Journal of Cleaner Production 112 (2016) 3232–3243

Contents lists available at ScienceDirect

Journal of Cleaner Production

journal homepage: www.elsevier.com/locate/jclepro

Comparative life cycle assessment of deinking sludge utilization alternatives

Ivan Deviatkin [a,*], Viktoriia Kapustina [a], Elena Vasilieva [b], Lev Isyanov [b], Mika Horttanainen [a]

[a] Laboratory of Environmental Engineering, Lappeenranta University of Technology, Skinnarilankatu 34, 53850, Lappeenranta, Finland
[b] Environmental Engineering Faculty, Saint Petersburg State Technological University of Plant Polymers, Ivana Chernykh 4, 198095, Saint Petersburg, Russia

ARTICLE INFO

Article history:
Received 26 March 2015
Received in revised form
5 October 2015
Accepted 6 October 2015
Available online 17 October 2015

Keywords:
Deinking sludge
Comparative life cycle assessment
Circular economy
Material recovery

ABSTRACT

The aim of this research was to quantify and compare the environmental impact of a number of different deinking sludge utilization approaches. A comparative life cycle assessment of deinking sludge material and energy recovery was performed for the baseline scenario—landfill disposal, and four alternative scenarios: two cement plants, a lightweight aggregate plant, and a stone wool plant. Sludge pretreatment and transportation processes were included in the scenario analyses. The results of the life cycle assessment showed that the use of dry deinking sludge in a cement plant in Finland, 45 km from the point of supply of the deinking sludge, to substitute 46% of the petcoke and 2.7% of the limestone showed the best performance. Therein, a global warming potential reduction of 13% and an eutrophication potential reduction of 12% – the highest reduction out of all impact categories studied – were achieved. A similar reduction in global warming potential of 12% was achieved when deinking sludge was incinerated and the ash utilized in cement production in a Russian plant located 350 km from the paper mill. However, abiotic depletion potential and acidification potential slightly increased by 2.6 and 1.5%, respectively. A maximum reduction of 2.1% out of al impact categories was achieved when dry sludge was used in a lightweight aggregate plant. That is considerably less compared to the reduction achieved at the cement plants. The use of deinking sludge ash in a stone wool plant to substitute 25% of cement resulted in a maximum reduction of 25% in the ozone layer depletion potential. Thus, the utilization of deinking sludge in construction materials production while preventing its landfilling has beneficial effects on the environment, in particular decreased greenhouse gas emissions.

1. Introduction

The concept of a circular economy—a core idea of industrial ecology describing the situation where material flows keep added value for as long as possible, eliminating waste generation (European Commission, 2014a)—is receiving increasing attention in modern society. The concept has been discussed at world leading conferences organized by the World Economic Forum (2014) and the European Commission (2014b) and advocated in such documents as the Communication of the European Commission (2014c) or the Recommendation of the Council of the Organisation for Economic Co-operation and Development on Resource Productivity (2008). Considerable success in this area has been achieved in the pulp and paper industry where nearly 60% of recovered paper is utilized to substitute virgin wood fiber on global scale, thereby aiming at the reduction of the negative impact on the environment (European Recovered Paper Council, 2014). However, the use of recycled fiber cannot be fully justified if waste paper recycling together with the management of the waste generated in the recycling process have a greater impact on the environment than the business-as-usual scenario.

Operations of paper mills manufacturing tissue paper from recovered fibre lead to generation of considerable amounts of deinking sludge, which must be properly managed to avoid the negative effect on the environment. Tissue paper consumption is increasing rapidly because of the growing world population and raised hygiene standards, and deinking sludge is the largest waste stream generated at RCF-based paper mills (Bird and Talberth, 2008). The generation of deinking sludge can be as high as 150 kg dry solids/t paper manufactured (Dahl, 2008). The easiest and still a

* Corresponding author. Tel.: +358 40 7619673.
E-mail address: ivan.deviatkin@lut.fi (I. Deviatkin).

http://dx.doi.org/10.1016/j.jclepro.2015.10.022
0959-6526/

Abbreviations

Scenarions

S0-LF_{RU}	baseline scenario implying landfilling of deinking sludge in Russia
S1-CEM_{FI}	scenario implying recycling of deinking sludge in a cement plant in Finland;
S2-LWA_{FI}	scenario implying recycling of deinking sludge in a lightweight aggregate plant in Finland
S3-CEM_{RU}	scenario implying recycling of deinking sludge in a cement plant in Russia
S4-SW_{RU}	scenario implying recycling of deinking sludge in a stone wool plant in Russia

Product systems

PS0-LF_{RU}	product system of a landfill
PS1-CEM_{FI}	product system of a cement plant in Finland
PS2-LWA_{FI}	product system of a lightweight aggregate plant in Finland
PS3-CEM_{RU}	product system of a cement plant in Russia
PS4-SW_{RU}	product system of a stone wool plant in Russia
ADP	abiotic depletion potential
AP	acidification potential
EP	eutrophication potential
GWP	global warming potential
LCI	life cycle inventory
LWA	lightweight aggregate
ODP	ozone layer depletion potential
PS	product system
TETP	terrestrial ecotoxicity potential

relatively common route for the final disposal of deinking sludge is landfilling, which harms not only the environment due to the release of landfill gas and leachate generation, but also the economy, by reason of the irreversible loss of the valuable materials contained in the deinking sludge. Paper recycling, while providing benefits and being a step on the way to a circular economy, might thus also pose certain risks for the environment and economy.

Following the principles of the waste hierarchy described in Directive 2008/98/EC on waste (The EU Parliament and the Council of the EU, 2008), deinking sludge should be recycled; first as a material, and when not possible, as an energy source. Complete prevention of deinking sludge generation or its reuse in the production of tissue paper is not possible since tissue paper must contain no or few impurities. Deinking sludge utilization methods have been introduced, for example, by Monte et al. (2009), Bird and Talberth (2008), Marsidi et al. (2011), and (Kotanen et al., 2014). A number of comprehensive studies, patents, and reports have been published with a focus on the utilization of deinking sludge in the production of cardboard (Alda and Jesús, 2008), cement (Frías et al., 2008), mortar (Yan et al., 2011), bricks (Raut et al., 2011; Sutcu and Akkurt, 2009), lightweight aggregates (Hu et al., 2012; Liaw et al., 1998), ceramic tiles (Maschio et al., 2009), fiberboard (Geng et al., 2007), particleboard (Taramian et al., 2007), cement-bound board (Fernandez et al., 2000), composite materials (Girones et al., 2010), compost (Gea et al., 2005), synthetic calcium carbonate (CalciTech, 2014), absorbent (Černec et al., 2014; Likon and Saarela, 2012), stone wool (Cuypers and Leismann, 2013), and pozzolana (García et al., 2008). Additionally, deinking sludge has been assessed for energy recovery through combustion, direct digestion, pyrolysis and gasification, in spite of its low heating value and high moisture content (CANMET, 2005; Frederick et al., 1996; Lou et al., 2012; Marsidi et al., 2011; Ouadi, 2012).

