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Report on responsibilities of LUT Energy in EMIR project, 2012 - 2014

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ABSTRACT

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Deinking Sludge Utilization Possibilities: Technical, Economic and Environmental Assessments
ENPI project on "EMIR - Exploitation of municipal and industrial residues"

70 pages, 15 tables, 11 figures, 2 annexes.

Keywords: deinking sludge, material recovery, energy recovery, LCA, economic assessment.

This report introduces the ENPI project called "EMIR - Exploitation of Municipal and Industrial Residues" which was executed in a co-operation between Lappeenranta University of Technology (LUT), Saint Petersburg State University of Economics (SPbSUE), Saint Petersburg State Technical University of Plant Polymers (SPbSTUPP) and industrial partners from both Leningrad Region (LR), Russia and Finland. The main targets of the research were to identify the possibilities for deinking sludge management scenarios in co-operation with partner companies, to compare the sustainability of the alternatives, and to provide recommendations for the companies in the Leningrad Region on how to best manage deinking sludge.

During the literature review, 24 deinking sludge utilization possibilities were identified, the majority falling under material recovery. Furthermore, 11 potential utilizers of deinking sludge were found within the search area determined by the transportation cost. Each potential utilizer was directly contacted in order to establish cooperation for deinking sludge utilization. Finally, four companies, namely, "Finnsementti" – a cement plant in Finland (S1), "St.Gobian Weber" – a light-weight aggregate plant in Finland (S2), "LSR-Cement" – a cement plant in LR (S3), and "Rockwool" – a stone wool plant in LR (S4) were seen as the most promising partners and were included in the economic and environmental assessments.

Economic assessment using cost-benefit analysis (CBA) indicated that substitution of heavy fuel oil with dry deinking sludge in S2 was the most feasible option with a benefit/cost ratio

This project is co-funded by the European Union, the Russian Federation and the Republic of Finland.

(BCR) of 3.6 when all the sludge was utilized. At the same time, the use of 15% of the total sludge amount (the amount that could potentially be treated in the scenario) resulted in a BCR of only 0.16. The use of dry deinking sludge in the production of cement (S3) is a slightly more feasible option with a BCR of 1.1. The use of sludge in stone wool production is feasible only when all the deinking sludge is used and burned in an existing incineration plant. The least economically feasible utilization possibility is the use of sludge in cement production in Finland (S1) due to the high gate fee charged.

Environmental assessment was performed applying internationally recognized life cycle assessment (LCA) methodologies: ISO 14040 and ISO 14044. The results of a consequential LCA stated that only S1 and S2 lead to a reduction of all environmental impacts within the impact categories chosen compared to the baseline scenario where deinking sludge is landfilled. Considering S1, the largest reduction of 13% was achieved for the global warming potential (GWP), whereas for S2, the largest decrease of abiotic depletion potential (ADP) was by 1.7%, the eutrophication potential (EP) by 1.8%, and a GWP of 2.1% was documented. In S3, the most notable increase of ADP and acidification potential (AP) by 2.6 and 1.5% was indicated, while the GWP was reduced by 12%, the largest out of all the impact categories. In S4, ADP and AP increased by 2.3 and 2.1% respectively, whereas ODP was reduced by 25%. During LCA, it was noticed that substitution of fuels causes a greater reduction of environmental impact (S1 and S2) than substitution of raw materials (S3 and S4).

Despite a number of economically and environmentally acceptable deinking sludge utilization methods being assessed in the research, evaluation of bottlenecks and communications with companies' representatives uncovered the fact that the availability of the raw materials consumed, and the risks associated with technological problems resulting from the sludge utilization, limited the willingness of industrial partners to start deinking sludge utilization.

The research results are of high value for decision-makers at already existing paper mills since the result provide insights regarding alternatives to the deinking sludge utilization possibilities already applied. Thus, the research results support the maximum economic and environmental value recovery from waste paper utilization.

ENPI

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TIIVISTELMÄ

Ivan Deviatkin, Asta Kujala, Mika Horttananinen

ENPI -projekti yhdyskuntien ja teollisuuden jätteiden hyödyntämisestä Leningradin alueella 2013

70 sivua, 14 taulukkoa, 11 kuvaa, 1 lisää tietoa

Hakusanat: siistausliete, materiaalin uusiokäyttö, energian uusiokäyttö, elinkaarimallinnus, taloudellinen arviointi

Tämä raportti kertoo ENPI-projektin ”EMIR”- Exploitation of Municipal and Industrial Residues”-tutkimuksesta, joka tehtiin yhteistyössä Lappeenrannan teknillisen yliopiston (LUT), Saint Petersburg State University of Economicsin (STbSUE), Saint Petersburg State Technical University of Plant Polymersin (SPbSTUPP) sekä Leningradin alueen ja suomalaisten teollisuuskumppanien kanssa. Tutkimuksen päätavoitteina oli selvittää mahdollisia siistauslietteen hyödyntämismahdollisuuksia yhdessä teollisuuskumppanien kanssa, vertailla mahdollisuuksien välisiä kestävyyseroja sekä tarjota Leningradin alueen yrityksille suosituksia siistauslietteen hallintaan parhaimmalla tavalla.

Kirjallisuusselvityksessä tunnistettiin 24 siistauslietteen hyötykäyttömahdollisuutta suurimman osan ollessa materiaalinhyödyntämiseen. Tämän lisäksi 11 mahdollista siistauslietteen käyttäjää löytyi kuljetuskustannusten määrittämälle alueelle. Jokaiseen mahdolliseen käyttäjään oltiin suoraan yhteydessä yhteistyön aloittamiseksi. Lopulta neljä yritystä, ”Finnsementti” – sementtilaitos Suomessa (S1), “St.Gobian Weber” – lekasoralaitos Suomessa (S2), “LSR-Cement” sementtilaitos Pietarin alueella (S3) ja “Rockwool” kivivillalaitos Pietarin alueella (S4) nähtiin eniten lupaavina yhteistyökumppaneina ja joiden kanssa tehtiin taloudellinen ja ympäristöllinen arviointi.

Taloudellinen arviointi hyödyntäen kustannus-hyötyanalyysia, osoitti, että raskaan polttoöljyn korvaaminen kuivalla siistauslietteellä S2:ssa oli käyttökelpoisin vaihtoehto sen ollessa hyöty/kustannus-suhteeltaan (HKS) 3.6 kun kaikki liete hyödynnettiin. Samalla, 15%

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kokonaislietemäärästä (määrä, joka voidaan mahdollisesti hyödyntää skenaariossa) antoi lopputulokseksi HKS 0.16. Siistauslietteen hyödyntäminen sementintuotannossa (S3) on hieman käyttökelpoisempi vaihtoehto HKS:llä 1,1. Hyödyntäminen kivivillatuotannossa on käyttökelpoista vain, jos kaikki siistausliete hyödynnetään ja poltetaan jo olemassaolevassa laitoksessa. Vähiten taloudellisesti käyttökelpoinen hyötykäyttömahdollisuus on käyttää lietettä sementtituotannossa Suomessa (S1) korkean porttimaksun vuoksi.

Ympäristöarviointi tehtiin hyödyntämällä kansainvälisesti tunnistettua elinkaariarvioinnin (Life cycle assessment – LCA) menetelmiä: ISO 14040 ja ISO 14044. Seuraamuksellisen LCAn tulokset osoittivat, että vain S1 ja S2 johtavat kaikkien ympäristövaikutusten vähenemiseen valittuissa vaikutusluokissa verratessa lähtötilanteeseen, jossa siistausliete viedään kaatopaikalle. Tarkastellessa S1-skenaariota, suurin vähenemä 13% saavutettiin ilmastonlämpenemispotentiaaliin (GWP). S2-skenaarion kohdalla saavutettiin suurin vähenemä uusiutumattomien mineraalivarojen ehtymispotentiaalissa (ADP) 1,7%, rehevöitymispotentiaalissa 1,8 % ja GWP:ssä 2,1%. S3-skenaariossa havaittiin ADP:ssä huomattava nousu 2,6% ja happamoitumispotentiaalin nousu 1,5%, kun taas GWP laski 12 %, eniten kaikista vaikutusluokista. Skenaariossa S4 ADP ja AP nousivat 2,3% ja 2,1 %, kun taas otsonikerroksen ohenemispotentiaali väheni 25%. LCA-tutkimuksen aikana huomattiin, että polttoaineiden korvaaminen (skenaariot S1 ja S2) johtaa suurempaan ympäristövaikutusten vähenemään kuin raakamateriaalien korvaaminen (skenaariot S3 ja S4)

Tutkimuksessa havaituista hyväksyttävästi taloudellisesti ja ympäristöllisesti sopivista siistauslietteen käyttömenetelmistä huolimatta, tarkastellessa pullonkauloja ja viestintää yritysten edustajien välillä paljastui, että tarjolla olevien raaka-aineiden käyttö ja lietteen käytön teknologiaan liittyvät ongelmat rajoittavat teollisuuspartnereiden halua aloittaa siistauslietteen käyttö.

Tutkimustulokset sisältävät arvokasta tietoa olemassa olevien paperitehtaiden päätöksen tekijöille, sillä tulos tarjoaa näkemyksiä jo käytössä olevien siistauslietteen käyttömahdollisuuksien eroista. Näin mahdollistuu jätepaperikäytöstä saatava suurin taloudellinen ja ympäristöllinen arvovirtojen hyötykäyttö.

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TABLE OF CONTENTS

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TABLE OF CONTENTS

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LIST OF ABBREVIATIONS

ANSI	American National Standards Institute
BAT	Best available technology
BCR	Benefit-cost ratio
CBA	Cost-benefit analysis
CEPI	Confederation of European paper industries
CHP	Combine heat and power
DM	Dry matter
EC	European Commission
EU	European Union
EUR	Euro
FBB	Fluidized bed boiler
FI	The Republic of Finland
GHG	Greenhouse gases
HHV	Higher heating value
JSC	Joint-stock company
LCA	Life cycle assessment
LLC	Limited liability company
LOI	Loss of ignition
low-BTU	low British thermal units
LWA	Light-weight aggregate
MC	Moisture content
MDF	Medium density fibreboard
MHF	Multiple Hearth Furnace
PB	Particleboard
PCD	Pulsed corona discharge
PPI	Pulp and paper industry
RCF	Recovered fiber
RU	The Russian Federation
RUR	Russian ruble
SPbSPU	Saint Petersburg State Polytechnical University
SPbSTUPP	Saint Petersburg State Technological University of Plant Polymers
SPbSUE	Saint Petersburg State University of Economics
TS	Total solids
WWTP	Wastewater treatment plant

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1. INTRODUCTION

The project "EMIR" (Exploitation of Municipal and Industrial Residues) was launched in November 2012, with the intention of investigating the use of an electric discharge method for wastewater purification, as well as to study the possibilities of the utilization of deinking sludge generated at a recovered fiber-based paper mill with an installed deinking unit. The study aimed at wastewater purification with the pulsed corona discharge (PCD) method was conducted by LUT Chemistry department, whereas the study related to the waste management of a recovered fiber-based paper mill was the responsibility of LUT Energy department. This report enlightens the progress and the results of the project tasks solely assigned to LUT Energy.

Out of all the tasks assigned, LUT Energy has primarily focused on seeking the most technologically acceptable and sustainable solutions for the treatment and utilization of deinking sludge generated at a recovered fiber-based paper mill. Additionally, the results of the research were used to assess the possibilities for benchmarking the proposed deinking sludge utilization methods for other paper mills located in both the Leningrad Region and Finland.

Furthermore, to achieve the targets related to the implementation of a more sustainable waste management system in the Leningrad Region, it was the intention of the project to increase effective cooperation between Finnish and Russian institutes and enterprises, particularly through the transfer of knowledge on waste and wastewater management and technologies across the border.

To achieve these targets, cooperation between Lappeenranta University of Technology, Saint Petersburg State University of Economics (SPbSUE) and Saint Petersburg State Technical University of Plant Polymers (SPbSTUPP) was found to be especially beneficial.

2. BACKGROUND

2.1. PPI residues

The concept of the pulp and paper industry (PPI) includes all industrial processes employed in the manufacture of various pulp and paper products from virgin wood, or recovered fibers (RCF) i.e. waste paper. The use of RCF is widely spread not only in the European Union (EU) and Russia, but all around the world with an increasing number of plants being installed. Monte et al. (2009) states that 70% of the total amount of waste materials generated by European PPI arises from the production of deinked recycled paper. As the total PPI waste generation in the EU is 11 million tonnes, the processing of RCF leads to the generation of 7.7 million tonnes of waste (Monte et al., 2009). The amount of deinking sludge generated during tissue production can be as high as 150 kg dry solids/t of product (Dahl, 2008).

In the past 20 years, research has been made to enhance the utilization of paper mill rejects as secondary energy or material sources. Over the period 1990-2002, the proportion of PPI residues disposed in landfills halved from 42 to 20%. At the same time, the proportions of the resudies used elsewhere increased, as following: energy recovery from 50 to 55%, land application from 8 to 15%, and exploitation of residues in other industries from 0 to 10% (Monte et al., 2009). In the sustainability report published by the Confederation of European Paper Industries (CEPI) (2011), it is stated that the amount of residues disposed in landfills decreased by 80% between 1990 and 2010. A drop in the specific amount of landfilled waste ($kg_{waste}/t_{product}$) from 76.7 $kg_{waste}/t_{product}$ to 15.2 $kg_{waste}/t_{product}$ was achieved, as can be seen in Figure 1.

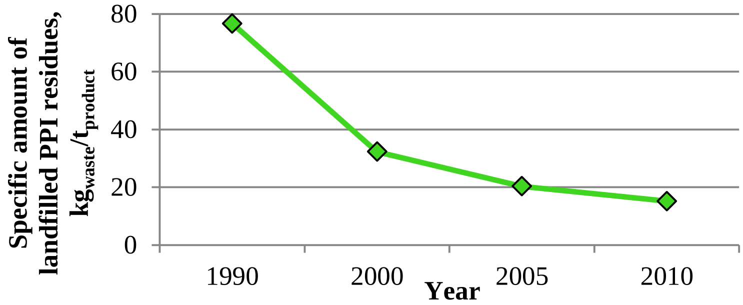

Figure 1. Development of landfilling rate in the PPI of CEPI member-states measured as specific landfilled waste (CEPI, 2011).

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To understand the motivation of industrial producers in the EU to reduce the amounts of waste being landfilled, one may refer to the EU Landfill Directive (EC, 1999) which states that the member-states should reduce the amount of biodegradable waste disposed in landfills to 35% of the 1995 level by 2016 (Monte et al., 2009). Eighteen member-states including Finland implemented this legislation by April 2012, and have encouraged the development of more sustainable waste management practices by imposing higher taxes and gate fees on waste landfilling (Watkins et al., 2012). Additionally, some countries have implemented a tax on the incineration of municipal waste or have considered doing so. Such economical instruments used to guide municipalities and industries to reduce the amounts of landfilled waste have been proven to be efficient.

Watkins et al. (2012) stated that all countries with the highest landfilling costs had the highest percentages of municipal waste recycled and composted. In Finland, the total landfilling fee is currently about 90 €/t, which is within the average range of total landfilling fees in the EU. Most likely, constantly increasing landfilling costs have also forced the industrial players to increase material efficiency and to reduce the amounts of waste generated. For example, the Finnish Forest Industries (2012) reported that about 90% of the forest industry's by-products are recycled. One third of the landfilled waste is incineration ashes. The development of other than landfilling utilization methods for waste generated by Finnish pulp and paper mills over the period 1992-2011, as well as the production capacity of PPI is depicted in Figure 2.

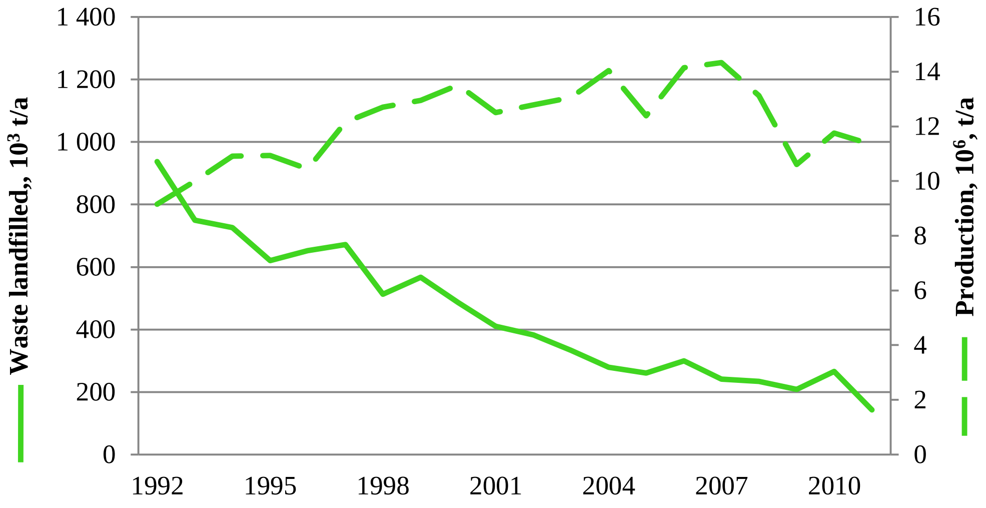


Figure 2. Finnish pulp and board production and amount of waste landfilled by the industry (Finnish Forest Industries, 2012).

Looking at the evolution of PPI residues management between 1990-2008 presented in Figure 3, it can be noted that in 2008 only 4% of the total PPI by-products was landfilled, which is 10 times less compared to 1990. The most notable increase, in contrast, is for the amount of waste used in other instudries by 30%. Only a slight reduction of several percent of the amount of waste incinreated was reported. Thus, incineration is still the most preferred utilization method. Lastly, the amount of waste applied on land, or used by other ways, expanded from 7 to 21%.

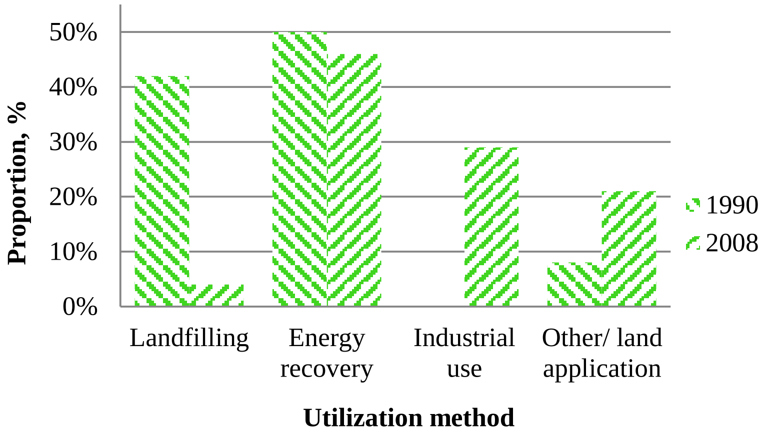


Figure 3. The development of the utilization of the PPI residues of CEPI member states (CEPI, 2011; Monte et al., 2009).

