to be refractory to further oxidation [83].

An advantage of the WO is that the majority of contaminants remain in the aqueous phase. Elemental sulphur is converted to sulphate, halogens to halides and phosphorous to phosphate [81] and chlorine to hydrochloric acid [84]. The final effluent contains low molecular weight organics, ammonia, inorganic acids and inorganic salts and can be treated biologically. Metal oxides, insoluble phosphate and sulphate salts may cause significant quantities of suspended solids requiring dewatering and landfilling processes. The off-gas may contain ammonia, CO and some volatile low molecular weight compounds in addition to nitrogen, CO\textsubscript{2}, vapor and oxygen [81].

Diagram 4.6: Flow-diagram of wet oxidation process

Since the WO is accepted to be suitable for the wastes with high COD content (20–200 g/l), it can be used for the disposal of wastes that are both too dilute to incinerate and too
concentrated for biological treatment. It is also applicable to the detoxification of hazardous wastes and of wastes toxic to microorganisms in biological processes and to convert non-biodegradable components into biodegradable ones. The capital costs for a WO system depend on the flow rate, wastewater composition, extent of oxidation and the required operating conditions [81].

The presence of catalysts enhances the reaction rate or attains an acceptable overall reaction rate at a lower operating temperature, resulting in a reduction of capital costs. It can also lead to a higher oxidation rate of organic material refractory to non-catalytic oxidation. The catalytic process can be used for either effluent pre-treatment prior to a biological step or as a complete destruction process. Homogeneous catalysts require be recovering from the treated effluent or discarding. Heterogeneous catalysts do not need any additional catalyst removal system [81] but on the other hand, homogeneous catalysts appear to be more active [85].

In the wet oxidation process most of the organic compounds are removed (about 99%) at the temperature interval of 200–280 °C within 15–60 min. Higher temperatures are needed to remove more refractory compounds [83].

However, the industrial practice is far in advance of basic research in this field. Despite the lack of a proper theoretical basis of the process, many industrial installations have been put in motion. They operate correctly and often achieve the designed production capacity. Now, due to development of computation techniques, it is possible to model precisely enough the processes that take place in wet oxidation reactors; however, the models used for this purpose are still far from being perfect. Hence, there is an urgent need to propose novel improved methods to describe this process, which will enable optimization of the reactor dimensions and improvement of operation safety of the wet oxidation system. This is related to the necessity of explanation of the mechanisms governing the process and determination of the kinetics of elementary chemical reactions occurring in the system [86].
4.2 Strategic Planning (SP): Basic Concept

SP process is about planning because it involves setting of targets or goals and developing a framework to achieve them. In other words, it can be explained as a vehicle for a journey, from the present situation to a better future. It is about the choices that are made from a number of alternatives, the prioritization of those choices, and the timing of the action associated with them. Thus, it is a proactive and target-oriented process-cum-methodology [88].
Lastly, SP is essential towards the achievement of long-term objective of developmental activities as it encourages a simultaneous consideration of social, environmental and economic factors. Figure 4.2 explains the basic steps in SP [88].

![Figure 4.2: Strategic Planning Process, [88]](image)

The main components of a strategy are [88]:

- Assessment including diagnosis (at the start of a strategy)
- Designing the actions (planning)
- Taking the actions (implementation).
- Monitoring and evaluation (during a strategy)

These components must continue together and reinforce one another. The best strategies have been based on participation, building on good existing plans and processes, with clear attention to an integrated approach. However, strategies are not panaceas, indeed they break new grounds in the way societies and governments tackle complex issues related to sewage sludge management [88].

### 4.2.1 What are the types of SP models

A number of SP models exist, all of which differ from one another in some degree. Some models provide a way to identify strategies, while others define the logic to identify strategies as well as actions. No one model can be said to suit all users. The following three models are generally used in SP [88]:
4.2.1.1 SWOT model

*SWOT Analysis* is a strategic planning tool used to evaluate the Strengths, Weaknesses, Opportunities and Threats involved in a project or in a business venture. It involves specifying the objective of the business venture or project and identifying the internal and external factors that are favourable and unfavourable to achieving that objective. The technique is credited to Albert Humphrey [88].

The SWOT model’s objective is to recommend strategies that ensure the best alignment between the external environment and internal situation. Organizations can develop a competitive advantage by identifying a fit between its strengths and upcoming opportunities [88].

The aim of any SWOT analysis is to identify the key internal and external factors that are important to achieve the objective. SWOT analysis groups key pieces of information into two main categories [88]:

**Internal Factors:** The strengths and weaknesses internal to the organization

- *Strengths* are the attributes of the organization that are helpful to achieve the objective.
- *Weaknesses* are the attributes of the organization that are hindrances in achieving the objective.

**External factors:** The opportunities and threats presented by the external environment

- *Opportunities* are the external conditions which are helpful to achieve the objective.
- *Threats* are the external conditions which are hindrances in achieving the objective.

4.2.1.2 Ansoff’s model

In this model, developed by Igor Ansoff, “strategy” is designed to transform the organization from its present position to the desired position as described by the objectives, subject to the constraints of the capabilities and the potential of the organization [88].

The Ansoff matrix entails four possible product/market combinations: Market penetration, product development, market development and diversification (Ansoff 1957-1989). A
common mistake made while conducting Ansoff analysis is that analysts are not able to acknowledge how different growth strategies are suitable for companies operating in different types of markets, and how changes in business environment make the same company choose a different strategic option at stage time in its organizational life cycle [89].