Despite the considerable body of research on deinking sludge recycling, no universal criteria for the optimal selection of an environmentally favorable recycling method have been developed, whereas deinking sludge can often be utilized simultaneously in a number of different ways. In addition to any environmental considerations, economic systems analysis has indicated that the use of deinking sludge as an alternative raw material and energy carrier can be economically feasible (Deviatkin et al., 2014).

Rising demands for environmental information from the general public and considerations of corporate responsibility on the part of companies have led to a situation where environmental impacts associated with planned activities or implemented policies must be thoroughly assessed. Environmental impact assessment can be implemented using several different methodologies, for example environmental input–output analysis, material flow accounting, and material input per unit of service (Finnveden and Moberg, 2005). In Europe, life cycle assessment (LCA) has been the preferred approach in solid waste management, and other analytical tools have seen only limited use (Pires et al., 2011). LCA is a suitable tool for the quantification of the overall environmental impact resulting from waste management, and as a way to reveal and thus enable the avoidance of possible environmental burdens associated with secondary materials use, which is a vital step towards circular economy implementation (EC-JRC, 2010a).

So far, only one scientific article (Likon and Saarela, 2012) has focused specifically on the environmental assessment of deinking sludge utilization. The paper presents an LCA of the utilization of deinking sludge in the production of absorbent for oil spills sanitation. In view of the limited amount of work done in this area, the assessment of the environmental impact of alternative deinking sludge utilization possibilities would provide a necessary and valuable contribution to the debate on the mitigation of the environmental burden of paper recycling.

The aim of our research was to quantify and compare the environmental impact of implementation of different deinking sludge utilization approaches. The utilization methods were chosen based on the results of the literature review and subsequent analysis of markets located reasonably close to the case study paper mill described in Section 2. The paper includes the descriptions of the scenarios identified, unit processes included in each scenario, and the data used in the study. The results of the study can be used for the cradle-to-grave LCA of paper recycling including the environmental impact associated with deinking sludge utilization. Thus, the study allows to extend the system boundaries of the LCA studies aimed at the comparison of paper production from virgin and recycled fibre, such as Gemechu et al. (2013), to provide more holistic and comprehensive data.

2. Materials and methods

LCA is a tool for strategic planning, as stated in ISO 14040/44 standards (SFS-EN ISO 14040, 2006; SFS-EN ISO 14044, 2006). The ISO 14040 standard distinguishes between two different approaches to LCA: the one which describes a specific product system (PS), and another which studies the environmental consequences of possible changes between alternative PSs. Even though, the approaches are not named in either of the ISO standards, they are widely known as an attributional LCA and a consequential one. Following the definitions included in ISO 14040 standard, the study seems to be a consequential LCA at a first approximation since it includes the direct effects caused by the implementation of an alternative deinking sludge management system. However, according to (Ekvall and Weidema, 2004; Weidema et al., 2009), the system boundaries of a purely consequential LCA must be expanded to include not only the direct impact, but also the secondary, or indirect, effects caused by a change in the demand on the materials possibly substituted with the deinking sludge: how they will be produced and consumed then? It might be assumed that the production of materials substituted would be avoided, thus extending the lifetime of pits, mines and oil deposits, but the production of co-products, such as heavy fuel oil, cannot be avoided and thus the material needs to be utilized. That should be considered in a consequential LCA. Purely attributional LCA, on another hand, does not focus on the consequences of planned changes, but rather on the description of a certain PS. Therefore, the study was performed as a comparative LCA with system expansion following ISO standards (SFS-EN ISO 14040, 2006; SFS-EN ISO 14044, 2006) and additional guidelines (EC-JRC, 2010b; U.S. EPA, 2006) to clarify the requirements of the ISO standards.

2.1. Goal and scope definition

The overall goal of the study was to identify the most environmentally sound deinking sludge utilization possibility for the case study paper mill by comparing the environmental burdens of several utilization methods and, therefore, to support the decision-making process on a company level. Since the study was primarily focused on recovery of deinking sludge, the unit processes preceding waste generation were left outside the system boundaries because the environmental impact from paper production would be equal in each scenario studied. Such practice is allowed by ISO 14044 standard (SFS-EN ISO 14044, 2006) and supported by Finnveden (1999), who elaborated on methodological aspects of LCA in waste management. Thus, the function of the study was material or energy recovery of the deinking sludge, whereas the functional unit was expressed as an annual amount of deinking sludge generated, which equals to 54,750 t. The functional unit was further used as a reference flow while quantifying the impacts and outputs of the PSs.

2.2. Description of the case study paper mill and deinking sludge

In the study, deinking sludge generated at the "SCA Hygiene Products Russia" paper mill was analyzed. The paper mill is located in Svetogorsk, which is in the North-West region of the Russian Federation, close to the Finnish-Russian state border. The paper mill manufactures tissue products utilizing recovered fiber from waste paper supplied mainly by printing houses. The amount of deinking sludge generated is approximately 54,750 t/a. Currently, most of the sludge is sent to landfill while a small fraction is used for cat litter production.

The deinking sludge was subjected to several analyses to determine the moisture and ash content, heating value, and ash composition. The major elements determined in the deinking sludge ash, namely, calcium, silica, and alumina oxides, enter the production chain via the fillers used in paper manufacturing. The content of these elements favors deinking sludge utilization in the production of construction materials. Organic matter is present in the sludge in the form of short wood fibers lost during the production process, which means that the sludge is suitable for use as fuel or for organic material substitution.

2.3. Description of scenarios

Five scenarios, including a baseline scenario, were analysed in the study (Fig. 1). The scenarios were selected based on the analysis of the deinking sludge properties presented in Table 1 and the review of literature on possible deinking sludge utilization methods presented in the introduction section. Further, market analysis was performed to identify the companies and production facilities that could utilize deinking sludge in their production processes. The search of the companies was performed using several Russian and Finnish online databases including "Rosfirm (2014)", "Navigator for Business Network (2014)", "Yellow Pages" (2014), the Directory of companies of the Leningrad Region (2014), and Fonecta (2014). The geographical area of the market analysis was limited such that transportation costs would not exceed the cost of the current deinking sludge management option and included South-East Finland and the Leningrad Region in Russia. The baseline scenario was the prevailing deinking sludge management option of landfill disposal. In Scenarios 1–4, the deinking sludge is not sent to the landfill but used in production processes, thus avoiding the environmental impacts associated with deinking sludge landfilling.