The increase in the proportions of by-products used in industrial processes and in other applications might partially be due to the EU waste management hierarchy (The EU Parliament and the Council of the EU, 2008) which states that material recovery is preferred to energy recovery, where possible.

Nevertheless, it is most likely that the properties of waste have greater impact on the choice of the means of utilization for PPI by-products. Such PPI residues as black liquor and bark have significant or high enough heating values to make their energy recovery feasible. However, such by-products as green liquor, lime mud, chemical flocculation sludge, deinking sludge, pulping rejects from RCF processing and dewatered sludge from wastewater treatment plants (WWTP) generally have high moisture and sometimes inorganic contents and therefore have poor heating values preventing their energy recovery.

2.2. Deinking sludge problem

Among all the solid waste types generated in PPI, wastewater treatment sludge (including primary and secondary ones) and deinking sludge are the largest waste streams (Bird and Talberth, 2008). If primary and secondary sludge is generated at almost every PPI plant, as a result of industrial wastewater treatment, deinking sludge is generated only at paper mills using RCF for the production of tissue or high quality market paper.

Over a long period, sludge management in the Leningrad Region, and Russia in general, has been characterized by the priority given to sludge landfilling rather than reuse, recycling or energy recovery within the pulp and paper sector. However, increasing awareness of the neighbouring community as regards environmental risks caused by sludge landfilling, popularization of corporate responsibility between leading companies in the sector, and tightening legislation in waste management are the major driving forces for the pulp and paper enterprises to seek for methods of sustainable sludge utilization. Despite several companies, mainly with overseas capital, having eliminated sludge landfilling, there are still those disposing sludge in landfills.

Where sustainable deinking sludge utilization systems are implemented, numerous benefits for the environment, local community, and economy can be achieved. Negative effects on the environment can be reduced mainly through the reduction of greenhouse gas (GHG) emissions generated at a landfill site. Additionally, groundwater pollution caused by leachate generation at landfills can be prevented. The environmental quality improvements, in turn, will positively affect human health and quality of life of the neighboring community in general. At the same time, deinking sludge can be used as an alternative source of raw materials or fuels in other industries, increasing the effectiveness of the local economy by proceeding from a linear economy to a circular one. Thus, the utilization possibilities related to deinking sludge use on landfills as a cover layer were excluded from the study.

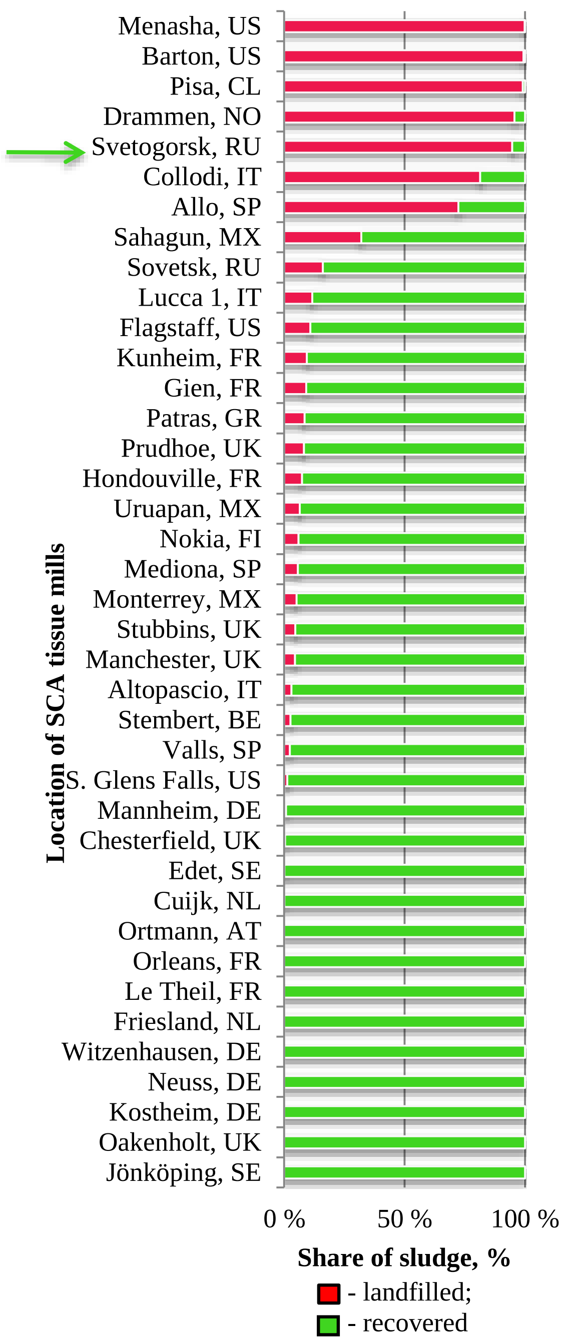
In such a manner, the implementation of the research related to deinking sludge utilization is necessary for different stakeholders and the results of the research can be of value for other companies facing a similar problem.

3. CASE STUDY PAPER MILL

The research on the possibilities for deinking sludge utilization performed by LUT Energy was applied to the case study paper mill. The paper mill belongs to the SCA group and is located in Svetogorsk close to the Finnish-Russian state border. The paper mill manufactures different types of tissue paper from waste paper collected primarily from printing houses. This fact ensures a relatively stable composition of raw materials consumed and, consequently, a rather constant composition of deinking sludge generated.

In 2012, approximately 54 000 t of deinking sludge was generated at the case study paper mill (SCA, 2012). However, the paper mill is not the only SCA tissue mill that landfills most of its sludge. Figure 4 clearly indicates that there are several other plants facing similar problem. Moreover, it is clear from the figure that the problem is not geographically relevant and appears in several countries, including developed ones.

Realizing the urgency of the problem, the administration of SCA Hygiene Products Russia tissue mill decided to evaluate possibilities for alternative options to the management of landfilling deinking sludge by taking part in the EMIR project.



tissue mills (SCA, 2012).

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The case study paper mill expressed a strong attitude towards seeking partners able to establish long-lasting cooperation leading to a win-win scenario for the parties involved. The possibilities to be considered can include both material and energy recovery from deinking sludge located on either side of the Finnish-Russian state border.

3.1. Characterization of deinking sludge

As a first step towards identifying possible deinking sludge recovery routes, determination of certain characteristics of the sludge is required. The sludge sampled at the case study paper mill is presented in Figure 5.

Figure 5: Appearance of deinking sludge generated at the case study paper mill.

It was decided that the properties of deinking sludge listed in Table 1 must be measured in order to characterize the sludge. The heating value of deinking sludge sampled at the SCA paper mill in February 2013, was determined in the laboratory of LUT Energy using Parr 6400 Calorimeter. Higher heating value (HHV) was determined from three parallel samples of the sludge dried in an oven at 105°C for 17 h. The moisture content of the sludge in arrival conditions was 49.6%. The results of the heating value measurements are presented in Table 2.

Table 1. List of properties to be determined in order to assess deinking sludge utilization possibilities.

Characteristic	Unit	Area of application
Higher heating value (HHV)	[MJ/kg]	incineration potential
Bulk density	[kg/m^3]	transportation costs
Moisture content	[%]	transportation, utilization
Ash content	[%]	utilization possibilities
Carbon content	[%]	utilization possibilities
Elemental (ultimate) analysis	[%]	incineration
Ash composition	[%]	utilization possibilities

Studies previously performed by LUT Energy propose that the variation between parallel measurements of ± 0.2 MJ/kg is acceptable and the values from the measurement can be considered as consistent and reproducible.

Table 2. Results of HHV determination of three parallel samples and chemical analysis of deinking sludge sampled at SCA.

Sample number	HHV, MJ/kg	LHV, MJ/kg
1	7.07	
2	7.04	
3	7.07	
Average	7.06±0.02	6.41[1]

[1] – assuming that average hydrogen content of deinking sludge of 3%.

Measured component	Test set 1 (2013)	Test set 2 (2014)
Moisture content,%	47.7	49.6
Ash content on dry basis, %	42.8	-
LOI, %	-	55.9
C_{tot} on dry basis, %	24.5	-
C_{org} on dry basis, %	19.2	-
CaO, %	21.7	26.7
MgO, %	0.38	0.44
Al_2O_3, %	12.1	7.37
SiO_2, %	-	8.88
Fe_2O_3, %	0.34	0.48
K_2O, %	0.17	0.13
Na_2O, %	-	0.11

The sludge has low calorific value on a dry basis and, therefore, it can be expected that incineration of the deinking sludge is economically unsustainable. This is also supported by the experience of the case study paper mill.

The bulk density of the sludge was determined at SCA and equal to 590 kg/m^3. The remaining deinking sludge analyses were performed by Saint-Petersburg State Technological University of Plant Polymers (St.Petersburg State Technological University of Plant Polymers, 2013) and the results of the tests are presented in Table 2.

3.2. Russian legislation on waste management

Legislation aspects concerning waste management in the Russian Federation could be found in the report prepared by St.Petersburg State Economic University (2013). The report describes which requirements are set on sewage sludge treatment and use, as well as the scheme of interaction between actors involved or engaged in the control of the field of waste management. One of the conclusions made in the report, about waste treatment in the Leningrad Region, is that there is an absence of options for processing the sewage sludge and recycling it, in this region.

Another report prepared by St.Petersburg State University of Economics (2014) contains information about the requirements set by Russian legislation for transportation of waste materials by road, railroad, and water transport within and outside the Russian Federation. The report also includes documents that must be completed when applying for certain permissions.

With regards to the utilization of deinking sludge in production processes and its pretreatment such as drying and incineration, permissions must be obtained from governmental bodies for the implementation of dangerous activity related to waste utilization. Considering sludge drying and incineration, permission regulating the maximum amounts of gaseous emission into the atmosphere must be granted, as well as performing an environmental impact assessment project.

4. ENERGY RECOVERY FROM DEINKING SLUDGE

Approximately one third of sludge generated at paper mills located in CEPI member countries was treated with energy recovery in 2003 (CEPI, 2005). In a study made at LUT in 2005, the generation of PPI waste in the Kouvola region was assessed (Hämäläinen, 2005). Three large paper and board manufacturers were included in this study. From their combined waste production, wood waste accounted for 58%, sludge-like waste for 25% and different types of ashes for 13%. The wood waste is easily incinerated and according to Hämäläinen (2005), in 2003 as much as 99% of wood waste was utilized mainly for energy recovery. It was stated by Hämäläinen (2005) that 90% of WWTP sludge and 80% of deinking residues can be utilized, as well.

In this chapter, possible energy recovery techniques used for deinking sludge treatment, which are also referred to as Sludge-to-Energy (StE) techniques, will be described. For the purpose of this chapter, technologies enabling deinking sludge conversion into energy carriers are considered as energy recovery. The techniques will include not only conventional recovery methods, e.g. combustion in grate boilers, but also ones considered to be potential in the future e.g. gasification and pyrolysis. Where possible, a description of the products left after the process and their utilization potential will be stated.

4.1. Combustion

Heating value is one of the most important parameters of waste intended for energy recovery. Higher (gross) heating value is determined in a bomb calorimeter from the total solids (TS) after drying. Net heating value in the arrival state (including moisture) is lower than the heating value on a dry basis, which is determined experimentally. The difference between higher and lower heating values is in the amount of heat that can be recovered from condensing water, which is formed from fuel hydrogen. Typical heating values, as well as ultimate analysis of several PPI sludge types are presented in Table 3.

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Table 3. Composition of sludge from various pulp and paper processes (bark is given for comparison).

Source/ Component	Solids, %	Ash on DB, %	Elements content on DB, %					Heating value on DB, MJ/kg
			C	H	S	O	N	
Kraft-pulp mill [2]	37.6	7.1	55.2	6.4	1.0	26.0	4.4	24.1
Kraft-pulp mill[2]	40.0	8.0	48.0	5.7	0.8	36.3	1.2	19.8
Pulp mill[2]	42.0	4.9	51.6	5.7	0.9	29.3	0.9	21.5
Bleached pulp mill[2]	33.4	1.9	48.7	6.6	0.2	42.4	0.2	20.1
Mixed sludge, paper mill[1]	-	16.0	45.0	5.8	0.1	-	0.6	-
Mixed sludge, paper mill[4]	-	9.6	45.9	6.5	0.7	9.6	3.7	18.9
Deinking sludge[2]	42.0	20.2	28.8	3,5	0.2	18.8	0.5	12.0
Deinking sludge[2]	42.0	14.0	31.1	4.4	0.2	30.1	0.9	12.2
Deinking sludge[3]	51.2	54.8	26.0	3.3	0.1	-	0.4	6.9
Deinking sludge[4]	-	50.1	26.9	2.9	0.2	18.8	1.2	8.6
Recycled paper mill[2]	45.0	3,0	48.4	6.6	0.2	41.3	0.5	20.8
Recycled paper mill[2]	50.5	2.8	48.6	6.4	0.3	41.6	0.4	20.6
Bark[2]	54.0	3.5	48.0	6.0	0.1	42.1	0.3	20.3

[1] – taken from (Dahl, 2008);
[2] – taken from (Abubakr, et al., 1995);
[3] – taken from (Gottsching & Pakarinen, 2000);
[4] – taken from (Niessen, 2002)

It is not specified in the source literature, used to compile the table above, whether the heating values are determined on a dry or as recieved basis. However, it can be seen from Table 3 that several PPI residues have heating values above 15 MJ/kg and those values are most probably either HHV or LHV on a dry basis. Often, the residues of pulp and paper mills are dewatered and possibly also thermally dried to maintain the highest energy efficiency from incineration. It was stated by Tchobanoglous, et al. (2004, p. 1588) that heating values of WWTP sludge are in the same range. Raw primary sludge (25 MJ/kg) is comparable with wastepaper and kraft mill rejects, whereas anaerobically digested sludge (12 MJ/kg) is comparable with deinking sludge. This is to be expected as deinking sludge typically has a relatively high proportion of ash compared to organic content, which is also true for anaerobically digested sludge. Therefore, it has been the most common procedure in the PPI to exploit the residues with high organic content in multifuel boilers with or without additional fuel.

Grate furnaces, fluidized bed boilers (FBB), multiple hearth furnaces (MHF) and rotary kilns are applied for sludge combustion, while grate type boilers and FBB are those used most often (CANMET, 2005) and thus will be described in this chapter.

Grate type furnace

Sludge incineration is commonly implemented as a co-combustion process with bark at PPI plants. Among all grate types, travelling ones have become the most popular for bark incineration. The amount of sludge that can be fed into the furnace depends on the particular characteristics of the boiler, as well as the composition of both bark and sludge. Sludge can be added if the moisture content (MC) of the bark is not higher than 55%. If the MC of the bark is 50%, then about 20% of the heat input of the furnace can be from deinking sludge. However, in vibrating or reciprocating furnace types, it is possible to supply hotter air to the combustion process and, thus, to increase the amount of sludge incinerated. (CANMET, 2005)

It is worth mentioning that recycled fiber factories with installed deinking units are often located separately from pulp and paper mills so that co-combustion of deinking sludge with bark can be challenging, and requires analysis of the local market in order to find a location for deinking sludge incineration. Moreover, multifuel boilers of pulp and paper mills located nearby can already be overloaded with waste so that the use of deinking sludge would be practically unfeasible.

Fluidized bed boiler

Fluidized bed boilers allow mono-combustion of sludge with moisture content of 58-62%. By doing so, no supplementary fuel is required by the process while no heat output can be achieved, meaning that the system is well balanced in terms of heat input/output. If the MC of sludge is lower, an in-bed cooling surface can be installed or a modification of FBB called circulating FBB could be used for additional heat removal. Generally speaking, this type of incinerator is more appropriate for deinking sludge energy recovery. The drawback could be the price of such installation, which is higher than the price of a grate boiler. (CANMET, 2005)

Ash utilization

In the study by Hämäläinen (2005) concerning waste from PPI in Kouvola, it was stated that ash from incineration and green liquor are the most difficult PPI waste to be utilized. In 2005, the most potential utilization targets for ashes were in cement production, in excavation works and as forest fertilizers. Later, the subject was also studied experimentally at LUT by Anttila (2008) who stated that fly ash from wood waste incineration was indeed applicable as a forest fertilizer, as excavation material, as well as in cement production. Concentration levels of nutrients in fly ash were very suitable for forest soil improvement and fertilizing. It was, however, stated that if the amount of peat in the fuel mix increases, it is better to utilize the ashes in the cement industry instead. In the production of cement, it is probably best to use the wood-based ash together with ash from coal incineration. As a conclusion, Anttila (2008) recommended that technologically the most suitable way for ash utilization is its use as a forest fertilizer during summer, and in cement production during winter.

Previously, the research projects EcoInfo and EcoRoad implemented in a co-operation between LUT, SPbSTUPP and Saint Petersburg State Polytechnical University have considered the use of bottom and fly ashes from JSC Svetogorsk, currently International Paper, as well as repulping flotation reject from the SCA Hygiene Products Russia mill and secondary sludge from JSC SPb KPK plant in road construction. Other types of waste materials were also considered. More information on the results can be found in the publication by Saint Petersburg State Polytechnical University (2008). It was recommended that the ashes should be used as binding materials in the construction of roadbeds. (Saint Petersburg State Polytechnical University, 2008). However, the road reconstruction projects in the region have not proceeded and thus other ways of recovery are needed.

4.2. Anaerobic digestion

It was stated elsewhere (Carrère et al., 2010; Luostarinen et al., 2011) that the efficiency of anaerobic digestion processes in general and the biogas production from certain municipal and industrial sludge can be enhanced by various methods. The most commonly used methods are to increase the solubility of sludge and the availability of nutrients and organic content for microorganisms. For instance, the process called hydrolysis was studied extensively and was mentioned as significantly increasing the energy potential of slowly biodegradable substances. Typically, residues of PPI contain significant amounts of lignin, which is a compound that biodegrades very slowly. An anaerobic digestion process was employed at some pulp and paper mills, mainly for the treatment of WWTP sludge.

Recently, for instance, Hagelqvist (2013) studied biogas production from WWTPs and stated that the hydrolysis process will enhance biogas production from hemicellulose and lignin, which is promising for the increase of biogas production within the PPI. However, it was mentioned in the study that incineration of sludge is still almost certainly better in terms of energy balance than the use of all WWTP sludge for biogas production. According to Hagelqvist (2013), the best overall energy balance in a pulp and paper mill was achieved with separate primary and secondary sludge treatment; thus, the primary sludge with high lignin content would be dewatered and incinerated, if it was not possible to reuse it locally at the mill, and the secondary sludge would be used in biogas production.