4.2.1.3 Porter’s model

This model is also called the “five forces model”. It is a framework for industry analysis and business strategy development formed by Michael E. Porter of Harvard Business School in 1979. It draws upon Industrial Organization (IO) economics to derive five forces that determine the competitive intensity and therefore attractiveness of a market. Attractiveness in this context refers to the overall industry profitability. An "unattractive" industry is one in which the combination of these five forces acts to drive down overall profitability. A very unattractive industry would be one approaching "pure competition", in which available profits for all firms are driven down to zero [88].

Three of Porter’s five forces refer to competition from external sources. The remainders are internal threats. The five forces include: (a) the risk of new competitors entering the industry; (b) threat of potential substitutes; (c) the bargaining power of buyers; (d) the bargaining power of suppliers and; (e) the degree of rivalry between the existing competitors [88].
5 Problem Definition
5.1 General description

Since land application of sewage sludge is restricted in order to prevent health risks to humans, there should be identified the one method concerning sewage sludge disposal, which is most appropriate for implementation in Greece.

5.2 Methodology

Through the literature review, emerging technologies are identified first and then SWOT analysis is carried out to analyse strengths, weaknesses, opportunities and threats of the technologies. A qualitative evaluation of the overall performance of the technologies is done on the basis of some criteria’s which are described below.

As an emerging technology, the study identified those technologies that are neither present at the current time in Greece, nor have been developed significantly for sewage sludge management system. For example, conventional technologies like composting or aerobic digestion are already established for sewage sludge treatment technologies in Greece. Hence, these technologies are not analysed in this study.

At this point, it should be noticed once more that the information available on thermal treatment technologies of sludge is often incomplete and based on widely varying assumptions, so comparisons between different technologies on a consistent and common basis are very difficult.

5.2.1 SWOT ANALYSIS

Sludge treatment technologies are analysed by SWOT analysis. SWOT analysis is a planning tool used to understand the Strengths, Weaknesses, Opportunities and Threats involved in a project or in a business. However, the tool is very useful to analyse particular process or technology. SWOT analysis is useful to understand the technology, in order to analyse probable strength, weakness, benefit and probable threats. In the next step, treatment methods are evaluated by a qualitative evaluation.
5.2.2 Qualitative evaluation

Technologies in sludge treatment sector are analysed by some selected criterias. Four criterias are selected for analysing each technology, those are:

- GHG emission is an essential criteria in order to adopt a management technology, since it must not exceed the limits and has an extra impact on the environment.

- Development stage is very important criteria because while planning for future sludge management system, development of technology and applicability in the real scenario is the key issue. Therefore, development stage of the technologies is one of the vital factors for their selection process and it is based on their efficiency, adaptability and development from lab scale to the large project scale.

- Criteria problem solving capacity is not only the focus in sustainable sludge management system but also the enabling factor. Economic as well as environmental performance must be considered in the overall sludge management system. Environmental performance of the technology gives the high priority in the problem solving capacity.

- For research work, data availability is undeniable criteria. It is not easy to get real and reliable data emerging technologies most of the time. Therefore, data availability is also considered as key criteria, while analysing the emerging technologies.

Table 5.1 shows the criteria for evaluating sludge treatment technologies while the qualitative evaluation is based on the level of significance.
Table 5.1: Evaluation criteria’s for selecting the appropriate technology

<table>
<thead>
<tr>
<th>Criteria</th>
<th>Table 4.1</th>
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<tbody>
<tr>
<td></td>
<td>Range/ranking</td>
</tr>
<tr>
<td>GHG emissions</td>
<td>High</td>
</tr>
<tr>
<td></td>
<td>Moderate</td>
</tr>
<tr>
<td></td>
<td>Low</td>
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<tr>
<td>Development stage</td>
<td>Lab scale</td>
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<td></td>
<td>Pilot scale</td>
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<td></td>
<td>Large pilot scale</td>
</tr>
<tr>
<td></td>
<td>Advanced/mature level</td>
</tr>
<tr>
<td>Problem solving capacity</td>
<td>Very poor</td>
</tr>
<tr>
<td></td>
<td>Poor</td>
</tr>
<tr>
<td></td>
<td>Good</td>
</tr>
<tr>
<td></td>
<td>Very good</td>
</tr>
<tr>
<td>Data availability</td>
<td>No data</td>
</tr>
<tr>
<td></td>
<td>Very limited data</td>
</tr>
<tr>
<td></td>
<td>Limited data</td>
</tr>
<tr>
<td></td>
<td>Available data</td>
</tr>
</tbody>
</table>

5.2.3 Further study

Selection of treatment technology for further study is done based on the sludge management problem solving capacity, development stage and data availability. The selected technology is then analysed elaborately on the following two axes:

a) economic basis

b) energy efficiency basis
6 Results & Discussion
CHAPTER VI RESULTS & DISCUSSION

6.1 SLUDGE TREATMENT METHODS SWOT ANALYSIS

In the following paragraphs the Strengths, Weaknesses, Opportunities and Threats of each sludge treatment technology through SWOT analysis are presented.

6.1.1 Anaerobic Digestion

Use of anaerobic digestion (AD) helps solve many economic, environmental and social issues for a sewage management plant (SMP) and for a country in general. AD systems can provide cost offsets in commercial fertilizer and LP gas purchases. Systems can also provide diversification of SMP revenues through electricity sales and, in some cases, digested solid sales which can be used as animal bedding or nutrient rich soil amendment. Some European utilities view AD systems favourable and seek biogas-generated electricity to help them meet the renewable portfolio standard or as a part of green energy programs.