2.3.1. Baseline scenario (S0-LF_{RU})

To date, most of the deinking sludge generated at the paper mill under the study is transported to a landfill site by truck. The landfill accepts waste for disposal from several business sectors and companies. Deinking sludge equals 23.3% of the total waste amount handled by the landfill site (RASEM, 2014). Landfilling of deinking sludge that contains organic matter leads to landfill gas generation; this gas is not collected at the landfill site assessed.

2.3.2. Cement production (S1-CEM_{FI})

In Scenario 1, deinking sludge substitutes limestone and petcoke in a cement plant located in Finland. In the modelling, it was assumed that the calcium oxide of the deinking sludge replaces a part of the limestone and the energy content of the sludge replaces a part of the petcoke energy. The substitution rate for limestone was calculated based on the calcium oxide content of the sludge and limestone so that the mass of calcium oxide in the system would remain unchanged. The substituted mass of petcoke was calculated by applying heating values. Substitution rate calculations are presented in Supplementary information S1.1, and the rates used in the study are given in Table 2.

The utilization of the deinking sludge in cement production needs additional processes since raw deinking sludge is not suitable for cement production by the dry method used in the production plant, and the sludge thus requires drying prior to the utilization. Consequently, the environmental impact of the sludge drying process and the subsequent transportation of the dry sludge to the cement plant was included in the scope of the study.

2.3.3. Lightweight aggregates (S2-LWA_{FI})

In Scenario 2, deinking sludge is assumed to be used in the production of light-weight aggregates (LWA) in a plant located in

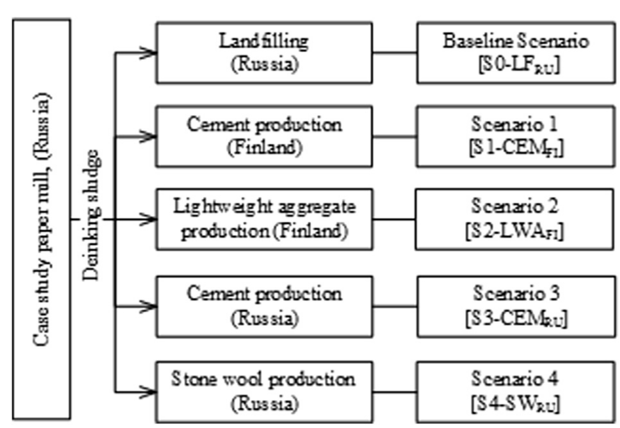


Fig. 1. Scenarios included in the study.

Table 1
Characteristics and composition of the deinking sludge and deinking sludge ash studied and data from literature for comparison.

		Test results	Literature data
Wet deinking sludge composition (%)	Moisture content	47.7	50–60[a]
	Ash content	22.4	20–30[a]
Ash composition on dry basis (%)	CaO	60.5	56.3[b]
	SiO_2	20.1	23.9[b]
	Al_2O_3	16.7	15.1[b]
	Fe_2O_3	1.09	1.02[b]
	MgO	1.00	1.90[b]
	K_2O	0.29	0.53[b]
	SO_3	n.d.	0.73[b]
	Na_2O	0.25	0.29[b]
Deinking sludge properties	Density, [kg m^{-3}]	589	–
	HHV on dry basis, [MJ kg^{-1}]	7.1	1.5–5.7[a]

[a] Data from (CANMET, 2005) where effective heating value is used.
[b] Data from (Frías et al., 2011).

Table 2
Expected rates of resources substitution with deinking sludge and amounts of deinking sludge utilized.

Scenario	Resource substituted	Expected
S1-CEM_{FI}	Limestone	2.7%
	Petcoke	46%
S2-LWA_{FI}	Heavy fuel oil	100%
S3-CEM_{RU}	Limestone	0.89%
	Clay	1.9%
S4-SW_{RU}	Cement	25%
Amount of deinking sludge utilized, % of annual sludge amount		
S1-CEM_{FI}	Deinking sludge	100%
S2-LWA_{FI}	Deinking sludge	15%
S3-CEM_{RU}	Deinking sludge	100%
S4-SW_{RU}	Deinking sludge	15%

Finland. LWAs, which are also referred to as expanded clay aggregates, are ceramic products with a uniform pore structure of fine closed cells and a densely sintered external skin (European Commission, 2007). The pore structure of the product is determined by the specificity of the production process, raw materials, and fuels consumed.

In the scenario, dry deinking sludge utilization is modelled for the substitution of heavy fuel oil. Since heavy fuel oil is used in the plant for LWA expansion, heavy fuel oil was selected for the substitution on the basis of the volume of fumes generated during heavy fuel oil and deinking sludge combustion. Corresponding calculations are presented in Supplementary Information S1.2, and the resource substitution rates used are presented in Table 2. Emissions from the drying of the deinking sludge and subsequent transportation to the plant are included in the scenario.

2.3.4. Cement production (S3-CEM_{RU})

In Scenario 3, deinking sludge is assumed to be supplied to a cement plant located in Russia. In Scenario 3, the cement production process is not able to utilize raw deinking sludge: the sludge must be incinerated first. The environmental impact of deinking sludge combustion and ash transportation is included in the analysis. Since only ash can be used, no fuel substitution in cement production is possible. In Scenario 3, the deinking sludge ash can substitute both limestone and clay at the substitution rates calculated in Supplementary Information S1.3. The rates used in the study are presented in Table 2.

2.3.5. Stone wool production (S4-SW_{RU})

In Scenario 4, deinking sludge is assumed for use in a stone wool manufacturing plant located in Russia. The major raw material consumed during the production of stone wool is basalt. However, in the scenario, deinking sludge is modelled for cement substitution because of the pozzolanic properties of deinking sludge ash. Thus, the deinking sludge must be incinerated prior to the use in the process. The substitution rate calculations are presented in Supplementary Information S1.4, with the rates used in the study presented in Table 2. The environmental impact from sludge incineration and ash transportation to the stone wool plant is included in the study.