4.3. Pyrolysis

As a thermal treatment method, pyrolysis takes place at temperatures of 280-850°C in complete absence of oxidizing agents. In general, pyrolysis can be fast, slow, and medium depending on waste residence time and the products being obtained. Fast pyrolysis results in the maximum yield of liquid, while the slow one yields mainly char. Medium pyrolysis results in the generation of solid, liquid, and gaseous compounds. It is worth mentioning that it is better not to apply slow pyrolysis to feedstock with high ash and low fixed carbon contents since a considerable amount of char requiring utilization will be generated.

The pyrolysis process has been intensively studied for PPI sludge treatment and utilization within the last decade. Ojanen (2001) discussed pyrolysis as a technology which makes possible utilization of the organic content of sludge to produce liquid fuels. The required organic content of the sludge was discussed as being in the range of 40-80%.

Ouadi (Ouadi, 2012) analyzed the composition and characteristics of products obtained from pyrolysis of deinking sludge generated at two different paper mills with a composition similar to deinking sludge generated at the case study paper mill. The results showed that the generated bio-oil had a high heating value of 36-37 MJ/kg. However, the largest share of the products from pyrolysis was solid residue, which accounted for 79 wt-% of the total products. The residues had a very low heating value of 3-5 MJ/kg.

Lou, et al. (2012), for instance, conducted experimental tests with deinking sludge pyrolysis. It was stated by the authors that the pyrolysis process resulted in the generation of about 30% gaseous compounds and 24% bio-oil. The amount of solid residues was 46% which is two times more compared to the 15-25% of solids achieved in the pyrolysis of sewage sludge, which was more extensively discussed by Fonts et al. (2012). This is of course to be expected, because the ash content of deinking sludge is much higher than that of sewage sludge. The reason why pyrolysis is still a viable option for deinking sludge utilization is that the final products generated by the process may be more valuable than the originating waste stream. This is especially the case if it is possible to obtain valuable chemicals, such as acids, esthers, toluene, etc. It was stated by Lou et al. (2012) that “pyrolysis products of deinking sludge mainly were aromatic hydrocarbons and a small amount of acids, i.e. styrene, toluene, benzene, etc. Among of them, the relative content of styrene was up to 57%. From the property of pyrolysis products, the compounds play an important role both as raw material in fundamental organic chemical industry and as intermediate in fine chemicals, and have high quantity of heat value to apply in fuel industry.” (Lou et al., 2012).

4.4. Gasification

Gasification is seen as a promising option to treat waste originating from PPI mills, although only a few installations are in operation currently. During gasification, organic matter contained in sludge is partially oxidized leading to the generation of so-called syngas that can also be referred to as producer gas or product gas. The gas mainly consists of CO, CO_2, H_2, CH_4, H_2O, and N_2, and can be used for electricity or heat generation. The calorific value of the produced syngas is not high and ranges between 3.7-9.7 MJ/Nm^3 if air or oxygen are used in the process (Xu and Lancaster, 2009).

For gasification of biomass and waste, three main types of reactor configuration exist, namely, a fluidized bed gasifier, an entrained flow gasifier, and a fixed bed downdraft gasifier. A typical gasification application for paper industry waste feedstock could be a CHP plant with an electricity output of approximately 500 kW_e (comprising of two 250 kW_e gasifier units). Around 12 000 t/a of sludge on a dry basis would be required to reach such an output (Ouadi, 2012).

In addition, it is recommended to dry the sludge until an MC of only 10% is reached in order to achieve maximum energy potential from the sludge (CANMET, 2005). Another product left after the process is ash or char, which will require further utilization.

Gasification of deinking sludge was studied by Frederick et al. (1996), who showed that the total efficiency of deinking sludge gasification can be as high as 70%. The total efficiency was calculated as the heating value of syngas plus the energy available for steam generation divided by the total energy input. The syngas produced had a calorific value of 2.6 MJ/Nm^3. The energy required for the drying unit operation was 204.7 MJ/t of sludge on a dry basis. Ash left after the process was not suitable for utilization as an admixture in the cement production process.

5. MATERIAL RECOVERY FROM DEINKING SLUDGE WITH RAW MATERIALS SUBSITUTION

For the purpose of this chapter, every utilization possibility that implies substitution of ordinary raw materials, which can be accompanied with simultaneous fuels substitution with deinking sludge, will be considered as material recovery. Utilization possibilities where deinking sludge is the only raw material are described in the next chapter. Such utilization possibilities differ from material recovery in the way that they require additional facilities for sludge utilization instead of using already existing ones, as in material recovery.

The properties of deinking sludge have been presented in various publications, and it is to be noted that the properties and the composition of deinking sludge are highly dependent on the composition of the waste paper used for paper production, as well as the properties of the paper being manufactured. Deinking sludge is a mixture of fillers and pigments, fibers, fiber fines, printing inks and adhesive components. Its dry matter content is normally within the range of 38-62%. The ash content of deinking sludge on a dry basis varies from 36 to 67%. The composition of typical deinking sludge from tissue production is presented in Figure 6. (Göttsching and Pakarinen, 2000) The typical values for trace heavy metals detected in deinking sludge, WWTP sludge, and soil are presented in Table 4.

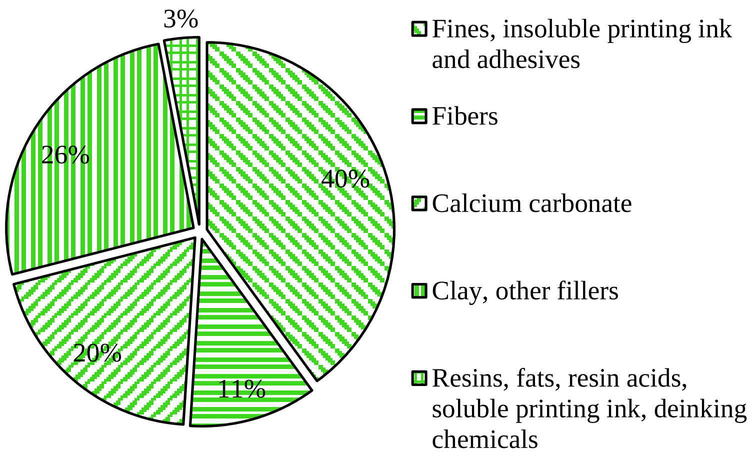


Figure 6. Composition of dry substances in deinking sludge from tissue paper production (Göttsching and Pakarinen, 2000).

This project is co-funded by the European Union, the Russian Federation and the Republic of Finland.

Generally, utilization of the possibilities of deinking sludge may benefit either from high mineral content of the deinking sludge or fibers. If deinking sludge is intended to be used in the production of corrugated material, hardboard, and insulation board, it is better to have a higher amount of fibers in the mixture. Long fibers contribute to the strength and flexibility of the final product, whereas mineral content may provide hardness and low biodegradability that are typically beneficial in construction materials. On the other hand, a high ash content may be desired in the production of bricks, cement, and building blocks (Krigstin and Sain, 2008; Kujala, 2011)

Table 4. Contents of typical pollutants in deinking sludge, municipal sludge and soil (IPPC, 2001, p. 251).

Component	Unit	Deinking sludge	WWTP sludge	Average soil concentration
Cadmium (Cd)	mg/kg_{DS}	0.02 -1.54	< 0.1	0.01-2
Mercury (Hg)	mg/kg_{DS}	0.1 – 0.9	< 0.1	0.01-5
Copper (Cu)	mg/kg_{DS}	64 -345	40	15-40
Zinc (Zn)	mg/kg_{DS}	34 – 1320	250	50-100
Lead (Pb)	mg/kg_{DS}	9.5 – 79.4	30	15-30
Nickel (Ni)	mg/kg_{DS}	< 10 – 31	10	15-30
Chromium (Cr)	mg/kg_{DS}	4.8 – 96.6	10	50-200
Volatile solids	% of DS	33 – 64	48	-

Several scientific studies have been published about the utilization of deinking sludge in various applications, some being more suitable than others. Lastly, such ways of utilization as landfill barrier material, reclamation of mine sites and similar ones are not considered as sustainable utilization methods. The reason for this is that deinking sludge contains valuable materials and can be used for manufacturing of products with high added value.

5.1. Cement and cement-based products

5.1.1. Cement

Cement manufacturing can be done by a dry, semi-dry, semi-wet, or wet method. In the dry method, all raw materials consumed are ground into powder provided that the moisture content of the raw meal is low. In semi-dry and semi-wet processes, water is used for raw meal preparation. In the wet process, raw materials are ground in water to form a slurry that is either directly fed into a rotary kiln, or dried before being sent to the rotary kiln. It is worth mentioning that the dry method is considered the method with the highest production and energy efficiency, while the wet method is an old fashion method rarely used nowadays.

Regardless of the manufacturing method, the basic raw materials in the production of cement are limestone, primarily consisting of $CaCO_3$, clay, sand, and iron ore. The proportion of limestone and clay in raw meal varies from 80 to 90% and 10 to 15%, respectively. In addition, silica and aluminum are required for the process to produce high quality cement (European Commission, 2013a).

When raw materials are subjected to temperatures of 1400-1500°C, they form clinker constituents such as alite and belite (Göttsching and Pakarinen, 2000). A hard substance coming out of the kiln is called clinker and is mixed with gypsum to produce Portland cement. The gypsum prevents the cement from flash setting. Usually, the proportions are 95% of clinker to 5% gypsum (European Commission, 2013a).

Deinking sludge ash, as described in the report written by SPbSTUPP (St.Petersburg State Technological University of Plant Polymers, 2013), contains mainly calcium, aluminum and iron oxides. Thus, the sludge could be a beneficial material to the process, theoretically. According to Göttsching and Pakarinen (2000), both deinking sludge and deinking sludge ash can be used as secondary raw materials in cement production. Deinking sludge ash from fluidized bed combustion can also be used as a hydraulic additive to cement clinker.

Champion Internationals at Hamilton in Ohio, U.S., used its sludge and boiler ash as fillers in cement manufacturing (Glenn, 1997). The sludge used for Portland cement manufacturing was primary sludge from a non-integrated paper mill. The sludge was dried in a rotary dryer to an 85% solids content (Hardesty and Beer, 1993). Since the wastewater and consequently the sludge originate only from the papermaking process, the sludge was expected to contain high amounts of inorganics and fibers. The inorganic content of the sludge was 40% clay and 19% limestone on a dry basis, while the fiber accounted for 30% of the dry basis of the sludge. Most likely, there was not much stickies and adhesives in the sludge making the drying and handling of sludge easier than sludge from a deinking process.

Some chemical compounds present in sludge may decrease the quality of cement. K_2O and Na_2O, as well as high Cl and S contents have been found detrimental to cement production. The influence of trace elements content in cement caused by sludge addition to the process was examined by Achternbosch et al. (2005), who concluded that the concentrations of trace elements in cement would increase. The maximum trace elements concentrations in Portland cement at present, according to the literature, are presented in Table 5.

Table 5. Maximum concentrations of trace elements in Portland cement (Achternbosch et al., 2005).

Trace element	MAX, ppm
Cadmium (Cd)	6
Mercury (Hg)	-
Copper (Cu)	98
Zinc (Zn)	679
Lead (Pb)	254
Nickel (Ni)	97
Chromium (Cr)	712

The problems of deinking sludge recovery in cement manufacturing are considered mainly economical, and caused by the high moisture content of sludge. High moisture content prevents the use of sludge in as-is conditions in cement manufacturing by a dry method, while it can be acceptable for a wet one.

5.1.2 Concrete additive

Concrete is a composite material consisting of an aggregate, usually sand or gravel, mixed with water and cement. Cement works in the mixture as a binder. Blawaik and Raut (2011) tested primary sludge as a concrete additive. The sludge was referred to as waste paper pulp in the article and its composition is given in Table 6.

Table 6. Composition of sludge utilized for concrete preparation.

Source	Elemental analysis, %												
	O	Ca	Si	Al	Mg	S	Ti	K	Fe	Na	Cu	P	Cl
	15.8	14.9	60.6	2.1	3.6	1.1	0.15	0.16	0.92	0.22	0.05	0.03	0.41
	Proximate analysis												
(Balwaik & Raut, 2011)	MC, %	Ash, %	Volatiles, %	Free carbon, %	HHV, MJ/kg								
	5.8	40.6	44.7	8.9	9.9								
	Ultimate analysis, %												
	C	H	N	S	O								
	22.2	2.5	0.3	0.4	23.6								

Substitution of 5-10% of the originally used cement for concrete preparation was proven to be the most suitable mix proportion. If more than 10% of the cement is substituted by sludge then a gradual decrease in strength occurs. Moreover, the water absorption of the specimens prepared increased because of the sludge hydration process.

5.1.3. Cement mortar

Cement mortar is a paste used to bind blocks together in masonry. Fundamentally, it is a mixture of cement, hydrated lime ($Ca(OH)_2$), aggregate, and water. Studies about the use of both metakaolin produced during deinking sludge incineration and direct use of sludge in mortar products were performed. As discussed in the previous chapter, ash is already considered to be suitable raw material for the cement industry, but use of sludge, as such, is still limited.

Yan et al. (2011) have studied the use of deinking as an additive in cement mortar products and its effects on the physical and mechanical properties of mortar. The composition of deinking sludge in presented in Table 7. Cellulose is a known retarding concrete admixture and 20 wt-% of sludge in the mixture studied delayed the final setting time by a factor of 4.4. The compressive strength with 20 wt-% sludge was 62% of that of the reference, with 20.5 MPa, however, it was considered to be in the range of masonry product usage.

Table 7. Composition of deinking sludge used in cement mortar preparation.

Source	Component, %										
	SiO_2	Al_2O_3	Fe_2O_3	CaO	TiO_2	BaO	CuO	S_2O_3	Na_2O	LOI	MC
(Yan, et al., 2011)	2.0	2.0	0.11	2.7	3.9	0.65	0.31	0.14	0.04	16.9	68.0

The sludge did not appear to make any difference in long-term cement hydration or hardened paste properties. The sludge proportion increased the drying shrinkage and volume of permeable voids in the final product. As concluded in the study, up to 2.5 wt-% deinking sludge did not affect the physical or mechanical properties of mortar significantly and incorporating deinking sludge can be a favorable supplementary addition to the product. (Yan et al., 2011)

5.2. Ceramic products

Ceramic materials are those made of non-metallic compounds such as clay, quartz, and feldspar by a firing process. The ceramic industry includes the manufacturing of different tiles, bricks, refractory products, lightweight aggregate etc. However, sometimes products not containing clay are also called ceramics. The manufacturing processes of different ceramics are similar and consist of the following steps: mining of raw materials, their transportation to the plant, storage and preparation, shaping, drying, surface treatment, firing, and final treatment. (European Commission, 2007)

Manufacturing of ceramic products with deinking sludge addition was studied. Furlani et al. (2008) investigated the possibility of manufacturing ceramics from coal fly ash and incinerated paper mill sludge. At the same time, Asquini et al. (2008) conducted research on how to produce sintered ceramics from paper mill sludge and glass cullet. Lastly, Furlani et al. (2011) developed the work started by Asquini and analyzed the production of ceramics from deinking sludge, glass cullet, and several types of clayey materials. The composition of the materials used in the research articles mentioned above is compiled in Table 8. Generally speaking, the deinking sludge analyzed mainly consisted of Si, Al, Ca, and Mg oxides which comprised more than three quarters of the total sludge weight. In some cases, the sum of components is either above or below 100%, however, the data is presented in the original form.

Table 8. Composition of material used for ceramics production.

Data source	(Furlani et al., 2008)		(Asquini et al., 2008)			(Furlani et al., 2011)				
Component, %	Deinking sludge	Coal fly ash	Glass cullet	Deinking sludge	Deinking sludge	Glass cullet	Deinking sludge	Red clay	Yellow clay	Kaolin
SiO_2	29.1	60.0	65.5	23.0	26.5	63.4	23.0	58.3	59.5	49.8
Al_2O_3	16.5	20.1	6.0	17.4	15.2	6.4	17.4	18.2	17.5	39.1
Fe_2O_3	2.5	8.9	0.5	6.7	2.0	0.8	6.7	7.6	4.7	0.3
CaO	43.1	2.2	13.9	18.5	27.5	3.7	18.5	3.2	4.1	0.6
MgO	2.7	2.3	2.0	16.0	11.5	1.0	16.0	2.0	2.2	0.5
TiO_2	0.42	0.9	0.2	2.5	1.5	1.1	2.5	1.2	0.9	0.5
K_2O	0.1	2.1	1.1	1.8	4.5	1.7	1.8	2.8	2.2	1.5
P_2O_5	0.01	0.2	0.01	4.9	1.7	2.0	4.9	1.5	1.7	1.3
SO_3	0.04	2.1	0.01	0.7	0.3	-	-	-	-	-
Na_2O	0.03	0.6	8.6	2.9	4.7	5.4	2.9	1.3	2.4	1.1
LOI	1.78	0.6	-	-	-	0.3	-	9.9	11.2	12.3

Furlani et al. (2008) proved that manufacturing of ceramics from deinking sludge alone is not acceptable for the manufacturing of monolithic products since ceramics obtained in the study fractured. However, a blend of sludge with coal fly ash in the proportion of 75 wt-% and 25 wt-% correspondingly showed the best behavior. Overall, the main negative result was the high shrinkage during firing.

In the study (Asquini et al., 2008), two types of deinking sludge were mixed with glass cullet and sludge from inks production, while the addition of the latter component did not result in a good product. Out of all the combinations, the one containing 60 wt-% of deinking sludge and 40 wt-% of glass cullet resulted in the ceramics with the best properties. Furlani et al. (2011) analyzed how this mixture would behave if different clays or kaolin were added. The main finding was that kaolin addition increases the overall quality of the ceramics manufactured in the laboratory.

In the following subchapters, manufacturing of specific ceramic products with the incorporation of deinking sludge will be described.