Electricity generation can mean an increased management burden for the SMP and make periodic need for expert troubleshooting and maintenance a large concern. For these and other reasons, the support and cooperation of a servicing utility is crucial to having a successful biogas-to-energy system. Installation costs of these systems tend to be high, and financial institutions are often reluctant to provide loans for new AD systems, which they view as mostly unrecoverable assets.

Reduction in costs of systems through standardization could improve the economics. Some other option could allow smaller operations to economically use AD as well. Opportunities for aggregation of resources such as collection of gas for upgrading at a centralized facility, or coordination of a solids product for sale are two means of improving return on AD products that may allow smaller operations to benefit from larger scale processing. Similarly, a centralized AD facility can allow smaller utilities to have access to the digester.

Hurdles and opportunities: A number of hurdles or factors limiting adoption of AD by SMP are apparent. Detailed study of implementation issue for digester projects would likely shed more light on how technology adoption decisions are made, allowing a more focused targeting of policies.
High system costs: Capital costs for AD systems and the implication of these costs on financing and payback periods are believed to be a significant disincentive for adopting these systems. Some of these costs stem from the lack of standardization of systems, but another factor is the high price of electricity generation equipment which generally costs about one-third to one-half the price of the entire system. [9] Development of standardized lower-cost systems would be an important step to a more widespread adoption of AD systems.

What is needed?

1. Financial assistance in the form of grants, loans or loan guarantees to help finance projects may be the simplest means of improving payback.
2. Enabling generators to receive higher payments sludge-based energy generation will make more projects economically feasible.
3. Increase support of research, development and demonstration of lower-cost modular systems.

Benefits are Externalities: Like the more well-known negative externalities associated with industrial society, positive externalities also result in suboptimal performance of markets. In the case of AD systems for sewage sludge, many benefits accrue to people other than the system owner, meaning the value of these benefits do not enter into the technology adoption decisions. Some of these benefits include reduction in greenhouse gas emissions, reduced reliance on fossil fuels, reduced energy imports, reduced odours and increased decentralization of energy supply.

What is needed?

1. Explore and encourage use of tradable incentives such as renewable energy credits, green tags and carbon credits.
2. Enabling generators to receive higher payments for sludge-based energy generation can be viewed as a general positive externality payment.
Table 6.1: SWOT analysis of *anaerobic digestion*
6.1.2 Incineration

Use of sludge as incineration feedstock requires considerably less energy used for drying and could offer a large renewable electricity generation source for Greece with lower emissions than existing coal-fired generation. The owner and locations of large operations in Greece may offer opportunities for aggregation of feedstocks and use of large-scale facilities.

Hurdles and opportunities: Proposals for incineration of sludge for energy may face uncertainties regarding air permits. Sludge incineration treatment plant may need to install emission control technologies similar to facilities burning fossil fuels.

What is needed?

1. Establishment of clear guidelines for permitting of these facilities and statement of incentives that are available for sludge-fired generation may prompt installation of more of these facilities in Greece.

2. Include sludge incineration as a technology qualifying under incentive programs for biogas generation.
Table 6.2: SWOT analysis of *incineration*

<table>
<thead>
<tr>
<th>SWOT Analysis</th>
<th>Details</th>
</tr>
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<tbody>
<tr>
<td>Strengths</td>
<td></td>
</tr>
<tr>
<td>Weaknesses</td>
<td></td>
</tr>
<tr>
<td>Opportunities</td>
<td></td>
</tr>
<tr>
<td>Threats</td>
<td></td>
</tr>
</tbody>
</table>
6.1.3 Pyrolysis

Pyrolysis may not have potential for widespread application in Greece, mainly due to the feedstock drying requirements. However in certain situations, such as when management of phosphorus and potassium are important and sludge is already relatively dry, there may be opportunities for beneficial uses. Adopters of pyrolysis systems will still face the challenge of finding value-added uses for the solid and liquid products.

*Hurdles and opportunities:* Pyrolysis of sludge is a somewhat more complex technology than incineration. Whereas incineration creates only heat and ashes, pyrolysis creates bio-oil, combustible gas and char. However, these products of pyrolysis have no established markets. While pyrolysis of char may be useful for certain livestock operations in management nutrients and pathogens issues, development of markets or higher value issues for the products will play a large role in whether pyrolysis is chosen over incineration.

*What is needed?*

1. Regulatory approval of char (as well as ashes from sludge incineration) for use as a fertilizer or soil amendment.
2. Inclusion of electricity generation from incineration of pyrolysis products (pyrolysis gas, oil and char) in financial incentive programs for biogas energy generation will help improve the economics of these systems.
Table 6.3: SWOT analysis of *pyrolysis*

<table>
<thead>
<tr>
<th>Strengths</th>
<th>Weaknesses</th>
<th>Opportunities</th>
<th>Threats</th>
</tr>
</thead>
<tbody>
<tr>
<td>High yield</td>
<td>Low efficiency</td>
<td>New markets</td>
<td>Regulations</td>
</tr>
<tr>
<td>Environmentally friendly</td>
<td></td>
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</tbody>
</table>
6.1.4 Gasification

Use of gasification on drier sludge is possible, but current technologies require such a large scale operation, so it does not appear likely that such a system will be feasible with sludge as an anchor feedstock in Greece.