2.4. Description of system boundaries

The LCA methodology applied to waste management adopts a different perspective from a classical LCA study of a PS performed from "cradle-to-grave" (Björklund et al., 2011). From the deinking sludge utilization point of view, the LCA study starts when the sludge is generated, that is, the "gate" of the RCF-based paper mill and continues until it is transformed into a final product of a production process, that is, the "gate" of a sludge utilizing company. Unit processes and LCA stages prior to sludge generation, for example wood harvesting, paper production, its use and recycling, which results in the deinking sludge generation, are not affected by the study and, thus, are omitted. However, considering the issue from the standpoint of the production processes in which the deinking sludge can be utilized, the study starts with the extraction of raw materials and fuels to be substituted with the deinking sludge, that is, the "cradle", and ends with the unit process, referred to as a transition unit process, in which the deinking sludge is transformed into a final product, that is, the "gate". Unit processes and LCA stages following the transition unit processes should not be affected by the use of the deinking sludge and can be omitted from the study. The PSs, as well as the system boundaries, are shown in Fig. 2.

Several assumptions were made in the life cycle inventory (LCI) of the study. First, no emissions to water bodies from the production processes where deinking sludge can be utilized were included in the assessment since the production processes studied are not water intensive and the sludge utilization is not expected to affect emissions to water. As regards leachate generated during deinking sludge landfilling, most of the environmental impact is associated with toxicity impact categories, which are however not included in the study due to great inconsistency in the results from different impact assessment methods (Martínez et al., 2015). Second, waste generation by the product manufacturing systems was not assessed since deinking sludge utilization is not expected to change the amounts of waste generated. Third, direct impact associated with the extraction of the raw materials substituted is excluded from the study due to the lack of sufficient inventory data and the low environmental impact associated with their extraction as shown by

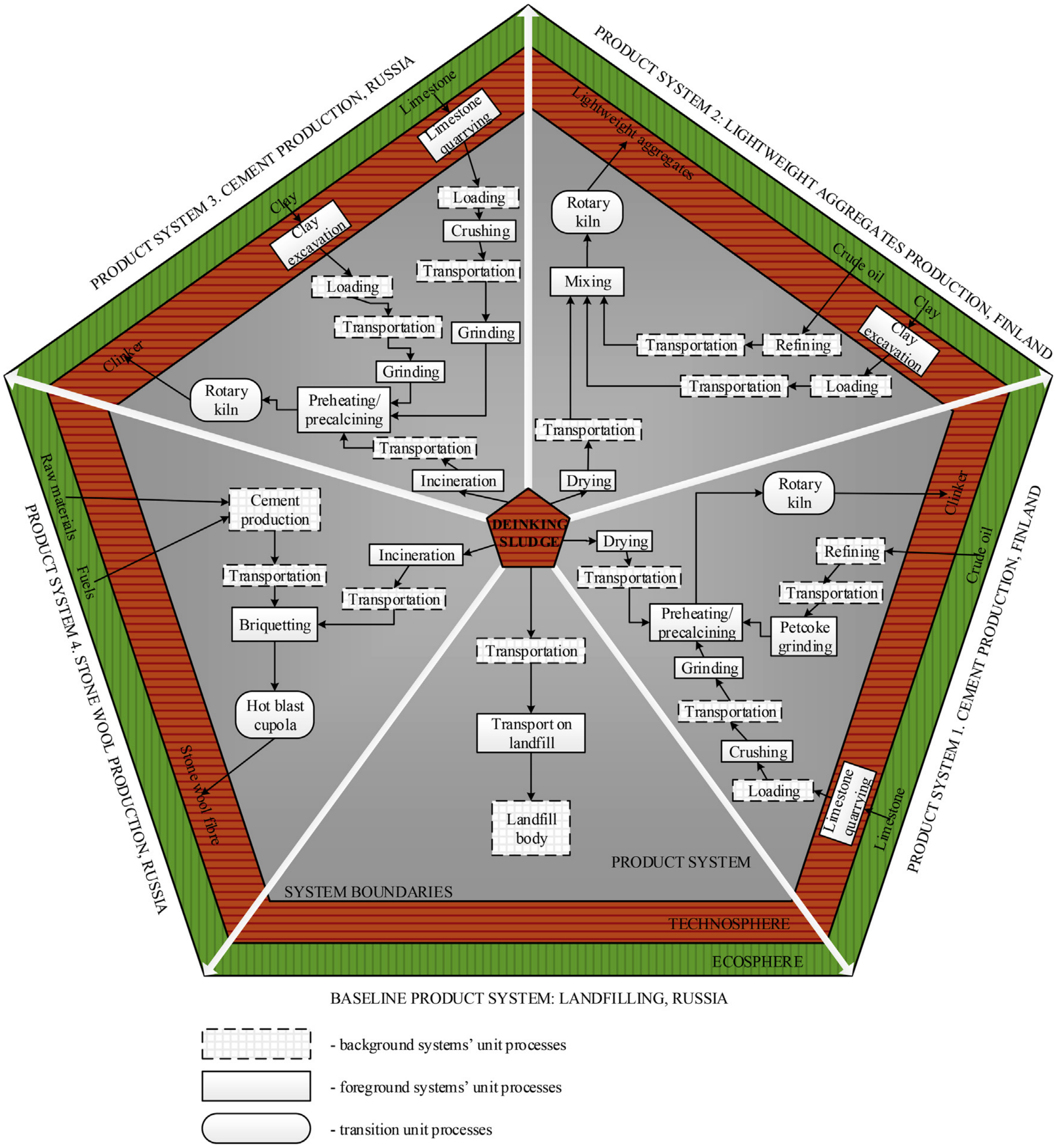


Fig. 2. Product systems of chosen deinking sludge utilization alternatives and their system boundaries.

Feiz et al. (2015). Feiz et al. (2015) showed that the extraction of limestone accounts for only 0.1% of the total GHG emissions of clinker cradle-to-gate life cycle, while the most important source of emissions during the extraction phase is electricity generation, which is included in the study. Moreover, the primary emission released during extraction is particulate matter, which does not contribute to the impact categories considered in this work. Lastly, the environmental impact caused by deinking sludge storage and feeding to the PSs is omitted from the analysis since the impact is expected to be similar in all scenarios.

The unit processes within the system boundaries belong either to a background or foreground system. The background system contains the unit processes that are not study-specific, whereas the foreground system is represented by study-specific unit processes. The differentiation between the systems affects the type of data used in the study with mainly primary data being used in the foreground unit processes and secondary data for the background ones. Additionally, the system boundaries include transition unit processes, which are the processes that enable deinking sludge conversion into the product of a particular PS.

2.5. Life cycle inventory

LCI is an LCA phase for the quantification of inputs and outputs of the systems being studied within its system boundaries and was performed for each scenario of the study.

2.5.1. Background system

The background system unit processes included in this study were taken from the GaBi professional database with extensions 2014, which includes high-quality LCI profiles based on primary data (PE International, 2014). Moreover, GaBi is one of the leading software tools for LCA studies (Herrmann and Moltesen, 2015). Table 3 contains information about the unit processes used, their

Table 3
Unit processes of the background system and distances used for transportation modelling.