5.2.1. Bricks

Wood sawdust, polymers, leather residues, mineral additives, polystyrene, coal dust, organic residues, paper-making sludge, and powdered limestone are known to be used in brick manufacturing (Sutcu and Akkurt, 2009). The production processes vary greatly, which is why there is no universal recipe for raw ingredients. (Rothwell and Eclair-Heath, 2007)

In brick production, fiber-containing waste is used to increase porosity and, thereby, the heat insulating properties of the final product. Aside from conventional paper mill sludge, it was found possible to use deinking sludge as a pore forming agent. Sludge as a pore forming agent can replace sawdust or pelletized polystyrene. In raw materials for brick production, grained clay and $CaCO_3$ can promote rheology. The $CaCO_3$ proportion in raw brick material can be 30 vol-% at highest. To produce bricks with an equivalent compressive strength, up to 20 vol-% of sludge, 10 vol-% polystyrene and 5 vol-% of sawdust can be used as pore forming material. (Göttsching and Pakarinen, 2000)

Raut et al. (2011) reviewed the literature dedicated to brick manufacturing with the incorporation of different waste types. It was indicated in the study that the compressive strength of bricks made with paper processing residues as described in (Sutcu and Akkurt, 2009) had almost the highest strength out of 19 brick compositions tested with different waste materials. At the same time, the water absorption of the bricks did not rise significantly. To produce bricks in a laboratory, ordinary raw materials used for bricks production and deinking sludge with the composition presented in Table 9 were preliminary dried and powdered. Then, the components were mixed together and dried again. Then, the blends were ground, granulated, and pressed to form specimens. The specimens obtained were left for atmospheric drying over one night, after which they were dried in an oven. Finally, the dried specimens were fired to produce bricks. The bricks containing up to 30% of deinking sludge still had a high enough compressive strength, while their thermal conductivity decreased by 50% compared to the conventionally manufactured bricks. Moreover, the use of sludge on an industrial scale was successful.

Table 9. Chemical composition of the dry matter of deinking sludge used in brick production.

Data source	Component, %										
(Sutcu & Akkurt, 2009)	SiO_2	Al_2O_3	Fe_2O_3	CaO	MgO	TiO_2	K_2O	P_2O_5	SO_3	Na_2O	LOI
	6.4	4.1	0.3	32.9	1.5	0.09	0.12	-	0.09		53.8
(Raut, et al., 2012)	Si	Al	Fe	Ca	Mg	Ti	K	P	Na	O	Ash
	60.6	2.1	0.9	14.9	3.6	0.15	0.16	0.03	0.22	15.8	40.6

Among the articles examined by Raut et al. (2011), there was one related to the utilization of Kraft pulp production residues (Demir et al., 2005). The production process for bricks proposed in (Demir et al., 2005) is basically the same as presented in (Sutcu and Akkurt, 2009). The main difference is the amount of sludge added and its nature. Demir et al. (2005) examined sludge from Kraft pulp production meaning that there was no filler present in sludge, i.e. the sludge was primarily of organic nature. According to the results, the most optimal amount of sludge for brick manufacturing was 2.5-5%.

Finally, Raut et al. (2012) investigated brick production from only deinking sludge and Portland cement. Deinking sludge with the composition presented in Table 9 was not dried prior to being mixed with the cement. The remaining production steps are similar to the ones presented above. Bricks with highest overall quality were obtained with the addition of 10% cement.

Rothwell and Éclair-Heath (2007) reported that untreated wet sludge from Aylesford was supplied to two brick manufacturers in the U.K. One customer demanded deinking sludge without wastewater treatment effluents since the biological activity can cause odors and be harmful to the brick manufacturing process. The customer incorporated sludge at a 2-3% addition rate to the bricks to replace fuel ash and assessed that the sludge can be used as an ash substituent for up to 7% of the total wet brick weight. Another customer used a 1% sludge addition to the overall brick weight. Both concluded that sludge did not change the appearance or physical properties of the bricks (Rothwell and Eclair-Heath, 2007). An especially valuable piece of information from the trials is that even though customers were first offered the filler fraction, they both agreed on using raw wet sludge.

To conclude, deinking sludge with high inorganic and lower organic content could be beneficial to the brick manufacturing process as opposed to other waste types. The general trend observed from the studies above is that despite the compressive strength of bricks produced with sludge addition being above the minimum required by standards, its water absorption capacity grows proportionally to the amount of sludge added, and that, in turn, can prevent bricks from being used in outdoor construction.

5.2.2. Lightweight aggregate

Lightweight aggregates (LWA) that also refer to as expanded clay aggregate are ceramics in the form of small balls with high porosity. LWA can be used as loose or cement bound material in the construction industry or horticulture. The product is manufactured mainly from clay, but the presence of slate, shale, bottom ash, sintered hard coal flue dust, and expanded glass is possible. (European Commission, 2007)

The possibility of manufacturing LWA with deinking sludge was assessed by Liaw et al. (1998). The production process used in the study included deinking sludge mixing with cement, pelletizing the blend obtained, and further drying. It is worth mentioning that there was no sintering or firing of the LWA produced. The main elements of sludge incorporated in the production process were Al and Si (Table 10).

Table 10: Composition of sludge used for LWA production.

Component, % / Data source	SiO_2	Al_2O_3	Fe_2O_3	CaO	MgO	Na_2O	K_2O	MC	LOI
(Liaw et al., 1998)	38.0	51.7	3.0	5.1	3.1	-	-	75.4	70.1
(Hu et al., 2012)	16.7	2.1	-	20.9	1.8	1.2	3.9	65.0	52.6

Testing of the material produced included determination of the volumetric specific gravity. The results from the analyses showed that the best mixing time was about 10 minutes when any cement/deinking sludge ratio can be used for material production to obtain lightweight aggregate with a volumetric density less than 1.0. If the material has been mixed for 40 minutes then only a cement/deinking sludge ratio of less than 0.6 can be used. Thus, the longer the raw meal is mixed, the more density is produced in the material produced. (Liaw et al., 1998)

In another study (Hu et al., 2012), paper sludge with the composition presented in Table 10 was used as the main raw material for LWA production. The production started with mixing the sludge with SiO_2, which is used to enable aggregate bloating and viscous glassy phase generation. This phase is needed to trap gases generated within LWA in order to maintain the required porosity of the final product. Then, the blend was dried and rinsed with H_3BO_3 to reduce the melting point. Finally, the blend was shaped and sintered. The highest quality LWAs were obtained when 18% of H_3BO_3 was added, the sintering temperature was 890ºC, and the sintering time was 30 min.

In a commercial process called Minergy LWA™, LWAs are produced from fly ash and paper sludge. First, fly ash and sludge are mixed together. Then, the blend is pelletized and dried. The core step is the sintering of the raw material in a rotary kiln. After sintering, the LWAs are cooled down, screened, packed, and supplied to the market. The facility is designed for 60 000 t of wet sludge and 90 000 t of fly ash to produce 100 000 t of lightweight aggregates. (Minergy Corporation Limited, 2011)

5.2.3. Tiles

Manufacturing of tiles with deinking sludge has received little attention in studies. Maschio et al. (2009) have studied fast firing of tiles with deinking sludge addition. Prior to being utilized, deinking sludge was dried and incinerated. Later, a blend containing 60% of deinking sludge ash and 40% of glass cullet was mixed with different amounts of natural red clay. The composition of the deinking sludge is presented in Table 8 under the reference (Asquini et al., 2008). The manufacturing process included milling and mixing of the raw materials, drying, sieving, pressing, glaze spraying on tiles, and single fast firing. The proportions of raw materials suitable for industrial production of tiles were 42 wt-% of deinking sludge, 28 wt-% of glass cullet, and 30 wt-% of natural red clay.

5.3. Wood-based panels

The following products are considered as wood-based panels: fiberboard including low density fiberboard (LDF), medium density fiberboard (MDF), and high density fibrerboard (HDF), particleboard (PB), oriented strand board (OSB), rigiboard (RB), flexboard (FB), softboard (SB), hardboard (HB), etc. The production process of these different panels includes drying of the wood particles or fibers, adding resin and other additives, blending, mat forming, pressing, cutting, drying, and finishing. (European Commission, 2013b)

5.3.1. Fiberboard

The use of deinking sludge in the production of medium density fiberboards has been studied by Geng et al. (2007) and Davis et al. (2003). In the study by Davis et al. (2003), 6% of phenol-formaldehyde resin was used, while the rest of the dry solids were fiber. Geng et al. (2007) used 12% resin with the fiber mixtures. A board made from glass and cellulose fibers and synthetic resin could consist of 20% of resin and 80% of fiber, of which 25-50% is cellulose, and the rest glass fibers (Bullock, 1984).

Davis et al. (2003) tested various different compositions, at highest the $CaCO_3$ content was 4% of the oven dried weight whereas the clay content was 20%. These proportions were determined regarding the composition of the deinking sludge in question. The deinking sludge consisted of 35% fines, 20% clay and 4% $CaCO_3$. The ratio of deinking sludge to virgin fiber was 50:50. Davis et al. (2003) states that the short fiber content of primary sludge fills the gaps between the virgin fibers providing the hardboard with increased bending strength. It was noticed that an increased clay content cause deterioration in all of the mechanical properties studied. The study concluded that the clay content should be decreased or eliminated with the preliminary treatment of the deinking sludge in order to improve the properties of deinking sludge /MDF board. (Davis et al., 2003)

In the study by Geng et al. (2007), spruce-pine-fir (SPF) fiber was mixed with deinking sludge and paper sludge (PS) at weight ratios of 3:7 or 7:3 and 12% urea-formaldehyde resin. Moreover, in this study, the fact that the high content of inorganic substances in deinking sludge could decrease the strength of fiberboard was discussed. A PS/SPF mixture, in the ratio of 7:3, fulfilled the requirements of the American National Standards Institute (ANSI) on mechanical properties set for an MDF grade of 120. In addition, a deinking sludge/SPF mixture with a weight ratio 3:7 met the same ANSI requirements. It was concluded in the study that the PS had more and longer fibers than deinking sludge and, therefore, had a more suitable fiber structure for fiberboard manufacturing, and provided MDF panels with better mechanical properties than deinking sludge. It was therefore considered to have excellent potential in the fiberboard manufacturing process. (Geng et al., 2007)

Davis et al. (2003) and Geng et al. (2007) both stated that inorganic content, especially clay, reduces the mechanical properties of MDF. This has been supported by Kordheili et al. (2012) who concluded that composite panels made of deinking sludge containing 45% fiber and 55% inorganic components and either polyethylene or urea formaldehyde had lower mechanical properties than commercially available MDF or PB. However, the physical properties such as the long term water absorption were better than that of MDF or PB.

A company called Homasote produces multipurpose panels for building and sound proofing purposes. The panel is produced from 100% post-consumer recycled newsprint with paraffin wax used as a binder (Greendepot, 2009). According to Davis et al. (2003), there is a plant in Turkey manufacturing hardboard incorporating primary sludge for furniture manufacturing.

5.3.2. Particleboard

Particleboard is a term for a panel manufactured from lignocellulosic, i.e. wood-based, particles or pieces combined with synthetic resin or other binder and bound under heat and pressure. The term particle in particleboard traditionally refers to chips or flakes, particles larger than individual fibers. In particleboard, interparticle bonds are created by the binder. Boards, which are mainly composed of lignosellulosic fibers, are called fibrous-felted board, respectively. In fibrous-felted products, internal bonds are created by interfelting fibers.

Taramian et al. (2007) conducted research with the aim of examining the possibility of particleboard manufacturing from paper sludge and wood particles. In the study, different compositions were analyzed and it was concluded that the highest results could be achieved if three-layer boards are manufactured with the addition of 15% paper sludge and 12% urine formaldehyde to the conventionally used wood particles. The major drawback to the idea was the decreased mechanical properties of the produced particleboards.

5.3.3. Millboard

Millboard is a generic term referring to various high density and thickness board products. It can mean hard board with high density, which is manufactured from 100% recycled fiber. The grammage of millboard varies from 1000 to 5000 g/m^2. It differs from corrugated board by caliber and contains no cavities, while usually millboard is manufactured by calandering. It is applied in e.g. the automobile industry, the shoe industry, furniture and luggage products. This type of use requires high fiber content and low ash content to guarantee the required caliber. (Rothwell and Eclair-Heath, 2007)

Trials using sludge as an additive in millboard production were run with the fiber fraction of Aylesford paper mill sludge from recycled newsprint production. The composition of the fiber fraction is presented in Table 11. (Rothwell and Eclair-Heath, 2007)

The incorporation of fiber fraction into the millboard in order to replace about 5% of recycled fiber obtained from old corrugated containers was successful. The final product was found to perform identically to the existing product and no influence on the specification of the final product was noticed. (Rothwell and Eclair-Heath, 2007)

Millboard can also refer to bituminized paperboard used in auto panels, or roofing felt which is paperboard impregnated with tar, bitumen or asphalt. Asphalt, or composite and shingle for roofing can for example be produced with organic felt mat, a base made of cellulose fibers of recycled paper formed into sheets. In shingle production, a roll of organic felt is mounted, dried, and presaturated after which it is coated with hot asphalt. (Hall, 2014)

Table 11. Composition and other characteristics of fiber fraction. (Rothwell and Eclair-Heath, 2007)

Characteristic	Typical specification
Moisture	10%
Fibrous and organic matter	47%
Approximal fiber content (of organic matter)	50%
Filler (clay and $CaCO_3$)	53%
Fiber length	2.0 mm
Gross caloric value	2490 kWh/tonne

The term can also refer to ceramic fiber millboard used in insulation. Ceramic fiber millboard consists of ceramic fibers, clay, insert fillers, and small amounts of organic or inorganic binders for better strength. Kaolin, a naturally occurring high-purity alumina-silica fireclay, is suitable for fiber raw material. Ceramic fiber millboard can be used in high-temperature insulation and heating applications. (Intersource USA Inc., 2014) This type of product could make use of the filler content, but should, most likely, have a low or even a zero content of organics to be fire proof.

5.3.4. Cement-bound boards

Cement-bound boards are the products used in interiors or exteriors of buildings. Cement-bound board are manufactured with the addition of cement as a binding material. Nevertheless, the boards are based on wood fibre contained in sludge and can be considered as wood-based panels. Moreover, the production process is similar to the ones used for MDF or PB manufacturing.

Fernandez, et al. (2000) discussed the possibility of cement-bound boards being manufacturing from deinking sludge. First, deinking sludge was soaked in water and then disintegrated before being blended with cement. Cement and deinking sludge were mixed in the proportions of 60:40 and 50:50. In addition to cement, calcium chloride, sodium silicate, and ammonium sulphate were introduced to the blend. After that, the blend was placed in a mould and pressed. Last, the boards produced were cured at room temperature for 28 days before being tested. The boards had mechanical and physical properties comparable to other similar products.

Furthermore, the manufacturing of cement-bound boards is a lab-scale proven process (Marsidi et al., 2011). Manufacturing of boards was done with the addition of up to 30% of sludge. Benefits from sludge incorporation are strength, fire resistance, and dimensional stability.

5.4. Stone wool

Traditional stone wool production process includes consumption of alumino-silicate rock, blast furnace slag, limestone, or dolomite. The production is performed at high temperatures of 2000ºC making waste utilization suitable. If a blast cupola is used as a furnace, then fibrous or dusty materials such as deinking sludge must be briquetted to prevent disruption of the blast air. Stone wool usually contains about 38-57% of silica oxide, 18-40% of earth alkaline oxides, 0.5-12% of iron oxides, 0-23% of alumina oxide, 0.5-5% of alkaline oxides, and 0.5-4% of titanium oxide. (European Commission, 2013c)

The world-leading producer of stone wool - Rockwool (ROCKWOOL International A/S, 2012) – took part in the Life project of the European Union called “From waste to resource” (Rockwool International A/S, 2007). It was stated in the project report that there is a great potential for waste recycling at Rockwool factories. Among the waste suitable for recycling, ash from sewage sludge incineration is listed. Thus, use of deinking sludge ash could be feasible as well, since its inorganic content is suitable for the stone wool production.

5.5. Plasterboard

As discussed previously, deinking sludge can contain up to 20% of $CaCO_3$. In an ideal case, it would be possible to separate the $CaCO_3$ from the sludge and purify it from contaminants in order to harness it for a desulphurization process, after which it could be oxidized to gypsum and used in the production of building materials. This would, however, require efficient separation processes that could preserve calcium carbonate in a viable state and make it free of impurities. Gypsum plaster is a building material used in a series of application, e.g. plasterboard, fibrous plaster, and mould. Drywall is a construction material consisting of thin panels of gypsum board. The primary component of these products is mineral gypsum in the form of powder. Water molecules in gypsum remain in a crystalline form before being heated to 100°C. To produce plaster, gypsum must be heated to remove water and then rehydrated, adding excess water and additives to form a slurry. To produce plasterboard, this thick slurry is then laminated between two paper boards.

The additives are used to change the density of the plaster or bind the plaster with cardboard. The board is then dried at temperatures up to 250°C to solidify the plaster. (Miller and Greig, 2008)

Paper sludge could possibly be utilized as an additive to the plasterboard. In theory, the fibrous material contained in sludge could improve the strength properties or provide a porous structure to the final product and, therefore, a lower density. According to Hall (2014), paper pulp is currently added to plaster to improve the tensile strength of the core, however, the composition and type of sludge is not mentioned.

Fiber proportion could be useful to increase the strength, but is possibly harmful to the fire-resistance of the plaster. When produced at high enough temperatures, the organic matter burns leaving pores in the product structure. However, almost certainly the drying temperature of 250°C is not high enough to enable organic combustion. Hall (2014) states that each additive of plaster can be a maximum of 0.5% gypsum powder, so the plasterboard production can, even in theory, provide reuse for only a limited amount of sludge.

Rothwell and Éclair-Heath (2007) ran trials on the filler fraction of Aylesford mill sludge to be used in acoustic plasterboard production. The material contained 57.5% of fillers, 31.7% of fiber, and 10.8% of water. At first the filler content of the mixture was 10%, but later filler content of 5-7% was found to be optimal. Moreover, in these trials, it was noted that the added material worked as a retardant, the setting time of mixed plasterboard being 11 minutes compared to the normal time of about 8. The results showed that incorporation of filler in plasterboard was successful.

6. CONVERSION OF DEINKING SLUDGE INTO A SINGLE PRODUCT

The conversion of deinking sludge into a single product is also in a way material recovery. However, this conversion requires new installations to be built in order to treat deinking sludge and this means higher economic costs and technological risks. Moreover, deinking sludge is the primary raw material in the utilization possibilities described in this chapter, without substitution of ordinary consumed raw materials and fuels.

6.1. Carbonization

The process is implemented in a rotary kiln under oxygen depleted conditions where thermal decomposition of preliminary dried sludge occurs. The operating temperature of the process is around 750ºC. Approximately 2/3 of carbon contained in the sludge is transferred to char, while the remaining carbon turns into gas with a low heating value. In the study by Mahmood and Elliot (2006), the char had a 50% carbon content and had high specific surface area which made it possible to use the char as an adsorbent. The gas generated could be used in the process to maintain a sufficiently high temperature without the use of external energy. Capital investments and operating costs of a carbonization unit are somewhat comparable to that of conventional incinerators.