*Hurdles and Opportunities:* Another important constraint that limits the adoption of gasification is that syngas market is undeveloped yet. In total about 6000 PJ/year of syngas is produced worldwide, corresponding to almost 2% of the present total worldwide energy consumption. The world market for syngas is dominated by the ammonia industry. Also the $\text{H}_2$ in oil refineries represent a significant share in present syngas applications.

*What is needed?*

1. New markets have to come forward. This is considered to be the transportation fuels and chemicals market.
2. Goals must be set from local authorities to decrease the dependency of oil producing countries.
Table 6.4: SWOT analysis of *gasification*

<table>
<thead>
<tr>
<th>Strengths</th>
<th>Weaknesses</th>
<th>Opportunities</th>
<th>Threats</th>
</tr>
</thead>
<tbody>
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</tr>
</tbody>
</table>
6.1.5 Wet Oxidation

Even though wet oxidation technology for sludge treatment has not been yet evolved in Greece, nowadays throughout the world many WO plants have been commercialized by several famous companies such as General Atomics, EcoWaste Technologies, Chematur, and Supercritical Fluids International, etc. Another SCWO plant with a treatment capacity of 7m³/h has also been built by Chematur Engineering AB (Sweden) to deal with sewage sludge. Nevertheless, the three key problems concerning corrosion, plugging and high running cost still exist.

**Hurdles and opportunities:** Harsh operation conditions (high concentration of oxidant, extreme pH value, high temperature and pressure) together with reaction intermediate/ultimate products (high concentrations of ionic species, free radicals, acids and inorganic salts) result in severe corrosion problem, especially in SCWO.

**What is needed?**

1. It is better to ensure the solution density everywhere in reactor is below 200kg/m³
2. Appropriate reaction conditions such as heteroatom types in feedstock, reaction temperature and pressure should be fixed in order to minimize corrosion rate for a chosen reactor construction material.

**High system costs:** High reaction temperature and pressure result in a relatively expensive running cost, which also further affects the development of WO.

**What is needed?**

1. Use of proper catalyst to moderate the harsh reaction conditions, to minimize oxidant consumption, to recover heat of reactor effluent as well as to increase byproduct income.
2. Designs and combinations of heat exchangers need to be optimized for recovering the heat in reactor effluent because energy recycle utilization is beneficial to further reduce the running cost.
Table 6.5: SWOT analysis of wet oxidation
### Table 6.6: SWOT analysis comparative table

<table>
<thead>
<tr>
<th>Method</th>
<th><strong>Strength</strong></th>
<th><strong>Weakness</strong></th>
<th><strong>Opportunity</strong></th>
<th><strong>Threats</strong></th>
</tr>
</thead>
<tbody>
<tr>
<td>Anaerobic Digestion</td>
<td>Inert ash is produced, while no dewatering is needed</td>
<td>It has long residence time which requires large scale &amp; increases cost, while the biogas product may need clean up</td>
<td>Large scale could be reduced by reactor design improvement, GHG emission reduction could be offered for sale</td>
<td>The development of new more complex anaerobic digestion designs present risk for early adopters</td>
</tr>
<tr>
<td>Incineration</td>
<td>The feedstock quality is not essential, while pathogens are destroyed</td>
<td>It has low efficiency with high CO₂ emissions</td>
<td>There is opportunity for co-firing</td>
<td>The process is restricted by the law in some case</td>
</tr>
<tr>
<td>Pyrolysis</td>
<td>It has low GHG emissions with high efficiency</td>
<td>There is not established market or value for products, while it is an expensive process</td>
<td>The liquid-fuel product could be used for energy and char as soil amendment</td>
<td>Bio-oil product is highly variable on composition of residues</td>
</tr>
<tr>
<td>Gasification</td>
<td>It has fewer emissions than incineration &amp; allows the use of multiple feedstocks</td>
<td>Feedstocks must be dry and pulverized while the external market is undeveloped yet for syngas</td>
<td>The syngas product competes directly with natural gas</td>
<td>Syngas is a vulnerable product in case of a price drop for natural gas substitute</td>
</tr>
<tr>
<td>Wet Oxidation</td>
<td>There is no need for feedstock dewatering, while it has little odour nuisance</td>
<td>The initial investment is very high &amp; the process has not been marketed well enough</td>
<td>The simultaneous use of more reactors can improve the energy consumption</td>
<td>The recovery of energy may not always be profitable (e.g. in a case of hot water)</td>
</tr>
</tbody>
</table>
6.2 Qualitative evaluation results

Qualitative evaluation of the treatment technologies are done by four criterias with certain evaluation value. Table 6.7 shows that, thermal wastewater treatment technologies have lower GHG emissions, except incineration. However, gasification and pyrolysis have higher development stage and problem solving capacity. Wet oxidation is still experimenting in lab scale, which might be developed in the near future.