Name	Location in the model	Function served	Distance, km	Payload capacity, t
GLO[a]: Truck	S0-LF_{RU}	Deinking sludge transportation	110	5.7
	S1-CEM_{FI}	Limestone transportation	4	12.4
		Dry deinking sludge transportation	90	5.7
	S2-LWA_{FI}	Clay transportation	26	11
		Dry deinking sludge transportation	270	5.7
	S3-CEM_{RU}	Limestone transportation	60	12.4
		Clay transportation	28	11
		Deinking sludge ash transportation	700	5.7
	S4-SW_{RU}	Cement transportation	600	5.7
		Deinking sludge ash transportation	120	8.7
GLO: Bulk commodity carrier	S1-CEM_{FI}	Petrol coke shipping	9150	
GLO: Truck-trailer	S2-LWA_{FI}	Heavy fuel oil transportation	170	
GLO: Excavator	S1-CEM_{FI}	Limestone loading		
	S2-LWA_{FI}	Clay loading		
	S3-CEM_{RU}	Limestone loading		
		Clay loading		
EU-27[b]: Diesel mix at refinery	All	Trucks and excavators fuelling		
FI[c]: Electricity grid mix	S1-CEM_{FI}	Electricity supply		
	S2-LWA_{FI}			
RU[d]: Electricity grid mix	S1-CEM_{FI}	Electricity supply		
	S2-LWA_{FI}			
	S3-CEM_{RU}			
	S4-SW_{RU}			
FI: Natural gas mix	S1-CEM_{FI}	Natural gas supply		
	S2-LWA_{FI}			
US[e]: Petrol coke at refinery	S1-CEM_{FI}	Petrol coke supply		
US: Heavy fuel oil at refinery (0.3wt.% S)	S1-CEM_{FI}	Bulk commodity carrier fuelling		
EU-27: Heavy fuel oil at refinery (1.0wt.% S)	S2-LWA_{FI}	Heavy fuel oil supply		
RER[f]: Portland cement (CEM I)	S4-SW_{RU}	Portland cement supply		

[a] The data set of the unit process is representative globally.
[b] The data set of the unit process is representative in EU-27 member countries.
[c] The data set of the unit process is representative in Finland.
[d] The data set of the unit process is representative in Russia.
[e] the data set of the unit process is representative in the USA.
[f] The data set of the unit process is representative in Europe.

location in the LCA model, and the function which the unit processes serve.

Most of the processes presented in Table 3 were not modified, with the exception of the processes used for transportation, that is, truck, truck-trailer, and bulk commodity carrier. Driving distance from the place of origin of the material to the place of the final utilization was changed so that the modelling data corresponded to the real world situation as closely as possible. Distances used in the study are presented in Table 3.

2.5.2. Foreground system

The foreground system is a system of study-specific unit processes directly related to the deinking sludge utilization. The foreground unit processes belong to different PSs and deinking sludge pretreatment methods like drying and incineration, as shown below.

2.5.2.1. PS0-LF_{RU}. Information concerning the amounts and composition of landfill gas at the landfill is confidential and not disclosed to the public according to Russian legislation. Thus, to quantitatively estimate the emissions caused by deinking sludge landfilling, landfill gas generation was calculated using a methodology developed by the scientific industrial enterprise “Logus” (Scientific Industrial Enterprise “Logus”, 2004). The methodology was developed for the calculation of airborne emissions resulting from the landfilling of municipal solid and industrial waste and taking account of such factors as waste composition and ambient air temperature that directly influence the amount and composition of landfill gas generated. The methodology is included in the catalogue of methodologies used for calculation, standardization, and monitoring of airborne emissions (Research Institute “Atmosphera”, 2013) which means that it has an official status in the current Russian legislation.

As well as the calculation of the emissions caused by biological decomposition of the deinking sludge, emissions caused by transport operations on the landfill were also calculated. Both calculations are presented in Supplementary Information S2.

2.5.2.2. PS1-CEM_{FI}. Inventory data used in the modelling of Scenario 1 was mainly retrieved from the cement plant data sources. The LCI data regarding cement plant operations, raw materials, fuels, and electricity consumption were taken from the most recent environmental permit of the cement plant under the study (Kaakkois-Suomen Ympäristökeskus, 2006). Unfortunately, no newer environmental permit including overall raw materials and fuels consumption has been issued, while subsequent permits have been related to small modifications to the plant and do not contain information of use for this study. Information about the emissions released by the plant was taken from the environmental profile report of the plant (VTT, 2011). Energy basis allocation was applied to assign specific amounts of emissions to each fuel type. Environmental impact from limestone crushing performed by a limestone quarrying company was evaluated using data from its environmental permits (Aluehallintovirasto, 2010; Kaakkois-Suomen Ympäristökeskus, 2004a).

2.5.2.3. PS2-LWA_{FI}. The LCI data was compiled from the environmental permit of the company (Kaakkois-Suomen Ympäristökeskus, 2004b), the Vahti database of the Finnish Environment Administration (Finnish Environment Administration, 2013), and company representatives.

2.5.2.4. PS3-CEM$_{RU}$. The inventory data were retrieved from multiple sources. Production capacity, share of raw materials consumed, their composition, and data about electricity consumption were provided by cement plant representatives. Data about the total consumption of raw materials and electricity distribution were taken from the best available techniques (BAT) reference document for the production of cement, lime, and magnesium oxide (European Commission, 2013) and Alsop et al. (2003), respectively. Emissions from limestone calcination were calculated using the methodology developed by the U.S. EPA (1998).

2.5.2.5. PS4-SW$_{RU}$. The LCI data for the scenario were compiled from several sources. The only primary data used in the model is the production capacity of the plant (Delovoi Peterburg, 2012). The remaining information concerning raw materials, fuels, and electricity consumption was taken from an LCA report about stone wool production prepared by Flury and Frischknecht (2012).

2.5.2.6. Drying. Emissions released during deinking sludge drying were measured in the laboratory using a Gasmet™ DX4000 gas analyzer for gas sampling and Calcmet™ software for spectrum analysis. Emissions from fuel combustion needed for sludge drying were calculated using the methodologies developed by the Research Institute "Atmosphera" (2003, 1999). The LCI of deinking sludge drying is presented in Supplementary Information S3.

2.5.2.7. Incineration. Emissions from deinking sludge mono-incineration were calculated using the methodologies developed by the Research Institute "Atmosphera" (2003, 1999). The LCI of deinking sludge incineration is presented in Supplementary Information S3.