6.2. Vitrification

Vitrification is a process of thermal destruction of materials at exceptionally high temperatures. The operating temperature can be up to 1500ºC which is higher than the temperature of an ordinary incineration process. Thus, ash left after vitrification is molten making it more stable. Vitrified ash can easily be utilized in the construction industry compared to conventional bottom or fly ash. However, the process is an expensive operation due to the need to maintain high temperature and cannot compete with ordinary sludge combustion. (Mahmood and Elliot, 2006)

This project is co-funded by the European Union, the Russian Federation and the Republic of Finland.

6.3. Supercritical water oxidation

Water at high temperatures (above 374ºC) and pressures (above 22.1 MPa) is known to be supercritical water, which enables effective destruction of organic substances. The process has already been applied to sewage sludge and deinking sludge treatment. Deinking sludge should not be dewatered so that content of the fiber is not higher than 6%. Along with the complete destruction of organic matter, the paper filler left after the process can be successfully reused in a newsprint paper manufacturing process (Ginder et al., 2001).

The process requires energy only at the start-up and in cases where the organic content of the sludge is lower than 3%. Otherwise, oxidation of organics contained in the sludge under pure oxygen conditions results in the generation of extra heat that is used for heating up deinking sludge fed to the process. Economic assessment has shown that the treatment cost of deinking sludge in a supercritical water oxidation installation with a capacity of 6 t/h would be about 10 €/t (Ginder et al., 2001).

6.4. Pozzolana

Pozzolanic material or simply pozzolana is defined as "materials that, though not cementitious in itself, contains silica (and alumina) in a reactive form able to combine with lime in the presence of water to form compounds with cementitious properties." (European Commission, 2013a). Pozzolanic activity means to react with lime under normal conditions resulting in the generation of viscous phases (MetaPro, 2011). Moreover, addition of 15% of pozzolana to cement makes bonds with lime, thus, preventing bloom generation that is known to be a problem in the construction industry (Building reconstruction, 2010). Pozzolana is used for pozzolanic cement production.

The process of pozzolana production from deinking sludge was studied by several researchers (Pera and Amrouz, 1998), (Frías et al., 2008), (García et al., 2008), (Vegas et al., 2006). It was proven in each article that deinking sludge is a valuable waste material for pozzolana production. Pozzolanic activity of deinking sludge is higher than that of commercially available metakaolins. The composition of the deinking sludge analyzed is presented in Table 12. The process of sludge transformation to highly reactive metakaolin includes its drying, incineration, calcination at 600-800ºC and further milling to homogeneous powder.

Table 12. Chemical composition of dry matter of deinking sludge.

Component, % / Data source	SiO_2	Al_2O_3	Fe_2O_3	CaO	MgO	TiO_2	K_2O	P_2O_5	SO_3	Na_2O	LOI
(García et al., 2008)	18.0	10.1	0.6	19.8	2.6	0.3	0.2	0.1	0.3	0.25	47.6
(Pera and Amrouz, 1998)	21.9	11.2	0.8	14.3	4.1	0.4	0.2	0.1	-	0.2	17.3

According to Pera & Amrouz (1998), the most optimal conditions for deinking sludge calcination are 700-750ºC for 2-5 hours. Moreover, Garcia et al. (2008) stated that the best results are achieved at 700ºC for 2 hours.

A real production plant was described in the patent (Hundebol, 1994). As stated in the patent, pozzolana is a material consisting of Al_2O_3, Fe_2O_3, SiO_2 or similar materials to those mentioned. The most obvious method of pozzolana production is thermal treatment in long rotary kilns as described in the patent (Hundebol, 1997). However, malodorous gases can be generated and additional fuels are required for the process.

Biermann & Bleijerveld (1996) in his patent proposed the use of fluidized bed boilers for pozzolanic material production at the same temperatures as in the previous patent in order to activate the pozzolanic properties of deinking sludge. Utilization of deinking sludge in the production of pozzolanic material had a positive influence on the properties of mortars prepared with pozzolana addition (Frías et al., 2011).

The production process of pozzolana from deinking sludge has been commercialized by MinPlus-CDEM Group, which has patented a product called TopCrete®, a stable, non-toxic mineral product. The product has high pozzolanic activity and only a few impurities, which makes its application in cement production preferred compared to other pozzolanic products. Moreover, the product has a high adsorption capacity that prevents emissions from the process where TopCrete® is used. It is worth mentioning that an SCA Hygiene paper mill located in Edet, the Netherlands, takes part in CDEM production. (MinPlus – CDEM Group B.V., 2014)

6.5. Composite materials

Polypropylene is a thermoplastic polymer used, e.g. in the production of carpets, plastics, containers, and automotive components. In a study by Girones et al. (2010), paper mill sludge with 30% fibers, 70% $CaCO_3$, and a moisture content below 15% was used as a filler and reinforcement agent for polypropylene composites production. During plastic processing, mineral fillers and fibers (e.g. fiberglass) are used to improve the mechanical properties and economic efficiency. The polypropylene was mixed with sludge at 25%, 37.5% and 50% based on dry weight. The mixture was granulated, homogenized, injected, and then conditioned. After which, tensile and flexual impact tests on the specimens were performed.

The results showed that the tensile strength of composites diminished as the share of sludge increased. There has been discussion on fiber hydrophilic by nature failing to provide effective reinforcement to the hydrophobic polypropylene matrix. This is why polypropylene based coupling agents have been used to form covalent bonds between polypropylene and natural fibers. The addition of a coupling agent (at a rate of 4%) was noticed to almost eliminate the decrease of tensile strength. Flexural strength increased with sludge content, even without a coupling agent. The study concluded that composites including 50% sludge and a coupling agent provided similar tensile and increased flexural strength compared to plain polypropylene and can be used as a substitute for mineral-filled composites in applications of low mechanical requirements (Girones et al., 2010). Theoretically, deinking sludge could be beneficial for the process if the hydrophilic nature of the fibers was noticed to be a problem, as most of the matter in deinking sludge is hydrophobic and, therefore, removed in the flotation process in the first place.

Ismail et al. (2008) have also studied paper sludge use in natural rubber composites. In the study, paper sludge was combined with a commercial filler, such as carbon black or silica, to produce a so-called hybrid filler, which could provide a better matrix and mechanical properties for the final products than the sludge alone. Partial replacement of paper sludge with carbon black improved some mechanical properties, while carbon black interacts with natural rubber. (Ismail et al., 2008) In the study, the origin of the paper sludge was not stated, but if carbon black can provide better interaction characteristics to the fiber-rubber matrix, then deinking sludge should be beneficial to the process; carbon black is often used in inks as a colorant and therefore is expected to be present in deinking sludge.

Recently, Huang, et al. (2012) evaluated how the addition of paper mill sludge influences the mechanical and rheological properties of high density polyethylene composites reinforced with wood fiber. In this study, different amounts of wood fiber were substituted with paper mill sludge. The sludge analyzed originated from pulping and paper recycling processes meaning that the sludge contained lignin and cellulose. It was revealed that an addition of 10% of paper sludge did not significantly change the mechanical properties of the composite. However, increasing the amount of paper sludge added deteriorates the mechanical properties of the composites, while improving its impact strength. Rheological tests showed that incorporation of the sludge does not affect the production process.

6.6. Animal bedding/ litter

The use of deinking sludge as animal bedding material is determined by the relatively high water adsorption capacity of deinking sludge that varies from 250% on a wet basis to 700% on a dry basis, which is comparable to the adsorption capacity of dry newspaper. Moreover, such use of deinking sludge is not dangerous for animals. (Beauchamp et al., 2002)

In the study by Beauchamp et al. (2002), the main elements present in the sludge were aluminum and copper. Their content in the blood of broiler hens and pigs did not increase during the experiments. For one experiment, sludge was dried on the floor for one week before the utilization. For another experiment, sludge was used in arrival conditions for pig bedding. In the latter experiment, red spots were identified on the pig legs which could be considered as the only negative effect on the pigs.

Another research results (Villagrá et al., 2011) showed that the MC of deinking sludge decreases with time as a result of atmospheric drying. Furthermore, deinking sludge as an alternative bedding material meets almost all the requirements for broiler hen bedding material.

Along with simple deinking sludge utilization as bedding material, it can also be pelletized as described by Bajpai (2012). In the study, sludge was pelletized for the production of kitty litter, poultry litter, and large animal bedding. The production process includes sanitizing, deodorizing, drying, and final pelletizing.

6.7. Composting

Composting of pulp and paper mill sludge was studied by Jokela et al. (1997). Overall, there was a need to adjust the C/N ratio to optimize the process, and it was concluded that the best C/N ratio was 22-35 for aerobic treatment. After the process, the dry solids content increased from 31.3% to 63.8% within 21 days. Anaerobic composting of deinking sludge and sewage sludge together led to biogas generation.

In another study made by Gea et al. (2005), composting was implemented without the addition of amendments or usage of bulking agents, which means a significant cost reduction for the process. Deinking sludge, despite its poor composting characteristics (high C/N ratio, low organic content) showed high performance during composting, thus, making deinking sludge composting an effective recycling option.

The composting degree of deinking sludge composting is higher for forced aeration than for mechanical pile turning. The reason for this is the higher temperature maintained in the pile, which was kept high even when the temperature of air injected was minus 20ºC. This means that the process is suitable not only for countries with a mild climate, but also for northern countries like Russia or Finland during the wintertime. (Brouillette, 1996)

In was proven by Zhou et al. (2005) that compost produced from pulp and paper mill sludge is a safe and valuable fertilizer in agriculture according to the tests. However, another research article (Beauchamp et al., 2002) stated that uncontrolled use of compost from deinking paper sludge is not favourable because some compounds contained in the sludge can accumulate in the environment and exceed the limits set by governmental standards.

The main drawback of the composting process is its duration that is measured in weeks. In addition, amendment of the C/N ratio will most probably be required to optimize the process, as well as the need to support the optimal moisture content of the compost pile. Moreover, the use of deinking sludge for composting is rather uncertain since the utilization of the compost product is questionable due to possible high content of heavy metals, toxic to the environment.

6.8. Synthetic calcium carbonate

CalciTech Synthetic Minerals Ltd. developed a technology enabling extraction of calcium carbonate from deinking sludge ash. The core step of the process is the dissolution of the ash to obtain calcium dissolved in water, which later reacts with carbon dioxide to generate calcium carbonate. Calcium carbonate can be later recycled within the pulp and paper industry for paper manufacturing. (CalciTech, 2014)

However, deinking sludge generated at a paper mill needs to be incinerated. In addition, it is not stated how the remaining solids contained in the deinking sludge would be utilized and how much wastewater is generated during the process.

7. SUMMARY OF UTILIZATION POSSIBILITIES

7.1. Review

Utilization possibilities revealed during the literature review are presented in Figure 7. Each possibility is described in the preceding chapters.

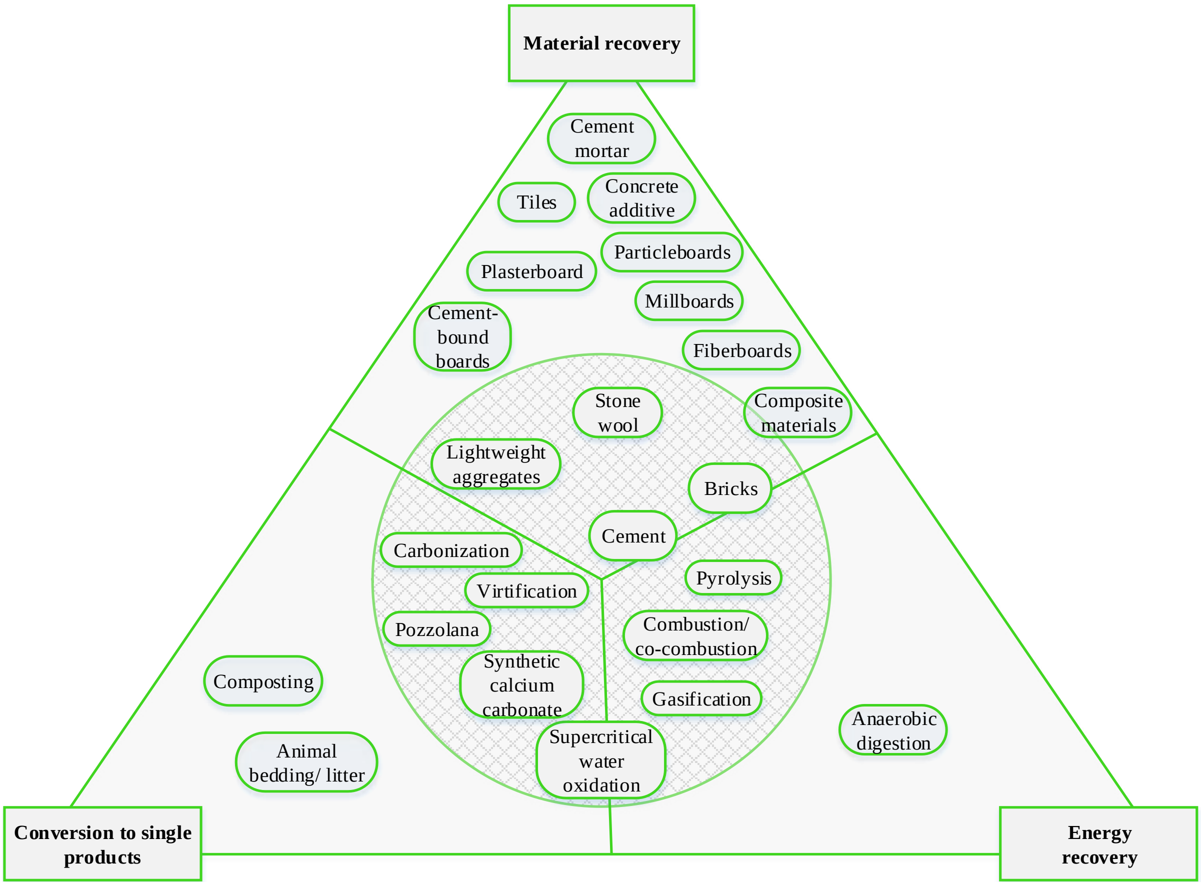


Figure 7: Processes successfully employed in deinking sludge utilization.

This project is co-funded by the European Union, the Russian Federation and the Republic of Finland.

7.2. Energy recovery

Energy recovery from deinking sludge differs from the thermal treatment of other waste streams generated by the pulp and paper industry because of its specific composition. High ash and moisture contents and low heating value make effective incineration of deinking sludge in ordinary grate furnaces problematic, without the addition of supplementary fuel. However, fluidized bed boilers enabling more efficient heat transfer in combustion processes make mono-incineration of deinking sludge possible. Nevertheless, the high ash content of deinking sludge results in large volumes of ash left after the combustion in any furnace type. Consequently, to decrease the negative effect on the environment, deinking sludge incineration without additional fuel, and deinking sludge ash recovery must be implemented.

Such processes as gasification and pyrolysis are seen as competitive alternatives to ordinary incineration technologies for thermal destruction of deinking sludge. Fewer emissions are released into atmosphere during sludge gasification. In addition, the efficiency of electricity generation from syngas produced during gasification is higher than that of incineration boilers. On the other hand, it is advised to dry deinking sludge before the gasification process to maximize the efficiency of syngas generation, which increases the total energy requirement of the process. In addition, char left after the process needs further utilization.

Pyrolysis as an energy recovery method allows the conversion of organic matter contained in deinking sludge into bio-oil, low-BTU gas, and char, whereas the yield of each component can be adjusted by changing the process parameters. Similar to gasification, deinking sludge should be dried first. Bio-oil can have a high heating value comparable to that of diesel, whereas char has a low heating value. However, another possibility to utilize char is to use it as an adsorbent due to its high specific surface area. Alternatively to gasification and pyrolysis, anaerobic digestion requires a high moisture content of deinking sludge. Nevertheless, anaerobic digestion of deinking sludge does not seem to be a viable option. First of all, the organic matter of deinking sludge is mostly cellulose, which requires pretreatment in order to make the nutrients available for microorganisms. Secondly, the amount of nutrients contained in cellulose is rather small and addition of supplementary nutrients will be required. Lastly, utilization of the sludge cake, left after the process, is needed.

7.3. Material recovery

Incorporation of deinking sludge into the production of cement-based and ceramic material seems technologically favorable, primarily due to the high content of inorganic matter contained in deinking sludge compared to other waste materials generated by the pulp and paper industry. Moreover, composition of deinking sludge inorganics is appropriate for such processes. Availability of calcium, alumina and iron oxides in deinking sludge makes its utilization in cement production most favorable. Utilization of deinking sludge will enable ordinary raw material savings at cement plants, whereas substitution of fuels is questionable and requires comprehensive studying. Cement manufacturing is a high temperature process enabling total destruction of deinking sludge organic matter, while most of the heavy metals contained in the sludge will be trapped within the cement clinkers, preventing its release into the environment.

Nowadays, cement is mainly manufactured by the dry method, meaning that the moisture content of deinking sludge supplied into the process must be as low as 5-15%. The amount of deinking sludge added has not been stated in previous research, however, the production capacities of cement plants are rather large so that the amount of deinking sludge added will not significantly influence the composition of the cement manufactured.

To avoid sludge drying and the consequent decrease of energy required for sludge treatment, sludge can be used in the preparation of concrete of cement mortar, where water is consumed. The amount of deinking sludge that can be used in concrete preparation ranges between 5-10% of the total cement used in the process, whereas that in cement mortar is only 2.5%. The results of concrete tests prepared using deinking sludge are sometimes controversial, stating that the sludge use exerts both a positive and negative affect on the final product quality. Nevertheless, most of the studies imply that the use of deinking sludge in cementitious products is preferable. It was also promising that none of the studies reported sludge fractionation to be obligatory since the sludge can be used as such.

In addition to cement and cementitous products, deinking sludge has been tested in brick and lightweight aggregate manufacturing processes. The role of sludge was to form the pores needed to decrease the density of the final product and consequently its thermal conductivity. Deinking sludge was also suitable for tile manufacturing.

Wood-based panels manufacturing with the addition of deinking sludge is another possibility for deinking sludge material recovery. Deinking sludge can be used as a substitution for other conventionally used fiber materials. It was experimentally proven that incorporation of deinking sludge reduces the mechanical properties of the panels manufactured, and increases its water absorption capacity.

7.4. Conversion into a single product

There are several processes known that can be used to successfully treat deinking sludge. During carbonization, deinking sludge is converted into char, which has a high specific surface area and can be used, e.g. as an adsorbent. Another high temperature process is vitrification. The process is aimed at deinking sludge incineration and consequent ash vitrification making it more stable. However, vitrification requires higher temperatures (around 1500°C) than combustion and, thus, requires more energy than the combustion process. Pozzolana production is similar to vitrification. However, the process is performed at the lower temperatures (around 800°C) needed to activate the pozzolanic properties of materials contained in sludge.