Table 6.7: Qualitative evaluation of the selected technologies

<table>
<thead>
<tr>
<th>Technology</th>
<th>Evaluation Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Thermal Wastewater</td>
<td>Lower GHG emissions</td>
</tr>
<tr>
<td>Gasification</td>
<td>Higher development stage</td>
</tr>
<tr>
<td>Pyrolysis</td>
<td>Problem solving capacity</td>
</tr>
</tbody>
</table>

6.3 Further study of the selected technology

Pyrolysis is selected as a treatment technology for further study. The main reasons for choosing pyrolysis are:

- It is a more advanced thermal treatment process than the others
- It produces energy, which is the leading economic benefit from it
- Moreover, the emissions data are available for the pyrolysis process rather than other wastewater treatment technologies
- Potential wastewater problem solving capacity

At this point of the study, an assessment of the commercial viability of pyrolysis technology for the processing of sludge will be carried out. To be commercially successful, the technology must be incorporated into a complete solution that is better in overall terms than that achievable with technologies that are already mature.
6.3.1 Economic evaluation of sludge pyrolysis

While pyrolysis of sewage sludges for the production of oils has been of interest for some time, full scale implementation of the technology has been limited. Acceptance of the technology has been limited by the low economic value of the produced oil as well as the relative complexity of the processing equipment. The economic viability of pyrolysis may be improved if the yield of oil were enhanced or if value-added products such as adsorbents could be produced from the pyrolysis chars. An energy-based economic analysis was conducted to identify the sludge source and pyrolysis conditions that are most economically viable for oil generation.

There have been a limited number of studies that have evaluated alternative strategies for enhancing the yield of oils from pyrolysis of wastewater sludges. This study was based on the experimental method of Kim Y. and Parker W. [90]. According to them, two types of sewage sludges were collected from the municipal wastewater treatment plant in Ottawa, Canada. Primary sludge was collected from the primary settling tank while digested sludge was collected as cake after anaerobic digestion and subsequent centrifugal dewatering by Alfa Laval model 76000DS dewatering centrifuges [90].

In the laboratory, the primary sludge was further dewatered using a Thermo Electron model 2349 laboratory centrifuge (Waltham, MA) that was operated at 6000 rpm for 10 min. The sample was then dried for 24 h at 105 °C in a Fisher Scientific Model 506G laboratory air convection oven (Pittsburgh, PA) and subsequently stored in an airtight container. The primary sludge was pulverized by hand as it tended to agglomerate during treatment. Digested sludge did not require size reduction [90].

In this study, 5 g of dried sewage sludge was used for each pyrolysis run, even though some of the pretreated sludges had lost mass during treatment. After sample preparation, 5 g of dried sample was placed in the reactor and it was tightly sealed using caps at both ends [90].

The pyrolysis conditions and the corresponding characteristics in general of sewage sludges and products are summarized in Table 6.8. Primary sludge has the highest volatile solids (VS) content with an average value of 84%, while digested sludge has the lowest VS content with an average value of 59%. The calorific value of the dried sludges corresponds well with the
VS and it is not differ significantly between sludge types when expressed on a VS basis with values ranging from 27 to 30 MJ/kg-VS. The calorific value of the produced oils ranges from 36 to 39 MJ/kg-oil and it is not seem to be related to the operating temperatures and sludge types. The calorific value of the pyrolysed chars ranged from 10 to 21 MJ/kg-TS and decreased, as the pyrolysis temperature increased. This agreed with the reduced VS content of the char that was generated at the higher temperatures [90].

The elemental composition of the oil does not vary with operating condition or sludge type. The values of carbon, oxygen, nitrogen and hydrogen concentrations range between 62 to 74, 8 to 22, 2.7 to 8.5 and 9.5 to 9.9 respectively. The composition of the char with respect to C, H and O content is a function of the pyrolysis temperature and decreases with increasing temperature [90].
### Table 6.8: Sludge pyrolysis products, [90]

<table>
<thead>
<tr>
<th>Characteristics</th>
<th>Pyrolysis feeding</th>
<th></th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Primary sludge</td>
<td>Digested sludge</td>
</tr>
<tr>
<td><strong>Dried sludge</strong></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Yield (VS fraction, wt.%)</td>
<td>84</td>
<td>59</td>
</tr>
<tr>
<td>Calorific value (VS-based, MJ/kg-TS)</td>
<td>23</td>
<td>17</td>
</tr>
<tr>
<td>TS-based</td>
<td>27</td>
<td>30</td>
</tr>
<tr>
<td>VS-based</td>
<td></td>
<td></td>
</tr>
<tr>
<td><strong>Oil</strong></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Yield (wt.%)</td>
<td>8-42</td>
<td>4-26</td>
</tr>
<tr>
<td>Calorific value (MJ/kg-oil)</td>
<td>36-38</td>
<td>38-39</td>
</tr>
<tr>
<td><strong>Elemental composition of oil</strong></td>
<td></td>
<td></td>
</tr>
<tr>
<td>C</td>
<td>62-74</td>
<td>69-74</td>
</tr>
<tr>
<td>H</td>
<td>2.7-8.5</td>
<td>9.9-9.9</td>
</tr>
<tr>
<td>O</td>
<td>8-22</td>
<td>8.4-15</td>
</tr>
<tr>
<td>N</td>
<td>9.5-9.9</td>
<td>5.6-6.3</td>
</tr>
<tr>
<td><strong>Char</strong></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Yield (wt.%)</td>
<td>33-85</td>
<td>53-87</td>
</tr>
<tr>
<td>Calorific value (VS-based, MJ/kg-TS)</td>
<td>17-21</td>
<td>10-16</td>
</tr>
<tr>
<td>TS-based</td>
<td>32</td>
<td>34-36</td>
</tr>
<tr>
<td>VS-based</td>
<td></td>
<td></td>
</tr>
<tr>
<td><strong>Energy loss (MJ/kg-ds)</strong></td>
<td>0-1.6</td>
<td>0.5-2.3</td>
</tr>
</tbody>
</table>

The energy loss ($E_{loss}$) values presented in Table 1 were determined from an energy balance that considered the dried sludges and the pyrolysis products (oil and char) as shown in Eq. (1) [90].

$$E_{loss} = M_{ds} E_{ds} - (M_{oil} E_{oil} + M_{char} E_{char})$$ (1)
where, \( M \) and \( E \) refer to the mass and calorific values and the subscripts \( ds \), \( oil \) and \( char \) refer to the dried sludge, oil and char, respectively. The calculation was based on the energy per unit mass of dried sludge and the energy that was present in the oil and in the char. It was assumed that the energy loss (\( E_{\text{loss}} \)) values quantified energy associated with the gas phase. The energy of the vented gases (non-condensable gases, NCG) was difficult to measure and they were not considered as major products in this study [90].