2.6. Life cycle impact assessment

In the study, the following impact categories were used to assign LCI results to specific environmental issues: Global Warming Potential (GWP) excluding biogenic carbon for 100 years, Ozone layer Depletion Potential (ODP), Terrestric EcoToxicity Potential (TETP), Acidification Potential (AP), Eutrophication Potential (EP), and Abiotic Depletion Potential (ADP). The impact categories belong to the CML 2001 impact assessment method, a method widely used by LCA practitioners, and which presents robust results compared to other impact assessment methods (Martínez et al., 2015). The characterization factors of the method are from November 2010. All impact categories, except ADP, were included in the study since they are assigned high impact factors in the CML 96 "Sustainable Development" weighting model, a model that depicts the potential of different impact categories to affect sustainable development. The inclusion of ADP in the study was determined by the goal of the study, which aims at the substitution of abiotic resources and, thus, the potential reduction of ADP.

3. Results and discussion

3.1. Life cycle inventory analysis

The main inputs and outputs of each PS included in the LCA study are summarized in Table 4. The table shows that only a part of the total annual deinking sludge produced can be utilized in PS2-LWA$_{FI}$ and PS4-SW$_{RU}$. The excess deinking sludge was modelled as being landfilled. In Scenario 2, all heavy fuel oil conventionally consumed by the production process was substituted with deinking sludge.

Table 4 shows that the amount of diesel consumed increased in PS1-3, with the lowest increase, by 10%, in PS3-CEM$_{RU}$, and the highest, by 110%, in PS1-CEM$_{FI}$. The increase was due to the sources of conventionally consumed raw materials and fuels transported by truck being located closer to the production processes than the case study paper mill, as well as the need to transport more deinking sludge than the ordinarily consumed resources, mainly as a result of the lower energy and calcium content of the sludge. In PS4-SW$_{RU}$, however, deinking sludge ash substituted cement, which was modelled as being transported from the closest Russian cement plant. This plant is more remote than the case study paper mill, which led to a reduction in diesel consumption by 18%.

Changes of nitrogen oxide and dioxide emissions were caused by different processes. The amount of diesel consumed by truck transport influenced the nitrogen monoxide emissions directly. The LCI results analysis demonstrated that approximately 97% of the relative change of NO emissions in PS1-CEM$_{FI}$ was caused by deinking sludge transportation alone. Nitrogen dioxide emissions were mainly released during deinking sludge pretreatment processes and transportation. Sludge drying and transportation resulted in 74% and 27% of the relative change of NO_2 emissions in PS1-CEM$_{FI}$. The sum is over 100% since there were reductions of NO_2 due to for example reduced transportation of limestone and reduced petcoke production. Similar tendencies were noticed in the other PSs.

Changes in the NO_x and SO_2 emissions had different causes. In PS1 and 2, most of the reduction in the relative changes of NO_x emissions (82% and 90%) and SO_2 emissions (98% and 106%) was due to the reduced emissions from the avoided fuel combustion and production. At the same time, increased electricity consumption caused an increase in the NO_x emissions (110% and 137% relative change) and SO_2 emissions (88% and 115% relative change) in PS3 and 4.

3.2. Life cycle impact assessment

3.2.1. Baseline scenario

When considering the entire system of the study shown in Fig. 2, the unit processes included in the baseline scenario, mainly the landfill body, often had a low proportional impact on the environment, as shown in Fig. 3. The results indicate that the baseline scenario had the greatest impact on GWP, accounting for 11.6% of the total GWP of the five PSs included in the study. The impact was primarily associated with the release of methane generated at the landfill. Likon and Saarela (2012) assessed the carbon footprints of absorbent production from paper mill deinking sludge and calculated that 2.1 kg CO_2-eq/1 kg of wet sludge is emitted during uncontrolled sludge landfilling. In our research, the calculated results indicated that 2.4 kg CO_2-eq/1 kg of deinking sludge landfilled was released.

The emissions of nitrogen oxides and ammonia generated under microbial activity contributed to AP and EP by 2.4% and 5.5%, respectively. Nearly 7% of TETP of the entire system associated with the baseline scenario was mainly related to methanal formaldehyde release.

3.2.2. Utilization scenarios

Changes in the environmental impact caused by the implementation of Scenarios 1–4 are presented in Fig. 4, while the absolute values are presented in Table 5. Each graph contains information about a single scenario. The changes in the environmental impact are defined as the difference between the impact of the baseline scenario and a PS of a certain scenario before and after deinking sludge was supplied to the PS divided by the initial impact of the baseline scenario and the same PS.

The changes in the impact were divided into four categories to enable clearer interpretation of the results. One of the categories

Table 4
Selected inputs and outputs of five deinking sludge utilization product systems for one year.