Supercritical water oxidation of deinking sludge was found to be economically and technologically feasible. The process allows the filler contained in deinking sludge to be recovered, while efficiently destroying organic matter. Another possibility for calcium carbonate recovery is to produce synthetic $CaCO_3$. However, the process has not been described widely and should be evaluated further in order to assess its applicability.

Recently, ever-increasing attention has been placed on the production of composite materials including ones based on deinking sludge. Several production processes have been described in literature and positive results were obtained. Deinking sludge being half comprised of wood fiber has been tested as an animal bedding material and shown its applicability for utilization in poultry and pigs farming. Another farming related application of sludge is compost production. The process has been successfully assessed and the results were positive with the main drawback being the duration of the process.

8. CRITERIA SETTING, SITES SELECTION, BOTTLENECKS EVALUATION

The search for alternative means for deinking sludge utilization, including the literature review, gained considerable attention during the overall study performance. As was clearly presented in the preceding literature review, there are numerous methods of effective deinking sludge utilization not only as an energy source but also as a raw material. However, several aspects that significantly limit the search area must be kept in mind, while seeking for real-world utilization alternatives.

First of all, the cost of the alternative deinking sludge treatment option must be comparable with the cost currently paid by the case study paper mill for deinking sludge landfilling. Second, only deinking sludge treatment in already existing installations/plants was assessed, thus leaving out conversion into single product possibilities, because of the need for the construction of new treatment facilities. Third and finally, the area of the search for potential utilizers of deinking sludge was constrained by the actual cost of sludge transportation from the case study paper mill to a potential utilizer. The search area included the North-West region of Russia and Finland.

The search for potential utilizers was performed with online databases. The following and most complete Russian databases were included in the study:

- all-Russian network of business communities “Rosfirm” (Rosfirm, 2014);
- business network “Navigator for Business” (Navigator for Business Network, 2014);
- Russian information network “Yellow Pages” (2014);
- Directory of companies of the Leningrad Region (2014).

The search was performed based on the product being manufactured. A similar approach was applied to the Finnish companies search.

All the companies identified during the search and fulfilling the requirements of the criteria set are discussed further in this chapter. It is worth mentioning that the companies will be presented and described regardless of whether there was cooperation established between a utilizer and the case study paper mill or not.

This project is co-funded by the European Union, the Russian Federation and the Republic of Finland.

The concluding chapter will explicitly state the reasons, i.e. bottlenecks, which could play a crucial role in the establishment of long-lasting cooperation. The bottlenecks will cover not only the technological applicability of the methods, but also the economic feasibility, which is inevitable in business operation planning.

8.1. Criteria for the alternatives selection

8.1.1. Current cost of deinking sludge treatment

Most of deinking sludge generated by the case study paper mill is currently being landfilled. The landfill site is located in Tammisuo, Viborg district, about 55 km distance from the case study paper mill. The landfill is managed by LLC "Rasem" which is a waste management company providing its service for the collection, transportation, and disposal of V hazard class waste only (Rasem, 2014). The landfilling fee includes the cost of sludge transportation to the landfill site and the gate fee for landfilling of 770 RUR/t (≈ 17.1 EUR/t[1]), and the fee for negative effect on the environment of 40 RUR/t (≈ 0.9 EUR/t) which makes a total of 810 RUR/t (≈ 18 EUR/t).

8.1.2. Transportation cost

The amount of deinking sludge landfilled annually is about 54 000 t on a wet basis, representing 150 t/day on average. However, the daily sludge generation rate can vary between 100-190 t, which can play an important role in the planning of an alternative utilization system. Deinking sludge is transported by trucks with a capacity of 15 t each. Thus, about 10 trucks per day are required to landfill the annual amount of deinking sludge.

Within the project implementation, a project partner JSC "Ecotrans" which is a waste management company providing waste transportation service among other services, was asked to estimate the sludge transportation fee. According to "Ecotrans", transportation of one tonne of deinking sludge over a 200 km distance in a truck with capacity of 40 t would cost 10.6

[1] - in the report, RUR/EUR exchange rate is 45.

EUR. Thus, under such conditions, it is possible to transport sludge as far as 320 km from the case study paper mill without exceeding the actual landfilling cost, if there is no gate fee.

The bulk density of deinking sludge, which is quite light and “fluffy” in its original state, was determined to be 590 kg/m^3. The specific volume of the deinking sludge is approximately 1.4-1.7 m^3/t. Therefore, a truck with the capacity of 30 tonnes should have a volume of 43 m^3. On the other hand, if the maximum volume of the container would be for instance 40 m^3, the truck could transport 28 t of sludge.

In studies made in Finland, it has been estimated, presuming a 30 t load for a truck, that the transportation fee is 2.2 EUR/km, which is the total fee invoiced by the transport company. Therefore, a 100 km transportation of 30 t of sludge would be 220 EUR. This adds up to approximately 7.3 EUR/ton for a truck with a capacity of 30 t

Another possibility for sludge transportation assessed in this study was railroad transportation. It was revealed that there was no experience of deinking sludge transportation by railroad in Russia. Thus, the first step that would be required is to obtain the permission for sludge transportation from the railroad administration. However, if wood sawdust is considered as the deinking sludge in the transportation cost analysis, then the transportation cost from the case study paper mill to Kolpino, a place closely located to a brick manufacturing mill, would range from 6.8 to 11.8 EUR/t depending on the railway vehicle type. This cost is for a case where the railroad vehicles are owned by either the case study paper mill or the sludge-utilizer, and does not include the operations related to sludge loading and unloading. Taking everything into account, it was concluded that sludge transportation by railroad is a rather challenging operation and will not be considered further.

8.2. Possible utilization sites

8.2.1. Cement plants, Finland

In total, there are two cement plants operating in Finland. Both cement plants belong to Finnsementti (CemNet, 2008). One of the plants is located in Parainen, which is outside of the search area, while another one is located in Lappeenranta, 45 km away from the case study paper mill. The latter cement plant consumes limestone as a major raw material for the production process. Limestone is quarried and preliminary crushed by the Nordkalk company (Nordkalk, 2014).

It was revealed that the supply of deinking sludge in arrival conditions is not possible, primarily due to its high moisture content. From the cement plant's standpoint, deinking sludge is considered as waste rather than a raw material, although its composition is suitable for the production process. Depending on the sludge feeding point, the sludge must be either dried or incinerated. If dry sludge is supplied then the gate fee for the treatment of one tonne of dry deinking sludge will be around 45 EUR/t. If deinking sludge ash is supplied, then the gate fee can be significantly lower.

8.2.2. Cement plants, Russia

There are three full-scale cement plants operating in the Leningrad Region. One of them, "Pikalyovskiy cement" (Eurocement Group, 2013), produces cement by a wet method which can be suitable for wet deinking sludge utilization. However, the cement plant is located in Pikalyovo, about 440 km away from the case study paper mill making transportation a limiting factor.

The other cement plants, "LSR Cement" (Gruppa LSR, 2014) and "Cesla"(HeidelbergCement, 2014), are located in the city of Slantsy. Both cement plants manufacture cement by a dry method. The plants are located at a distance of 350 km from the case study paper mill, which is slightly more than the search area determined. For the study, it was assumed that the gate fee for deinking sludge treatment in these cases could be around 10 EUR/t.

In any of the cement plants located in the Leningrad Region, amount of the sludge consumed accounts for not more than 2.5% of the total raw material consumption, meaning there are low risks for negative effects on the cement composition due to sludge utilization (Deviatkin, 2013).

8.2.3. Lightweight aggregate plant, Finland

Lightweight aggregates (LWAs) are manufactured in a plant located in Kuusankoski, about 135 km away from the case study paper mill. The main raw material in the production process is clay with a MC of around 50%. In addition to clay, organic materials like heavy or waste oils are utilized to enable pore formation when the raw meal is heated to 1100ºC in a rotary kiln. In the process, deinking sludge can be used as a pore-forming agent. It was identified that the moisture content of sludge is still high and should be decreased for more thorough mixing with the clay. Another reason for sludge drying is to prevent its freezing during the wintertime. The gate fee for the deinking sludge treatment would be low or even absent.

8.2.4. Lightweight aggregate plant, Russia

There is only one lightweight aggregates plant located in the Leningrad Region – "Keramzit". The plant is located about 220 km away from the case study paper mill. It was identified that there was an earlier attempt to utilize the deinking sludge at the plant and the result was negative. As was stated by the production manager of the plant, first, there was no positive effect on the LWAs produced and, second, deinking sludge utilization caused a strong offensive odour that resulted in complaints from the workers.

8.2.5. Brick plants, Russia

In the Leningrad Region, ceramic bricks are mainly manufactured by "Pobeda LSR" brick corporation. The corporation owns two mills located in Kolpino and Otradnoe which are located 220 and 230 km from the case study paper mill, respectively (LSR-Stenovie, 2014). The plants produce several brick types including ones with high porosity. As regards the brick manufacture, deinking sludge can be seen as a valuable material due to its high fibre content that will generate pores during the bricks sintering process at high temperatures. The amount of deinking sludge accounts for only 3.7% of the total raw materials consumed by the mills as was estimated in (Deviatkin, 2013).

Deinking sludge generated at the case study paper mill has already been supplied to the brick plant located in Kolpino. However, it was not feasible to continue deinking sludge utilization there due to logistics: deinking sludge was requested to be supplied at an exact time, which was difficult to perform due to the long distances, and possible traffic congestion on the way.

8.2.6. Stone wool plant, Russia

Within the search area, stone wool is only manufactured at the "Rockwool-North" plant (Rockwool International A/S, 2014). The mill location is beneficial for the project since the distance between the case study paper mill and the stone wool plant is only 55 km. The main raw material consumed by the plant is alumina-silicate rock, i.e. basalt, dolomite. However, according to the mill representatives, deinking sludge could substitute cement used at the factory. Such a substitution is possible since deinking sludge ash possesses pozzolanic properties.

To enable deinking sludge feeding, the sludge must first be incinerated. Ash left after the incineration should to be briquetted or can be used for briquetting other raw materials. Deinking sludge analysis made by the plant representatives has shown the sludge ash to be applicable for the process. If ash is supplied for the process, then no gate fee or a low gate fee will be charged for the treatment.

8.2.7. Stone wool plant, Finland

There is one stone wool manufacturing plant located in Finland that is close enough to the case study paper mill (45 km) – "Paroc". The plant uses similar materials to the Russian stone wool manufacturing mill. However, the plant is to be closed in the near future meaning that no possibility for further cooperation exists.

8.2.8. Medium density fibreboard plant, Finland

Another possibility assessed was the utilization of deinking sludge in the production of medium density fibreboards. The MDF is manufactured at Mellano Oy plant located at a distance of about 300 km from the case study paper mill. According to the plant production manager, they are interested in the production of MDF from different materials, but there are presently no resources that can be allocated to this research.

8.2.9. Wood-based insulating material, Finland

Ekovilla is a company producing insulating material from wood fibres coming from recycled paper. Thus, it was assumed that there is potential for deinking sludge to be utilized in that process. The plant is located in Kuusankoski about 135 km from the case study paper mill. According to the CEO of the plant, a material similar to deinking sludge has already been tested, however, it did not lead to cooperation. Nevertheless, it might be possible to return to the topic later when the company has obtained additional resources.

8.3. Evaluation of bottlenecks in selected methods

For the purpose of this report, such constraints or limitations that totally or partly prevent the utilization of deinking sludge in as-is conditions by the methods preliminary identified are called bottlenecks. While searching for suitable deinking sludge utilization locations and analyzing them, it was noticed that there are general bottlenecks that can be applied to each utilization method assessment, as well as site specific ones.

8.3.1. General bottlenecks

There are several general bottlenecks that were discovered within this research. From a broad perspective, the physical and economical availability of ordinary used raw materials or fuels is seen as the most limiting factor, which hinders cooperation activities. Quantitative disparity is another bottleneck in the implementation of an alternative deinking sludge management system. The disparity can be caused by differences between the supply of deinking sludge, i.e. amount of sludge generated and demand for it, i.e. treatment capacity of utilizers. If the supply of deinking sludge exceeds the demand on the sludge at a certain mill, then a paper mill will need to find another utilization site. If it is the other way around, then the interest of the deinking sludge utilizer can be significantly reduced.

Being more specific, the absence of storage space is another bottleneck. Of all the companies, none had a space for temporary deinking sludge storage, and there was no possibility of storing the deinking sludge with the other raw materials consumed.

8.3.2. Method-specific bottlenecks

Other factors limiting deinking sludge utilization in as-is conditions is its high moisture content. It is important for cement, LWAs, and brick manufacturing processes that the deinking sludge moisture content is not higher than 5-15%. This is important not only because of the technological problems that can arise, but also the increasing heat requirement of the processes due to the utilization of wet deinking sludge. For stone wool manufacturing, a bottleneck is caused by the organics contained in deinking sludge. Only sludge ash can be incorporated in the process.

Overall, the composition of deinking sludge was not seen as a limiting factor. Mostly, deinking sludge accounts for a small percentage of the raw materials consumed so that the little variation caused by deinking sludge addition to the process is not a problem.

8.4. Chapter conclusions

It was concluded, provided the criteria chosen for the utilization methods selection, and the information obtained as a result of personal communications with the representatives of companies potentially able to utilize the deinking sludge, that the following companies could be assessed further in the research:

- cement plant, Finland — Scenario 1;
- cement plant, Russia — Scenario 2;
- LWAs plant, Finland — Scenario 3;
- stone wool plant, Russia — Scenario 4.

The technical applicability of deinking sludge utilization in Scenarios 1 and 4 was approved during negotiations with the companies' representatives, while that in Scenarios 2 and 3 was studied experimentally by STUPP and LUT Energy, respectively. The experimental setup of LUT Energy is described in Annex I of the report.

The companies that were excluded from the forthcoming economic and environmental assessment, as well as the reason for the exclusion, are presented in Table 13.

Table 13. Reasons for the exclusion of certain companies from the economic and environmental assessment within the EMIR project.

Utilization site	Reason for exclusion
Brick plants, RU	Negative experience of sludge utilization: problems with logistics
Lightweight aggregates plant, RU	Negative experience of sludge utilization: offensive odor during utilization
Stone wool plant, FI	Upcoming closure of the plant
MDF, FI	Not enough resources for cooperation
Wood-based insulating, FI	Not enough resources for cooperation

9. ECONOMIC EVALUATION

Having identified several potential utilizers of deinking sludge, it is essential to evaluate the economic viability of each method chosen. There are several system analysis tools that can be applied to evaluate and compare different alternatives from an economic standpoint. However, cost-benefit analysis (CBA) has been accepted as the most suitable tool for economic assessment.

A complete CBA of deinking sludge utilization methods can be found in (Deviatkin et al., 2014), whereas, the main ideas of the assessment and the conclusions are presented here. The CBA was implemented in situations where all the deinking sludge would be utilized in different scenarios. The CBA is based on quantification and comparison of direct and indirect costs and benefits within the system. The costs included in the study are the gate fee for the sludge treatment, the cost of pretreatment equipment needed, legislative costs, and the transportation. On the other hand, benefits included avoided landfilling fees and earnings from possible sales of electricity generated during sludge incineration.

The CBA results clearly indicate which utilization possibilities are the most and the least economically viable when all the deinking sludge is utilized. The data related to each of the costs and benefits categories for each selected utilization possibility are presented in Table 15. Utilization of deinking sludge in the production of LWAs in the Finnish plant is the most favorable utilization option, even if the gate fee for the sludge treatment rises to 22 €/t or the cost of a drying unit will be higher than estimated. In contrast, the most unprofitable utilization possibility is the use of the sludge in the production of stone wool in the Russian plant due to the need to install an incineration plant.

However, it was stated during negotiations with the companies' representatives, that scenarios 2 and 4 could not treat an annual amount of deinking sludge. The amount of sludge utilized in each scenario is presented in Table 14. These amounts were further used in the environmental impact assessment.

Table 14: Expected rates of resources substitution with deinking sludge and amounts of deinking sludge utilized, as well as the minimum and maximum values of the substitution rates used in the sensitivity analysis.

Scenario	Resource substituted	Substitution rate, % of total consumption	Scenario	Amount of deinking sludge utilized, % of annual sludge amount
Scenario 1	Limestone	2.7%	Scenario 1	100%
	Petcoke	46%	Scenario 2	15%
Scenario 2	Heavy fuel oil	100%	Scenario 3	100%
Scenario 3	Limestone	0.89%	Scenario 4	15%
	Clay	1.9%		
Scenario 4	Cement	25%		

When using the amount of deinking sludge as presented in Table 14 in the economic analysis, the BCR of Scenario 2 decreased to only 0.16 making the scenario unprofitable. Similarly, the BCR of Scenario 4 with incineration of deinking sludge in an existing incineration plant decreases to 0.18. Thus, only Scenario 3 is economically acceptable.

Table 15: Costs and benefits of deinking sludge utilization possibilities.

Cost category, 10^3 EUR/a	Land-filling (RU), S0	Cement plant (FI), S1	LWA plant (FI), S2	Cement plant (RU), S3	Stone wool plant (RU)	
					New incineration plant, S4.1	Existing incineration plant, S4.2
1. Investment and operational costs						
1.1 Drying	0	47	47	47	0	0
1.2 Incineration	0	0	0	0	6 611	0
2. Gate fee	936	1 289	0	286	0	1 095
3. Regulatory						
3.1 Tax for landfilling	49	0	0	0	0	0
3.2 Permission for transboundary waste shipment (RU)	0	4.4	4.4	0	0	0
3.3 Permission for transboundary waste shipment (FI)	0	1	1	0	0	0
4. Transportation	-[1]	68	205	531	36	36
TOTAL COSTS	**990**	**1 400**	**260**	**860**	**6 600**	**1 100**
Benefit category, 10^3 EUR/a	Land-filling (RU)	Cement plant (FI)	LWA plant (FI)	Cement plant (RU)	Stone wool plant (RU)	
					New incineration plant	New incineration plant
5. Avoided landfilling fee	0	936	936	936	936	936
6. Incineration revenue	0	0	0	0	291	291
TOTAL BENEFITS	**0**	**940**	**940**	**940**	**1 200**	**1200**
BENEFITS/COSTS RATIO (BCR)	0	**0.67**	**3.6**	**1.1**	**0.18**	**1.1**
BENEFITS/COSTS RATIO (BCR) when 100% sludge is used in in S1 and S3, and 15% in S2 and S4	0	**0.67**	**0.16**	**1.1**	**0.03**	**0.18**

[1] – is included in gate fee.

10. ENVIRONMENTAL IMPACT ASSESSMENT

Before the actual environmental assessment was performed, it was anticipated that all the alternative methods would reduce the negative effect on the environment. However, it was not possible to know which particular method would result in the greatest reduction, if any. To answer these questions, it was beneficial to apply the life cycle assessment (LCA) methodology.