The most energy loss is observed with digested sludge at 500 °C with a value of 2.3 MJ/kg-ds. For all cases, the energy loss increased with increasing pyrolysis temperature and is less than 10% of the initial energy content of the dried sludges. In this work, it was assumed that all mass loss was due to NCG. The measured total yields that the dried sludges transferred to the oils, chars and reaction water during pyrolysis ranged from 80% to 91%, hence 9–20% of the mass was estimated to be lost as NCG [90].

### 6.3.1.1 Energy consumption for drying

Dewatering technologies vary between plants and the energy consumed by this process could be highly variable. Therefore, comparing energy consumption for dewatering was not factored into the calculations but should be considered when making future conclusions [90].

The energy consumption for drying (\( Q_{\text{drying}} \)) of dewatered sludge is calculated using Eq. (2). The temperature difference employed in this equation is assumed to be 80 °C (105 °C drying temperature minus 25 °C storing temperature of dewatered sludge) [90].

\[
Q_{\text{drying}} = M_{\text{ws}} \times W \times \left[ (C_{p_{\text{water}}} \times \Delta T) + \Delta H_{\text{vap}} \right] + \left[ M_{\text{ws}} \times (1-W) \right] \times C_{p_{\text{sludge}}} \times \Delta T
\]  

(2)

where, \( M_{\text{ws}} \) is unit mass of wet sludge after dewatering (kg), \( W \) is fraction of water in sludge, \( \Delta H_{\text{vap}} \) is latent heat for vaporization of water (2090 kJ/kg), \( C_{p_{\text{water}}} \) is heat capacity of water (4.18 kJ/kg °C), \( C_{p_{\text{sludge}}} \) is heat capacity of solids in sludge (1.95 kJ/kg °C), and \( \Delta T \) is temperature difference between initial and 105 °C [90].
The heat capacities of primary and digested sludge are likely different due to the differing chemical contents of the individual sludge types. However, for this study it is used a fixed value of 1.95 kJ/kg °C because it is not possible to accurately estimate the heat capacities for the different sludges [90]. This value was determined based upon the range of heat capacities of general organic and inorganic materials. The heat capacity of general organic material ranges between 2.1 and 2.5 kJ/kg °C and the range for inorganic material is 0.8–1.3 kJ/kg °C [91]. The dried sewage sludge contains 59–84% organic matter as presented in Table 6.8. Therefore, minimum and maximum values of heat capacity would be between 1.6 and 2.3 kJ/kg °C. The average value 1.95 kJ/kg °C is therefore used for this study [90].

Water content has a major impact on the energy consumption predicted by Eq. (1). The water contents after dewatering of primary and digested sludge as cake are 75% and 70%, respectively. The estimated energy consumption for drying the two sludge types was calculated as 1857 and 1744 kJ/kg-ws [90].

### 6.3.1.2 Energy consumption for pyrolysis

There are two components considered in the calculation of energy consumption for pyrolysis. One component involves heating the dried sludge from the temperature after drying to the target temperature. The second component is the heat consumed to decompose the sewage sludge during the pyrolysis reaction.

The energy consumption to heat dried sludge to the target temperature ($Q_{\text{target}}$) can be calculated using Eq. (3). The average value of heat capacity for dried sludges was used for this equation. The temperature of the sludge after drying was considered as 105 °C. The calculated energy consumptions to heat the sludge to 300, 400 and 500 °C are 380, 575 and 770 kJ/kg-ds, respectively [90].

\[
Q_{\text{target}} = M_{ds} \times C_{P_{\text{sludge}}} \times \Delta T_{\text{target}}
\]

where, $\Delta T_{\text{target}}$ is temperature difference between target and 105 °C.

The second component is the heat of reaction for dried sludge pyrolysis which is an endothermic process. The precise measurement of the heat of reaction for individual sewage sludges requires complex experimental work which is outside the scope of this work.
Hence, literature data is employed [90]. It is reported the reaction energy for sewage sludge pyrolysis as 300 kJ/kg. The reported value was measured at temperatures that ranged from 100 °C to 500 °C. The carbon and hydrogen content of the sludges were approximately 32 and 5 wt. % respectively, on a dry basis. They also revealed that the main decomposition for the sludge occurred between 250 °C and 500 °C [92]. Therefore, the total energy consumption \( Q_{\text{total}} \) for pyrolysis is calculated from Eq. (4) [90].

\[
Q_{\text{total}} = Q_{\text{drying}} + Q_{\text{target}} + Q_{\text{pyrolysis}}
\]

The energy consumption for drying \( Q_{\text{drying}} \) ranges from 1744 to 2220 kJ/kg and is the main energy input as it is approximately 2 to 3 times higher than pyrolysis inputs \( Q_{\text{target}} + Q_{\text{pyrolysis}} \) [90].