Inputs	Amount		Unit	Relative change, %	Outputs	Amount		Unit	Relative change, %
	Before	After				Before	After		
Baseline product system									
Deinking sludge	5.48E+07	0.00E+00	kg	−100%	CO_2	8.55E+05	0.00E+00	kg	−100%
Diesel	2.53E+05	0.00E+00	kg	−100%	CH_4	5.31E+06	0.00E+00	kg	−100%
Crude oil	1.13E+07	0.00E+00	MJ	−100%	NO	5.28E+03	0.00E+00	kg	−100%
					NO_2	1.14E+04	0.00E+00	kg	−100%
					NO_x	5.14E+02	0.00E+00	kg	−100%
					SO_2	1.44E+03	0.00E+00	kg	−100%
Product system 1: cement production, Finland									
Deinking sludge	0.00E+00	5.48E+07	kg	100%	Clinker	3.82E+08	3.82E+08	kg	0%
Diesel	1.05E+05	2.21E+05	kg	110%	CO_2	2.33E+08	2.19E+08	kg	−6%
Electricity	5.18E+07	5.17E+07	MWh	−0.13%	CH_4	9.63E+04	7.35E+04	kg	−24%
Natural gas	1.32E+08	2.10E+08	MJ	60%	NO	3.97E+02	3.23E+03	kg	714%
Crude oil	4.36E+08	2.47E+08	MJ	−43%	NO_2	4.87E+01	8.41E+02	kg	1628%
Petcoke	1.40E+07	7.56E+06	kg	−46%	NO_x	1.89E+05	1.44E+05	kg	−24%
Limestone	5.48E+08	5.34E+08	kg	−2.7%	SO_2	9.79E+04	7.32E+04	kg	−25%
Product system 2: lightweight aggregates production; Finland									
Deinking sludge	0.00E+00	8.41E+06	kg	100%	LWA	1.05E+05	1.05E+05	kg	0%
Diesel	1.80E+05	2.30E+05	kg	28%	CO_2	7.81E+06	3.99E+06	kg	−49%
Electricity	7.29E+06	7.29E+06	MWh	0%	CH_4	9.14E+03	7.11E+03	kg	−22%
Natural gas	1.71E+07	2.82E+07	MJ	65%	NO	1.09E+03	2.33E+03	kg	114%
Crude oil	5.64E+07	1.19E+07	MJ	−79%	NO_2	8.43E+01	2.46E+02	kg	192%
Clay	2.03E+08	2.03E+08	kg	0%	NO_x	1.80E+04	9.49E+03	kg	−47%
Heavy fuel oil	1.14E+06	0.00E+00	kg	−100%	SO_2	1.66E+04	7.07E+03	kg	−57%
Product system 3: cement production; Russia									
Deinking sludge	0.00E+00	5.48E+07	kg	100%	Clinker	1.49E+09	1.49E+09	kg	0%
Diesel	3.23E+06	3.56E+06	kg	10%	CO_2	7.48E+08	7.46E+08	kg	−0.2%
Electricity	1.01E+08	1.06E+08	MWh	5.5%	CH_4	1.40E+05	1.51E+05	kg	8.0%
Natural gas	6.78E+08	7.16E+08	MJ	5.6%	NO	7.31E+04	8.13E+04	kg	11%
Crude oil	1.75E+08	1.92E+08	MJ	9.3%	NO_2	5.60E+03	1.00E+04	kg	79%
Clay	2.08E+08	2.04E+08	kg	−1.9%	NO_x	1.95E+05	2.05E+05	kg	5.5%
Limestone	1.76E+09	1.74E+09	kg	−0.89%	SO_2	2.72E+05	2.88E+05	kg	5.9%
Product system 4: stone wool production; Russia									
Deinking sludge	0.00E+00	8.10E+06	kg	100%	Stone wool	7.00E+07	7.00E+07	kg	0%
Diesel	1.37E+05	1.12E+05	kg	−18%	CO_2	1.91E+07	2.12E+07	kg	11%
Electricity	2.08E+07	2.72E+07	MWh	31%	CH_4	3.11E+04	3.85E+04	kg	24%
Hard coal	2.55E+07	3.34E+07	MJ	31%	NO	3.25E+03	2.74E+03	kg	−16%
Crude oil	1.26E+07	1.34E+07	MJ	7.0%	NO_2	2.53E+02	7.74E+02	kg	206%
Limestone	9.57E+06	7.19E+06	kg	−25%	NO_x	5.20E+04	6.07E+04	kg	17%
Cement	7.28E+06	5.46E+06	kg	−25%	SO_2	6.07E+04	7.48E+04	kg	23%

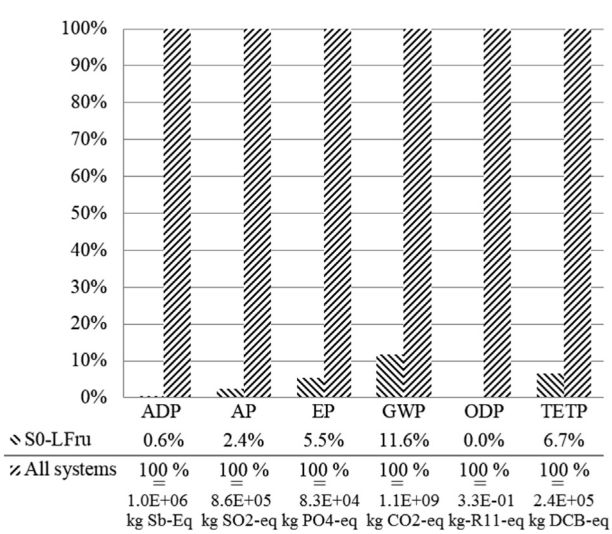


Fig. 3. Share of environmental impact caused by the baseline scenario, i.e. deinking sludge landfilling, compared to the reference level of emissions, i.e. total emissions from five scenarios included in the study.

was "Sludge preparation", which included the unit processes needed to dry or incinerate deinking sludge depending on the requirements of a production process. The impact under the "Product system" category was associated with the avoided emissions from the production process due to the substitution of certain materials with deinking sludge. Another category—"-Transportation"—represented the relative impact of the processes related to the transportation of all raw materials, fuels, and deinking sludge, as well as the production of fuel for the vehicles. The last category—"Avoided landfilling"—represented the impact of a baseline scenario that would not occur due to the deinking sludge utilization in a production process. The impact of the baseline scenario was included in the study since the study is a comparative LCA and presents the results as consequences of the particular changes in the systems being studied. The relative impact caused by either of the categories mentioned above, as well as the net impact, is shown in the tables below the graphs in Fig. 4. It should be noted that the changes presented in Fig. 4 for each of the scenarios cannot be compared as absolute values since the systems being compared are not identical. The comparison of different scenarios is handled in Section 3.2.4.

Fig. 4 clearly indicates that Scenarios 1 and 2 have positive effects on the environment, whereas Scenarios 3 and 4 affect the environment both positively and negatively depending on the impact category. Changes in the environmental impact are primarily associated with the avoided landfilling emissions, changes