Life cycle assessment is a type of study that can estimate the environmental burdens of different processes and link them to real world environmental issues such as global warming or eutrophication. The methodology is widely applied in systems analysis in the waste management sector (Pires et al., 2011).

The current LCA study was performed in accordance with ISO 14040 and 14044 standards (SFS-EN ISO 14040, 2006; SFS-EN ISO 14044, 2006) that contain guidelines on how to perform LCA studies. In addition, the guidelines developed by the Institute for Environment and Sustainability (European Commission - Joint Research Centre - Institute for Environment and Sustainability, 2010a, 2010b) and the handbook developed by a research group led by Guinee (2002), were employed in order to strengthen the research.

The entire LCA study performed during the research has not yet been published, but the essentials of the study, namely, the steps of the LCA study, the production system under study, and the results obtained will be introduced in the report.

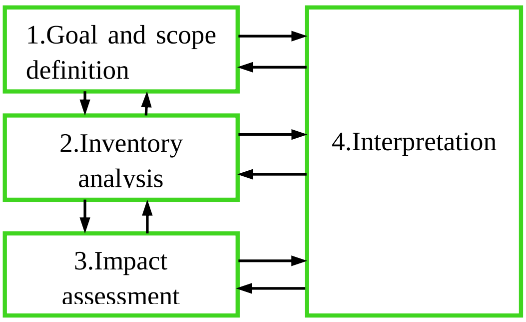


Figure 8. LCA stages (SFS-EN ISO 14040, 2006).

An ordinary LCA study includes the steps presented in Figure 8. The first step determines the reason(s) for the study and possible limitations to the life cycle stages, thus, specifying the direction of the research. The second includes the reporting of the data included in the research and information sources. The third step characterizes the life cycle inventory data under several impact categories such as global warming potential, acidification, etc. The last step – forth – explains why some alternatives exert greater impact on the environment than others.

10.1. Product systems and system boundaries

A life cycle assessment was performed for a certain product system that included the unit processes related to each scenario and was necessary for the system to perform its function. The product system of the current study is depicted in Figure 9.

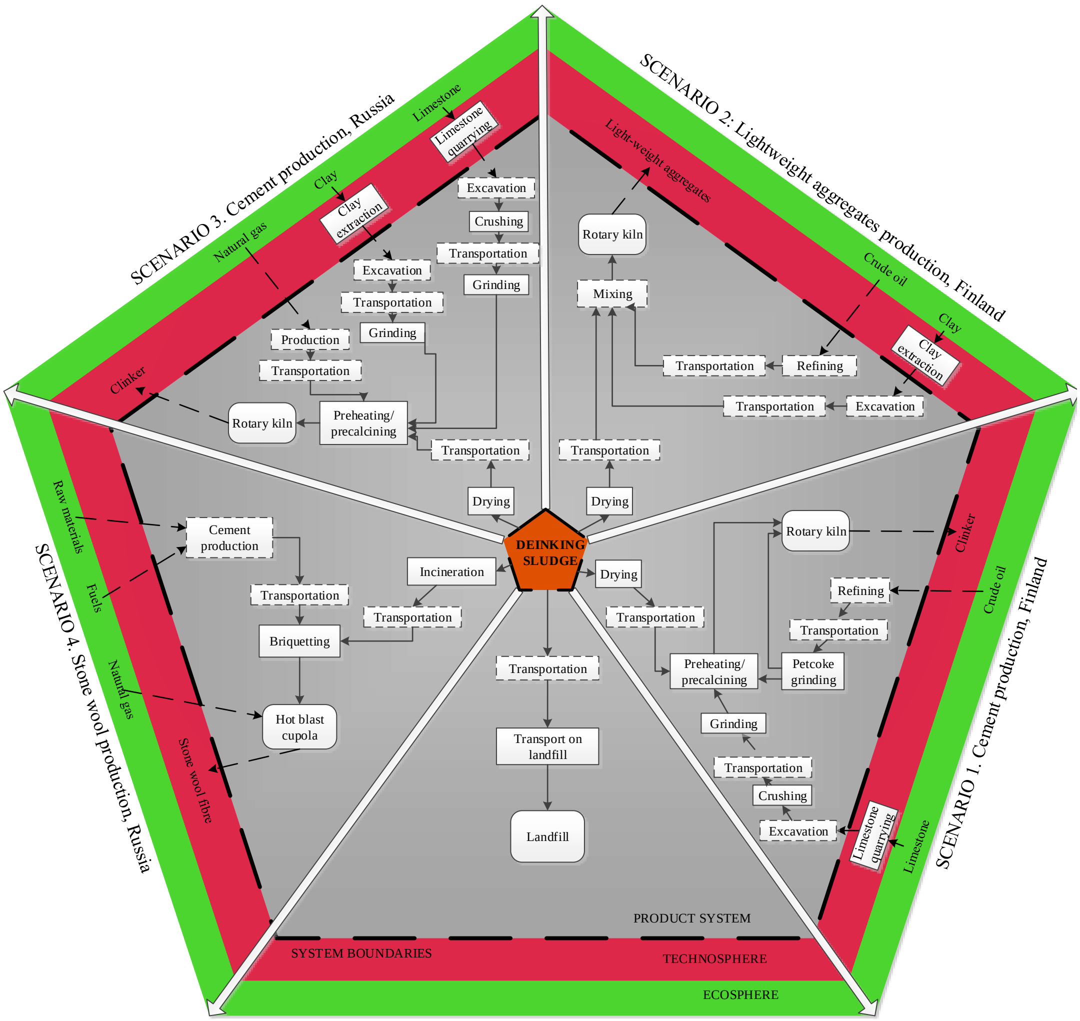


Figure 9. Product systems, unit process, and system boundaries.

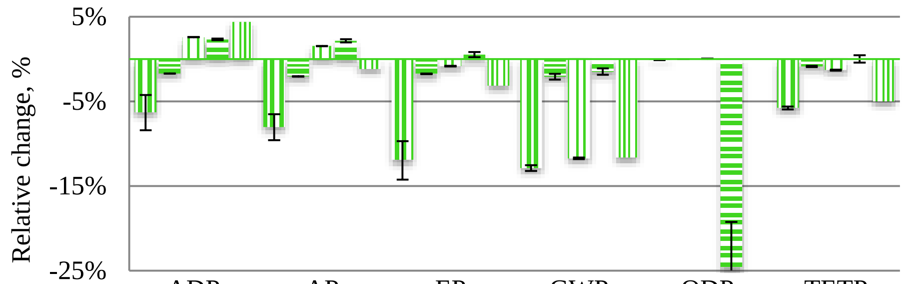
Figure 9 depicts five product systems, their boundaries, ecosphere, and technosphere. The system boundaries show which unit processes were assessed in the study. In addition to the processes displayed in the figure, electricity and diesel production were included in the study. More precisely each scenario is depicted in Figure 10.

Figure 10. Detailed flow-chart of the unit processes included in each product system assessed in the study.

According to the LCA principle, the assessment must include the elementary flows as much as possible, i.e. those coming from and released into the ecosphere in the form they are generated by nature. Where this is not possible, the use of flows that come from the technosphere is allowed. Figure 10 clearly indicates which elementary flows will be substituted by deinking sludge. Not only elementary flows will be substituted, but also consumption of electrical and thermal energy conventionally utilized to quarry, transport and prepare ordinary raw materials can be reduced.

10.2. LCA results

To enable comparison of different product systems, the life cycle impact assessment results were normalized to the total impact caused by all the systems studied; this is presented in Figure 10. Comparative LCA results about the scenarios studied are presented in Figure 11. As can be seen, the best scenario is the use of deinking sludge to substitute limestone and petcoke in cement production in Finland. However, if only limestone is substituted, the impact on the environment becomes similar to that from the cement production process in Russia. Another scenario positively affecting the environment is the use of sludge in lightweight aggregates production in Finland.



	ADP	AP	EP	GWP	ODP	TETP
Scenario 1	-6,3 %	-8,0 %	-12%	-13%	-0,11%	-5,8 %
Scenario 2	-1,7 %	-2,1 %	-1,8 %	-2,1 %	-0,01%	-0,89%
Scenario 3	2,6 %	1,5 %	-0,86%	-12%	0,02%	-1,3 %
Scenario 4	2,3 %	2,1 %	0,50%	-1,5 %	-25%	-0,02%
Scenario 1, no petcoke	4,4 %	-1,2 %	-3,1 %	-12%	0,01%	-5,0 %

Figure 11: Part of LCA results.

More detailed description and discussion of the results can be found in (Deviatkin et al., n.d.), which is the article to be submitted to a journal with the focus on waste management or sustainable development.

11. CONCLUSIONS

The activities planned within the EMIR project were fully performed. The results of the research are presented in the report. The report is intended for assistance in decision-making at recovered fiber-based paper mills generating deinking sludge, and seeking for alternative and sustainable possibilities for the utilization of deinking sludge.

The literature review performed within the project indicated that deinking sludge utilization as an alternative raw material or energy source was studied extensively. The results of the literature review provide information on valuable properties of deinking sludge when used as an alternative fuel/energy source or raw material. Being comprised of both organic (wood fibers) and inorganic matters (fillers), deinking sludge found wide application in the production of construction materials where both wood fibers and fillers are required. In contrast, the high ash content of 40-45% on a dry basis makes most of the energy recovery technologies unfeasible, due to large amount of ash left after incineration, which will still require utilization. Moreover, the low energy content of deinking sludge does not favor energy recovery.

Having performed the literature review, a market analysis was performed to reveal existing companies that are capable of deinking sludge treatment and that satisfied the criteria set for the alternatives selection. The analysis took into consideration four companies that potentially could treat all or a part of the deinking sludge generated at the case study paper mill. The companies formed four scenarios used in the economic and environmental assessment.

In the first scenario, the deinking sludge was used in a Finnish cement plant substituting the 2.7% of limestone and 46% of petcoke conventionally used at the plant, and the greatest environmental impact reduction was achieved in all impact categories. GWP was reduced by 13%, while EP was reduced by 12%. ODP was reduced by 0.11%, which was the least out of all the categories. The reduction was caused primarily due to the substitution of petcoke. Petcoke accounts for around 25% of the total heat input by the plant and is used in both a precalciner and rotary kiln. In contrast, the economic assessment indicated that the use of deinking sludge in the cement plant is unfeasible due to the high gate fee of 45 €/t dry sludge charged. The possibility would be economically acceptable if the gate fee is decreased to 28€/t.

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The second scenario, entailing utilization of the total amount of deinking sludge in a Finnish lightweight aggregate plant, is the most economically feasible alternative with benefits exceeding costs by 3.6. This can be achieved due to the absence of a gate fee for sludge utilization and the fact that all the sludge is utilized. However, considering that only 15% of deinking sludge could be treated, the BCR decreases to 0.16 making the possibility economically unfeasible. The environmental assessment results indicate that complete substitution of heavy fuel oil, conventionally used as a pore-forming agent, with 15% of the annual amount of deinking sludge reduces the environmental impact in all impact categories. ADP was reduced by 1.7%, EP by 1.8%, AP and GWP by 2.1%, the last being the largest reduction. These reductions are mainly due to the decrease in heavy fuel oil consumption, and the avoidance of landfill emissions.

The third scenario, involving substitution of 0.89% of the limestone and 1.9% of the clay in a Russian cement plant was slightly economically feasible with a BCR of 1.1. A great share of the arising costs (more than 60%) is associated with deinking sludge transportation, while the small assumed gate fee of 10 €/t of dry deinking sludge accounted for a third of the total costs. LCA results proved that the scenario exerts both negative and positive environmental impact. The largest positive impact is achieved for GWP, which was reduced by 12%, mainly due to the avoidance of landfill emissions. In contrast, ADP and AP increased by 2.3 and 2.1%. In this scenario, unlike in the first one, the sludge was used for raw materials substitution, which quarrying causes less environmental impact than fuel extraction and refining, thus, resulting in smaller impact reduction.

Scenario 4, entailing substitution of 25% of the cement consumed at a stone wool producing plant with 15% deinking sludge generated annually, showed controversial impact on the environment. The largest impact reduction of 25% was achieved for ODP, while the results interpretation show that the reduction is only possible due to emissions of halon being prevented,. Halon is a gas generated during cement production and included in the inventory used in the study. GWP was reduced by 1.5%. The largest negative impact on the environment is for ADP by 2.3%, and AP by 2.1%. Economic assessment indicated that the need to build a new incineration plant is the greatest constraint making the possibility absolutely unacceptable with a BCR of 0.03. However, if deinking sludge could be combusted for a gate fee of 20 €/t

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and only 15% of deinking sludge ash would be utilized, then the BCR increases to 0.18.

Thus, the research results provide insights into which deinking sludge utilization possibilities exerts the least environmental impact and brings the highest economic benefits. Overall, the use of dry deinking sludge in the production of lightweight aggregates to substitute heavy fuel oil is seen as the best overall possibility, in terms of economic feasibility and environmental impact. The least viable possibility is the use of deinking sludge in stone wool production to substitute cement.

Moreover, extraction and processing of crude oil to produce fuel oil or petcoke exerts a much greater effect on the environment than that of limestone and clay. The sensitivity analysis has shown that the results are more sensitive to the substitution rate of fuels, as the results vary very little even if the substitution rates varied by 20%.

To apply the results to other companies facing similar problems, the pulp and paper markets in the Leningrad Region and Finland were analyzed. Considering the Leningrad Region, the case study paper mill was the only plant where deinking sludge is generated. There is another company using recovered fiber in their production process, SPb KPK, which manufactures cardboard or similar products. Such products do not have strict requirements on the level of impurities that are allowed in the final products, therefore most of the filler and inks that would turn into deinking sludge in tissue production stay in the final product; this results in smaller amounts of sludge being generated. Moreover, the sludge generated has a different composition compared to the sludge from SCA Hygiene Products Russia. Considering Finland, there is only one recovered fiber-based paper mill where deinking sludge is generated – UMP Kaipola mills located in Jämsä. The mill representatives confirmed that deinking sludge is burned with energy recovery at their plant. Nevertheless, the results of the EMIR project can easily be benchmarked to other paper mills since the methodologies used in the study and the information sources are presented in the report.

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ANNEX I. EXPERIMANTAL SETUP FOR DETERMINATION OF DEINKING SLUDGE APPLICABILITY IN LWA PRODUCTION

The tests were performed in accordance with the guidelines provided by representatives of the lightweight aggregates manufacturing plant.

Required materials and equipment:

Clay
Deinking sludge
Drying oven for 16 h at 105±5ºC
Pipe oven for 10 min at 250ºC
Electric oven for 6-8 min at 1130±15ºC
Exicator, Scales, Sand with mesh size of 0-0.2 mm
Cylinder, Rubber mat, Plate

Test procedure:

1. Determination of MC of clay and deinking sludge. Materials are placed in an oven for 10 h at 105±5ºC. MC is determined by weight difference;
2. Clay and deinking sludge are blended at certain proportions on dry basis as presented in Table AI.1;
3. The blend is dried for about 20 min and then certain amount of balls is formed. The balls are placed then in the drying oven for at least 16 h at 105±5ºC;
4. Due to absence of the pipe oven, deinking sludge was heated up in the same drying oven until the temperature was 250ºC and kept so for 10 min;
5. Dried balls are covered with lime powder and sintered in the electric oven for 6-8 min at 1130±15ºC;
6. Sintered LWAs were placed in an exicator until it is cooled down until room temperature;
7. Determination of LWAs density. A cylinder was filled with sand until 60 ml volume. The cylinder was beaten against soft rubber mat 20 times before final sand volume determination (Vsand). Then, 6-8 most expanded LWAs we weighted (Wp). Nearly all sand from the cylinder was taken out onto a plate, then LWAs were placed inside the cylinder which was filled with the sand from the plate. Again, the cylinder was beaten 20 times and final volume was measured (Vtot).

   Density was calculated as follows: $\rho = (Wp/Vtot - Vsand) \cdot 1000, [kg/m^3]$.

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Moisture content of clay was 56.86%, of deinking sludge – 44.49%. Density of produced LWAs is presented in Table AI.2.

Table AI.1. Proportions of deinking sludge and clay used in the study.

Test	Mass of wet clay	Mass of dry clay	Mass of wet sludge	Mass of dry sludge	% of sludge added
1.1.	266.7	148.1	10.98	4.74	3.2
1.2.	-	-	-	-	-
2.1.	88.36	49.05	7.96	3.43	7
2.2.	-	-	-	-	-
3.1.	94.1	52.24	12.11	5.22	10
3.2.	-	-	-	-	-
4.1.	88.2	48.96	17.02	7.34	15
4.2.	-	-	-	-	-
5.1.	98.9	54.89	31.81	13.72	25
5.2.	-	-	-	-	-

Table AI.2. Density of produced LWAs.

Test	Total № of LWAs	№ of best LWAs	Vsand, ml	Vtot, ml	Wp, g	ρ, kg/m3	ρ_{av}, kg/m^3
1.1.	7	7	60	83	13.87	603	808
1.2.	10	7	36	45	9.63	1014	
2.1.	11	7	36	45	9.72	1080	1059
2.2.	11	6	7.4	8.2	0.83	1038	
3.1.	10	7	36	42	4.92	820	870
3.2.	10	7	7.4	8.4	0.92	920	
4.1.	10	7	36	42	6.83	1138	1058
4.2.	11	7	7.3	8.2	0.88	978	
5.1.	10	6	36	41	6.28	1256	1228
5.2.	10	7	7.3	8.1	0.96	1200	

Figure AI.1 depicts dependence of LWAs density on the amount of deinking sludge added. As can be seen, density varies significantly. However, it can be seen that addition of more than 11-13% of deinking sludge lead to LWAs density more than 1000 kg/m^3.

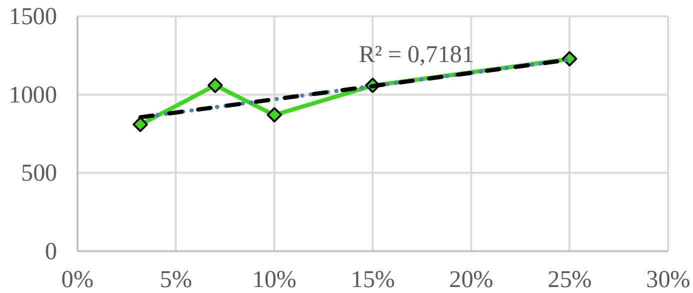

Figure AI.1. Dependence of LWAs density on amount of deinking sludge added.