The economic value of the bio-oil is evaluated based on the least valuable crude oil (No. 6 fuel oil) that has been traded at 70% of crude oil [93]. Hence, the economic value of the bio-oil was evaluated as 70% of the current oil price (US $96/barrel) and is determined to be $67.2 US/barrel- oil. The density of the bio-oil based on a reference value is 0.888 kg/l for crude oil [91]. Therefore, the converted bio-oil value is approximately 0.369 $ US/kg-oil or 0.259 €/ kg-oil.

An economic assessment of the value of producing bio-oil from the various dried sludges, over the range of pyrolysis temperatures was performed (Table 6.9). In Table 6.9 the required energy for pyrolysis is calculated using Eq. (4) [90]. The energy cost for the operation of the laboratory-scale pyrolysis reactor and drying processes is evaluated based on 0.06083€/kWhr as Greece’s current cost of electricity [Appendix A] because electricity accounted for most of the operational costs of the processes. The energy cost was calculated using Eq. (5) and a conversion of 3600 kJ/kWhr.

\[
C_R = E_{\text{consumed}} \times C_E
\]

where, \( C_R \) and \( C_E \) are the cost of required energy and electricity.

Based on the calculated economic value of the oil, the most valuable sludge is primary sludge pyrolysed at 500 °C which has a value of 0.056 €/kg-ds. Digested sludge is the least valuable at 0.025 €/kg-ds. The economic values of primary and digested sludge increase with
increasing pyrolysis temperature. In other words, both sludge types have the greatest economic value at the highest operation temperature (500 °C). Overall, primary sludge pyrolysed at 500 °C produces the largest economic benefit, with temperature and volatile content being the most important factors that affect oil-yield.

Table 6.9: Economic value of bio-oil

<table>
<thead>
<tr>
<th>Temperature (°C)</th>
<th>Oil Yield (wt.%) kg-oil/kg-ds</th>
<th>Value €/kg-ds</th>
<th>Energy Required kJ/kg-ds</th>
<th>Cost €/kg-ds</th>
<th>Economic value of oil €/kg-ds</th>
</tr>
</thead>
<tbody>
<tr>
<td>Primary sewage sludge</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>300</td>
<td>26</td>
<td>0.067</td>
<td>2555</td>
<td>0.043</td>
<td>0.024</td>
</tr>
<tr>
<td>400</td>
<td>39</td>
<td>0.101</td>
<td>2750</td>
<td>0.047</td>
<td>0.054</td>
</tr>
<tr>
<td>500</td>
<td>42</td>
<td>0.109</td>
<td>2945</td>
<td>0.050</td>
<td>0.059</td>
</tr>
<tr>
<td>Digested sewage sludge</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>300</td>
<td>14</td>
<td>0.036</td>
<td>2424</td>
<td>0.041</td>
<td>(0.005)</td>
</tr>
<tr>
<td>400</td>
<td>24</td>
<td>0.062</td>
<td>2619</td>
<td>0.044</td>
<td>0.018</td>
</tr>
<tr>
<td>500</td>
<td>28</td>
<td>0.073</td>
<td>2814</td>
<td>0.048</td>
<td>0.025</td>
</tr>
</tbody>
</table>

6.3.2 Energy Efficiency

In terms of fuel conversion efficiency, the complete combustion of the fuel is more efficient than any other thermal process. Therefore pyrolysis cannot have higher thermal efficiencies (conversion of sludge and auxiliary fuel energy to syngas energy) than combustion. In most practical cases, the thermal efficiencies for pyrolysis technologies will be lower than for combustion technologies.

In terms of the efficiency of standalone plants optimized for power generation, all existing pyrolysis technologies have lower efficiencies than that currently achieved by modern combustion technology. The only standalone pyrolysis configuration that might result in a higher overall electrical efficiency (overall conversion of waste and auxiliary fuel energy to net exported electricity) than combustion technology is one based on the use of a combined cycle gas turbine for power generation, but this configuration is currently unproven on sewage sludge.

The overall efficiency of pyrolysis processes may be improved by co-firing of the syngas, and possibly also the char, with other fuels in a large conventional power station. However, this
application in Greece may be inhibited by the Environment Agency’s interpretation of Waste Incineration Directive (WID).

6.4 Discussion

In this chapter, a discussion takes place about the impediments and the potential development of the selected emerging technology in Greece.

6.4.1 Impediments to development of pyrolysis technology

There are few plants for treating sludge based on pyrolysis technology in commercial operation or under construction in Europe and none at all in Greece.

The main impediments to development are:

1) A mismatch between the risk bearing capabilities of suppliers, consumers and lenders. The parties involved are generally unable or unwilling to accept an adequate portion of the risks in a project if the technology involved is unproven.

2) Difficulties in securing funding for those technologies with limited operating experience and track record.

3) Low gate fees for sludge treatment and disposal is a deterrent for all types of waste projects but more so for those utilizing capital intensive plant and equipment

4) Expenditure of scarce resources and effort on perceived benefits that do not exist rather than focusing on developments that may result in real benefits.

Unless some of these obstacles are addressed, commercially successful standalone plants based on pyrolysis technology for the thermal treatment of sludge will be difficult to deliver in Greek in the near future.

6.4.2 Potential deployment and areas for further development

Although there are many barriers to the general implementation of pyrolysis technology for treatment of sludge in Greece, there are also strong incentives to encourage further efforts to bring about its deployment.

The energy efficiency (i.e. resource utilization) of standalone small scale pyrolysis plant generating electricity is likely to be significantly less than a combustion plant. Development
of pyrolysis merely as a way to dispose of sewage sludge with low efficiency, electricity generation appears to be an insufficient ambition.

Potential developments of pyrolysis in Greece in the near to medium term are:

1) Use of the syngas as a fossil fuel substitute in power stations, industrial processes or CHP schemes. These configurations can potentially benefit from using existing higher efficiency energy conversion equipment and also, if the host plant is large, significant economies of scale. The quality requirements and demand pattern of the host plant must match that of the syngas produced.

2) Use of pyrolysis technologies in standalone power generation with a conventional steam turbine cycle if the application is commercially competitive or the local authority has precluded the use of combustion.

Longer term potential areas for development are:

1) Cleaning the syngas for use in a combined cycle gas turbine plant to give higher net electrical efficiencies.

2) Further processing of the syngas for use in producing valuable transport fuels.

3) Use of syngas as a chemical feedstock.

These applications are at various stages of research, development and demonstration which may require considerable time, effort and political will. However, if technically and commercially successful, they may ultimately offer substantial benefits. The potential benefits would be lower costs, lower environmental impact, and lower dependency on ever decreasing fossil fuel reserves.
7 Conclusions & Recommendations
7.1 Conclusions

The study aimed to understand the technical development trends of the sewage sludge sector in Greece and to identify the driving forces that actually lead to future development. It is important to understand the development trends while planning for future sewage sludge management. It is not only the technology that influences sludge management system for a region, but also other parameters like sludge regulations, policy or socio-economical matters that influence the overall waste management system.

The present study identified different technologies as potential emerging sludge treatment methods for Greece. While thermal technologies are more efficient in energy recovery, biological treatment options are more favourable concerning biodegradable wastewater fractions treatment. Among thermal methods, pyrolysis and gasification seem very promising for sludge management in the future. Nevertheless, decision support tools are needed in order to help decision makers to come up with the right choice while plan for the future.

Sewage sludge has been utilized in agricultural applications for several years as it represents an alternative source of nutrients for plant growth and is an efficient soil conditioner. However, land application of sewage sludge is restricted to prevent health risks to humans and livestock due to potentially toxic components and organic pollutants and to the high amounts of soluble salts, which may negatively affect the soil properties.

An extensive review of current literature was being carried out concerning Anaerobic Digestion, Incineration, Pyrolysis, Gasification and Wet Oxidation for sewage sludge management. All five methods are feasible and desirable, from a treatment perspective. The challenge is finding a process that meets social, economic and environmental objectives, as well as being affordable and cost effective.

SWOT Analysis, a strategic planning tool, was used to evaluate the Strengths, Weaknesses, Opportunities and Threats involved in each treatment method. A qualitative evaluation of the overall performance of the technologies was done on the basis of four criteria’s: GHG emission, Development stage, Problem solving capacity and Data availability. For further
analysis of the selected technology, an economic evaluation and energy efficiency conduction were performed.

According to the study, pyrolysis could be an important sludge treatment technology for Greece. One of the main reasons supporting this conclusion is that pyrolysis produces higher amount of heat and electricity than incineration. Also, pyrolysis has greater potential wastewater problem solving capacity compared to other methods. Moreover, the emissions data is available for the pyrolysis process rather than any other wastewater treatment technology.

Two types of sludges, primary and digested, were used for the identification of pyrolysis conditions that are most economically viable for oil generation. According to economic evaluation, primary sludge pyrolysed at 500 °C produces the largest economic benefit. Temperature and volatile solids are the most important factors affecting the yield of oil. As far as the energy efficiency of pyrolysis is concerned, it was concluded that the overall efficiency of the process could be improved by co-firing syngas with other fuels in a large conventional power station.

Nevertheless, there are many barriers to the general implementation of pyrolysis for sludge treatment in Greece. Difficulties in securing funding for technologies with limited operating experience and track record is one of the serious constrains. Moreover, adopters of pyrolysis systems will still face the challenge of finding value-added uses for the solid and liquid products since they have not established market yet.

However, there are solutions in order to encourage further efforts to bring about pyrolysis deployment. Regulatory approval of char for use as a fertilizer or soil amendment would help improve the economics of these systems. Also, inclusion of electricity generation from incineration of pyrolysis products (pyrolysis gas, oil and char) in financial incentive programs for biogas energy generation may prompt installation of more of these facilities in Greece.

It is hard to predict which technologies are going to take place in sludge management sector in the future. Nevertheless, it can be assumed that a technology supportive to “waste hierarchy” will get priority for sustainable sludge management in the future.
7.2 Recommendations

✓ The study has only considered pyrolysis process as an emerging technology. Other emerging technologies such as plasma gasification, hydrolysis etc. should be analysed in a future study.

✓ The study has been done by considering only technological solutions. However, other methods such as recycling, reusing are also important and should be considered in a future study.
References
References


[74] Figure of Burgau pyrolysis plant, Germany, available at: http://www.dgengineering.de/Rotary-Kiln-Reference-Plants-Municipal-Waste-Disposal.html


EU seminar, The Use of Coal in Mixture with Wastes and Residues II, Cottbus, Germany.


Appendix
Appendix A

Estimation of kWh price in Greece


(Source: http://www.dei.gr/Documents2/Γενικό%20Βιομηχανικό%20MT%20Τιμοκατάλογος%202011%20Ανταγωνιστικών%20Μονοπωλιακών%20Χρέωσεων%20(2).pdf)