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ANNEX II. ECONOMIC SYSTEMS ANALYSIS OF DEINKING SLUDGE RECOVERY OPTIONS: A CASE STUDY IN LENINGRAD REGION, RUSSIA

SUMMARY: Deinking sludge, which is generated in large quantities and landfilled, poses a serious threat not only to the environment and society, but to economy as well. The economic damage results from the missed opportunity to utilize sludge as alternative raw material or fuel and especially because of landfill fees and pressure to increase it. Literature review indicated that there are many possibilities enabling deinking sludge utilization for energy or material recovery. Based on the results of the literature review, four possible utilization scenarios were identified within the case study area. Negotiations with companies representing different scenarios provided information required for the economic systems analysis, as well as the requirements set on deinking sludge properties. Systems analysis results demonstrated that the use of deinking sludge in lightweight aggregate plant in Finland, in a cement and in a stone wool plants located in Russia can be economically reasonable under certain conditions. In addition, the results clearly stated that the need to build a new incineration plant for deinking sludge pretreatment makes the further deinking sludge ash utilization unprofitable. For the exhaustive comparison of the alternatives, also their environmental and social impacts need to be evaluated in further studies.

1. INTRODUCTION

Commodities produced by the pulp and paper industry cannot be easily substituted by other products, especially in the case of tissue paper. The consumption of tissue paper is increasing because of constant population growth and increasing hygiene standards, most notably in developing countries (European Tissue Symposium, 2014; Uutela, 2013). At the same time, tissue paper production relies more on recycled paper, whose recycling rates are increasing (European Recovered Paper Council, 2012).

However, the production of tissue paper from recovered fibre results in the generation of deinking sludge which is the largest waste stream at paper mills with installed deinking units (Dahl, 2008; European Commission, 2013). While developed countries are actively searching and have already implemented more sustainable deinking sludge utilization management systems in many cases, deinking sludge is still landfilled in the Leningrad Region, Russia. Landfilled deinking sludge is a serious threat not just to the environment and local community, but to the economy as well, since deinking sludge could be considered as an alternative fuel or raw material and especially because of landfill fees and pressure to increase it. (Marsidi et al., 2011; Bird and Talberth, 2008; CANMET, 2005).

There is no single commonly applied deinking sludge utilization technique, but instead, many are known with focus on energy and/or material recovery. Thus, to evaluate a range of alternative techniques, we propose to use economic systems analysis in order to get an overall better solution than if the system's elements were studied separately. However, previously the systems analysis has mainly been applied to municipal waste management (Chang et al., 2011).

The aim of this study was to evaluate several alternative deinking sludge utilization systems

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consisting of a paper mill, current deinking sludge treatment place, i.e. landfilling, a sludge-utilizer, and a waste transportation company with the aid of cost-benefit analysis (CBA).

2. METHODOLOGY

2.1. System description

In general terms, a system is a set of single elements which interact with each other, where the interaction is aimed at reaching higher overall efficiency than if the elements would operate independently. When analyzing deinking sludge utilization alternatives, a system essentially consists of a paper mill where deinking sludge is generated, current deinking sludge treatment place, a sludge-utilizer (any factory or installation capable of sludge treatment and utilization), and a waste transportation company. In addition to the main system elements, a company or an installation required for sludge pretreatment, e.g. drying, can be included if necessary.

Each of the system elements has a unique set of attributes which characterize them and influence the results of the study. Those attributes are presented in Figure 1 within a box of each system element. Not only system elements have attributes, but also the geographical location possesses additional attributes expressed through political including legislative, social, and cultural aspects of business operation in a waste management sector. However, only geographical attributes identified within the study were considered. The data can be inquired directly from a paper mill, literature review, personal communications, or laboratory analysis. Practically, the mixture of these data can be used depending on the availability of time and financial resources.

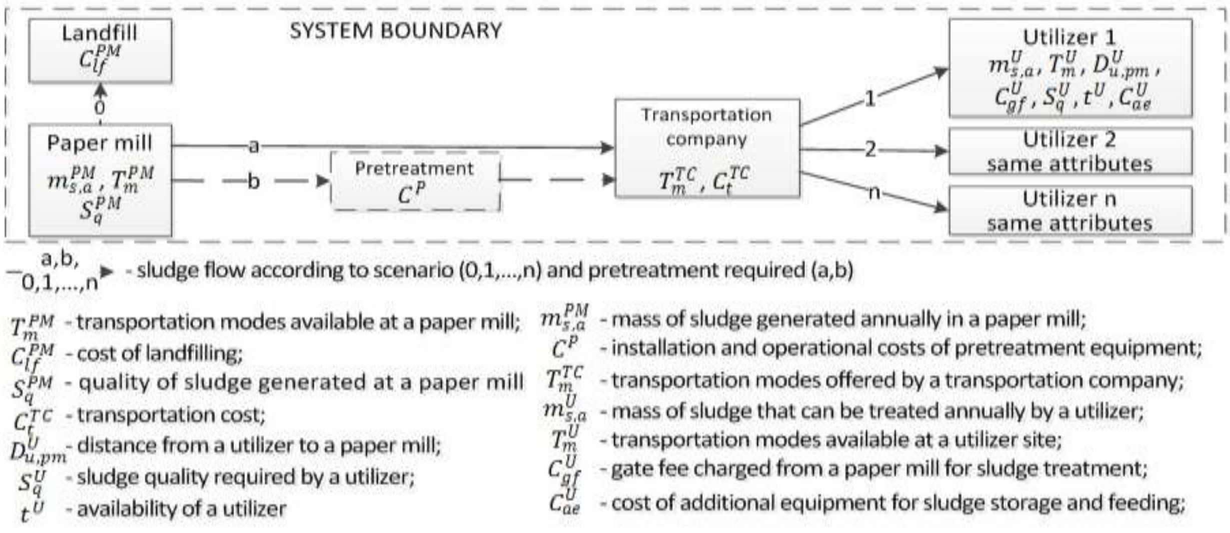

Figure 1. Deinking sludge utilization system, its boundaries, elements and attributes.

For the selection of deinking sludge alternative utilization methods, literature review is required. During the literature review, both energy and material recovery possibilities should be revealed and, once the literature review has been finished, local market analysis should be performed to discover potential deinking sludge utilization sites.

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2.2. Case study paper mill

Out of all paper mills located in the Leningrad Region, only "SCA Hygiene Products Russia" paper mill produces high quality tissue paper from recovered fibre. The treatment of the factory's wastewater leads to the generation of deinking sludge. The deinking sludge contains primarily short cellulose fibres lost during the production process and filler used in the recovered paper manufacturing, while the inks and coatings are present in smaller quantities. The annual amount of deinking sludge generated at the case study paper mill is approximately 54 000 t.

At present, most of the deinking sludge generated at the mill is landfilled, whereas only a small portion of the sludge is transported to a cat litter manufacturer. Before being landfilled, the deinking sludge is subject to in situ treatment until its final moisture content is 45–50% which is as low as advised in the Reference Document on Best Available Techniques for the Production of Pulp, Paper and Board (European Commission, 2013).

2.2.1. Deinking sludge characterization

The gross calorific value of the deinking sludge was determined in a bomb calorimeter. Other analyses of the sludge included moisture content, loss of ignition, as well as organic and inorganic carbon contents determination. The composition of inorganic matter was determined by inductively coupled plasma atomic emission spectroscopy. The analyses have been performed in accordance with the standards (Finnish Standards Association SFS, 2008) and methodological recommendations (Chemico-analytical centre "Arbitrazh," 2013).

2.3. Economic assessment

To reach a decision on which alternative deinking sludge utilization system should be implemented in reality, system engineering tools might be applied. Cost-benefit analysis is a system engineering tool which is used to design the system rather than to describe it, and, out of all system engineering tools, it is the most appropriate one for economic systems analysis since it provides the basis for the comparative assessment of alternatives based on financial flows. (Chang et al., 2011)

In general, cost-benefit analysis includes a quantification and comparison of all relevant direct costs and benefits within the project scope. Alternative projects can be ranked based on the CBA results, and the one with the highest benefits/costs ratio (BCR) should usually be implemented taking into account environmental and social aspects of sustainability.

Depending on the situation, the system can be viewed from different standpoints meaning different outcomes of the analysis. If a paper mill initiates sludge utilization, i.e. as in the current case study, all costs and benefits are considered from its standpoint and vice versa if a potential utilizer starts cooperation.

2.3.1. Costs

Four cost categories are considered in the study. First of all, the investment costs required to store, prepare, and feed the deinking sludge into the treatment process are evaluated. From a sludge utilizer point of view, the investment costs are the ones needed to install new equipment required to enable sludge treatment, while from a standpoint of a paper mill these costs are the gate fee charged by the utilizer. Thus, to conduct the economic evaluation of alternative deinking sludge treatment methods, gate fees will be used instead of investment costs.

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Secondly, operational and maintenance costs arising at a utilization site are included in the gate fees for deinking sludge treatment. However, a paper mill can be responsible for sludge preparation, like drying or incineration, before leaving sludge to a final utilizer and, thus, covers all expenses related to the pretreatment equipment construction and maintenance.

To convert the investment costs of the pretreatment equipment into annual payments, the capital recovery factor (CRF) was used. CRF was calculated as follows:

$$CRF = \frac{i \cdot (1+i)^n}{(1+i)^n - 1}; \tag{1}$$

where i – the discount rate (assumed to be 15%);

n – time horizon or the number of annual payments (assumed to be 20).

The third group of costs derives from the legislation valid in a certain country. One example of such costs identified in the study is the fee for transboundary waste transportation.

Lastly, the transportation costs must be analysed. The costs are dependent mainly on the specific transportation fee, distance to be driven, and the amount of sludge to be transported:

$$C_t = C_{km} \cdot D \cdot m; \tag{2}$$

where C_{km} – the specific cost of transportation, (0.53 €·km^{-1}·t^{-1});

D – the transportation distance, km;

m – the amount of sludge transported, t.

In addition, physical properties of sludge can influence the transportation costs. For example, for wet and dry sludge transportation, different vehicles can be required.

Since the study was analysed from a sludge generating company point of view, the investment and operational costs included only the costs of the equipment required for the deinking sludge pretreatment before the utilization in a particular production process. The investment costs of a drying installation were estimated from the information available on the market (LLC “StroiMechanika”, 2014), while the operational costs mainly presented by the cost of natural gas (Federal State Statistics Service, 2013) required for sludge drying were calculated. The investment and operational costs of an incineration plant were assumed to be the same as the costs of an incineration plant recently built in the Leningrad Region for sewage sludge treatment (Joint Implementation Projects Supervisory Committee, 2010).

The gate fees are assumptions based on preliminary discussions with the potential utilization companies. The tax for sludge disposal and the landfilling fee correspond to the real costs paid by the case study paper mill in compliance with the governmental regulations. The costs of permissions for transboundary sludge transportation were taken from the governmental documents.

2.3.2. Benefits

Similar to the costs, the benefits will be evaluated from a standpoint of a paper mill to make the data consistent and to avoid double counting of costs and benefits. Benefits arise from the avoided or decreased landfilling costs, and from the selling of the electricity generated during sludge incineration, which was calculated as follows:

$$B_i = E_{el} \cdot C_{el}; \tag{3}$$

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where E_{el} – the annual electricity production, MWh/a;

C_{el} – the average price of electricity in Russia, RUR/MWh.

3. RESULTS AND DISCUSSION

3.1. Sludge analysis

The analysis of deinking sludge showed that the average moisture content was about 48% and the ash content on dry basis was 43%. The major elements identified in the sludge ash were calcium (44%), silica (9.6%) and aluminium (7.5%). Along with these, elements such as Fe, Mg, Na, K, Co, Ni, Pb, Cd, Cu, Zn, Mn, Cr, As, and Ti were detected, but in smaller quantities. The higher heating value for the dry matter determined in a bomb calorimeter was 7.1 MJ/kg, and the lower heating value in arrival conditions was 1.8 MJ/kg.

3.2. Utilization options

The deinking sludge utilization options can be broadly divided into energy and material recovery possibilities depending on the desired product.

3.2.1. Energy recovery

Any method aimed at obtaining energy from deinking sludge or any method of thermal destruction of deinking sludge without its incorporation into another product is considered as an energy recovery possibility. Such possibilities are: 1) combustion in boilers of different types, 2) vitrification, 3) gasification, 4) pyrolysis, and 5) supercritical water oxidation (CANMET, 2005).

High moisture content combined with high ash content leads to the unfeasibility of energy recovery. Support fuels are needed to reach the temperatures required in waste incineration and for the destruction of possible toxic products of combustion.

3.2.2. Material recovery

Any method aimed at the utilization of organic and/or inorganic parts of deinking sludge in the production of another product as primary or alternative raw material or other purposes without thermal destruction, is considered to be a material recovery possibility.

Deinking sludge can be used for such purposes or utilized in the production or preparation of the following materials: 1) cement 2) concrete, 3) mortar, 4) bricks, 5) lightweight aggregates, 6) tiles, 7) fibreboards, 8) particleboards, 9) millboards, 10) cement bound boards, 11) adsorbent, 12) pozzolana, 13) composites, 14) animal bedding, 15) compost, 16) synthetic calcium carbonate, 17) stone wool, 18) other paper/board grades, and 19) land management. (Marsidi et al., 2011; Bird and Talberth, 2008)

As can be seen, there are plenty of available utilization possibilities enabling deinking sludge material or energy recovery.

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3.3. Scenarios

On the basis of the identified utilization possibilities, the markets of Leningrad Region and closely located Finland were screened to find real possibilities for the utilization of deinking sludge generated at the case study paper mill. Thus, the chosen scenarios are the most probable ones within the case study area and will be compared to the baseline one.

Baseline scenario (BS) – *Landfilling in Russia.* Deinking sludge is transported by a waste transportation company to a landfill site where landfilling fee is charged from the paper mill. In addition, the paper mill pays a tax for waste disposal.

Scenario 1 – *Cement plant in Finland*. Deinking sludge which should be dried before the utilization can substitute limestone. However, the plant would request for a gate fee for the sludge treatment. In addition, an officially granted permission for transboundary waste transportation is required from both countries.

Scenario 2 – *Lightweight aggregate plant in Finland.* Preliminarily dried deinking sludge can substitute organic material consumed by the plant and a small share of clay with the inorganic part of sludge. The gate fee is assumed to be zero, but the cost of the permission for transboundary waste movement will be required.

Scenario 3 – *Cement plant in Russia.* Similarly to Scenario 1, preliminarily dried deinking sludge will substitute limestone. Gate fee will be charged as well.

Scenario 4 – *Stone wool plant in Russia.* Deinking sludge will be used as additional material. Only sludge ash is acceptable in the plant. Two incineration possibilities were assessed: in a new incineration plant (S4.1) and in an existing one (S4.2). No gate fee for ash treatment is assumed.

3.4. Cost-benefit analysis

The theoretical amount of electricity generated from the combustion of the deinking sludge from the case study paper mill is 6 900 MWh/a (Deviatkin, 2013), while the average electricity price in Russia is about 42 €/MWh (Federal State Statistics Service, 2013). The costs and benefits are stated in Table 1.

The results state clearly that at the current conditions only the deinking sludge utilization in the production of lightweight aggregates in Finland, stone wool, and cement production in Russia are economically feasible, while the benefits of the lightweight aggregate production possibility are three and a half times greater than the cost. In the other scenarios, the costs exceed the benefits, especially in Scenario 4.1, which is related to the need to build and maintain the incineration plant. In Scenario 1, the gate fee accounts for most of the costs, while the cost of transportation is less important.

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Table 1 - Costs and benefits of deinking sludge utilization alternatives.

Cost category, 10^3 €/a	BS	S1	S2	S3	S4.1	S4.2
7. Investment and operational						
1.3 Drying	0	47	47	47	0	0
1.4 Incineration	0	0	0	0	6 611	0
8. Gate fee	936	1 289	0	286	0	1 095
9. Regulatory						
3.4 Tax for landfilling	49	0	0	0	0	0
3.5 Permission for transboundary waste transportation (RU)	0	4.4	4.4	0	0	0
3.6 Permission for transboundary waste transportation (FI)	0	1	1	0	0	0
10. Transportation	–(1	68	205	531	36	36
TOTAL COSTS	985	1 409	257	864	6 647	1 131
Benefit category, 10^3 €/a	**BS**	**S1**	**S2**	**S3**	**S4.1**	**S4.2**
1. Avoided landfilling fee	0	936	936	936	936	936
2. Incineration revenue	0	0	0	0	291	291
TOTAL BENEFITS	0	936	936	936	1 228	1 228
BENEFITS/COSTS RATIO	0	0.66	3.64	1.08	0.18	1.09

(1 – is included in the gate fee.

3.5. Sensitivity analysis

To see the influence of certain assumptions on the results of the study, a sensitivity analysis has been implemented. The idea behind the analysis was to evaluate how the costs must be decreased in any of unfeasible scenarios to get a BCR>1 or alternatively increased for

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economically feasible scenarios to get BCR close to one. In Scenario 1, the gate fee for sludge treatment should be decreased from 45 €/t to at least 26 €/t to make the possibility feasible.
In Scenario 4, the assumed discount rate can be decreased to 10% what tends to the decrease of the annual payment for the incineration plant to 5 385·103 € resulting in BCR increase to 0.23 only. At such conditions, investment and operational costs of the incineration plant should be decreased further by almost five times to get BCR>1.
Altering assumption about zero gate fee charged for sludge treatment in Scenario 2 revealed that the gate fee can be increased up to 22 €/t of dry sludge without undermining the economic applicability of this possibility. Likewise, the estimated cost of the drying unit can be increased by almost 15 times until BCR≥1.
As regards to Scenarios 3 and 4.2, as soon as the gate fees will be increased, the scenarios will become unprofitable. Moreover, Scenario 4.2 is dependent on the calculated amount of electricity that can be produced during sludge incineration and its price.

4. CONCLUSIONS

Some of the possibilities identified can be economically profitable for a sludge generating company. The utilization of deinking sludge in the lightweight aggregates producing plant located in Finland is the most favourable possibility out of all studied, with its benefits being three and a half times greater than its costs. Moreover, even the significant increase of the gate fee up to 22 €/t of dry sludge or that of the drying installation, would still make the possibility economically reasonable.
Other feasible possibilities are to use the sludge in the cement manufacturing plant located in Leningrad Region of Russia or in stone wool production if the sludge is co-combusted in an existing boiler. However, in these cases, the benefits are slightly exceeding the costs, which means that any cost increase will lead to BCR<1.
It was also noted that the need for the construction and operation of an incineration plant can be a limiting factor for example in stone wool production. On contrary, investment and operation costs of a drying unit are not critical for the final results.
Notwithstanding the fact that the economic value of any project is the most important in the business operations, pressures on the environment should and will be evaluated in further studies to assess the overall sustainability of the alternative deinking sludge utilization systems.

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