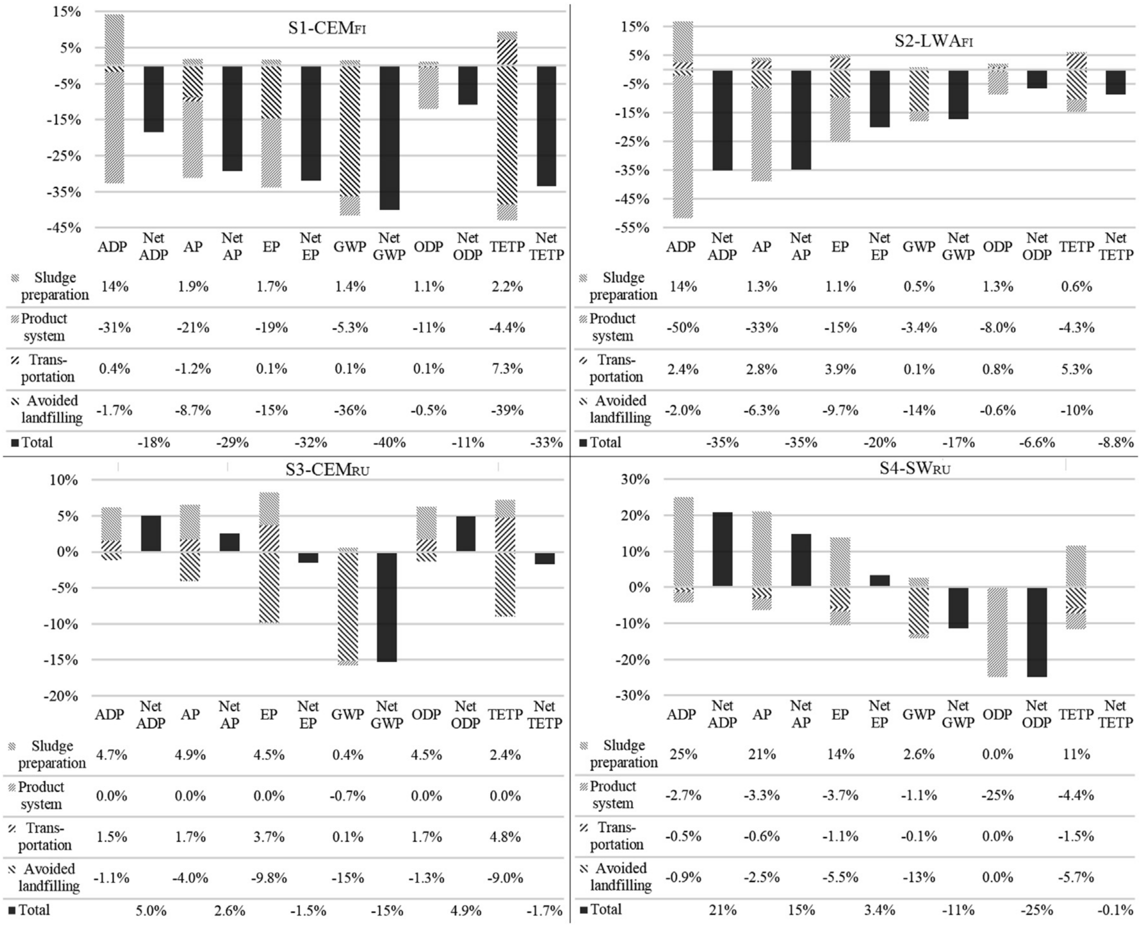


Fig. 4. Changes in environmental impact caused by implementation of the four scenarios in the study.

in the PSs, and the unit processes employed for sludge pretreatment. Transportation and production of fuel for vehicles do not contribute to the changes significantly.

Considering S1-CEM$_{FI}$, the greatest reduction, by 40%, was achieved for GWP, mainly because of the avoided landfill emissions. The significant reduction in EP, by 32%, as well as ADP and AP, by 18% and 29%, respectively, was related to the decreased consumption of petcoke. The reduced impact on TETP, by 33%, was due to the avoided emissions from the baseline scenario. ODP showed the least reduction out of all the impact categories studied, by 11%. The reduction is a result of the substitution of petcoke in the production process.

Valderrama et al. (2013) studied the utilization of dried or lime stabilized sewage sludge in a cement production process to substitute 10% of petcoke or 2.8% of limestone. Their results indicated that GWP can be reduced by 1% for fuel and 0.3% for raw material substitution, whereas in our study, a 3.8% reduction of GWP was achieved when petcoke and limestone were simultaneously substituted. The greater reduction of GWP in our study occurred because of the larger amount of petcoke substituted in our study than in the study of Valderrama et al. (2013).

Similar to S1-CEM$_{FI}$, the environmental impact of S2-LWA$_{FI}$ was reduced in all impact categories. The greatest reduction, by 35% was reached for ADP and AP, while EP was reduced by 20%. In all three categories, the reduction was due to a decrease in the impact of the PS, mainly as a result of the substitution of heavy fuel oil. The least notable reduction in the scenario was for ODP. It can be noticed from Fig. 4 that the avoided impact from deinking sludge landfilling does not contribute to the overall change as much as in S1-CEM$_{FI}$. This is because in S2-LWA$_{FI}$ not all the deinking sludge is supplied to the production process but some is still landfilled, which affects the environment negatively. The environmental impact associated with the deinking sludge pretreatment in S2-LWA$_{FI}$ was less than the avoided impact from heavy fuel oil substitution. This finding does not apply to the other scenarios.

Table 5
Absolute values of changes caused by implementation of the four scenarios.

Impact category	Unit	S1-CEM$_{FI}$			S2-LWA$_{FI}$			S3-CEM$_{RU}$			S4-SW$_{RU}$		
		Before	After	Difference	Before	After	Difference	Before	After	Difference	Before	After	Difference
ADP	kg Sb-Eq.	3.41E+05	2.78E+05	−18%	4.88E+04	3.17E+04	−35%	5.16E+05	5.42E+05	5.0%	1.11E+05	1.34E+05	21%
AP	kg SO_2-Eq.	2.35E+05	1.66E+05	−29%	5.07E+04	3.30E+04	−35%	5.11E+05	5.24E+05	2.6%	1.24E+05	1.42E+05	15%
EP	kg PO_4^--Eq.	3.11E+04	2.11E+04	−32%	7.24E+03	5.77E+03	−20%	4.65E+04	4.58E+04	−1.5%	1.22E+04	1.27E+04	3.4%
GWP	kg CO_2-Eq.	3.69E+08	2.21E+08	−40%	1.42E+08	1.18E+08	−17%	8.85E+08	7.50E+08	−15%	1.54E+08	1.36E+08	−11%
ODP	kg R11-Eq.	3.27E−03	2.91E−03	−11%	4.02E−04	3.75E−04	−6.6%	1.16E−03	1.22E−03	4.9%	3.20E−01	2.40E−01	−25%
TETP	kg DCB-Eq.	4.11E+04	2.74E+04	−33%	2.41E+04	2.20E+04	−8.8%	1.77E+05	1.74E+05	−1.7%	4.28E+04	4.28E+04	−0.1%

In S3-CEM$_{RU}$, the environmental impact on ADP, AP, and ODP due to deinking sludge incineration and changes in the transportation exceeded the avoided the impact from deinking sludge landfilling together with the reduced impact due to the substitution of limestone and clay in the production process. Fig. 3 clearly indicates that the impact from the PS changes is nearly zero for each impact category. This result is caused by the low substitution rate of the raw materials with deinking sludge and because of the insignificant environmental impact caused by raw materials extraction, preparation, and utilization in the production process. Nevertheless, deinking sludge utilization in the Russian cement plant had a positive impact on EP, TETP and, most notably, on GWP. The 15% reduction in GWP was possible due to the avoided methane emissions from the landfill.

In S4-SW$_{RU}$, the impact on ADP, AP, and EP associated with deinking sludge incineration and transportation changes was higher than that from the PS changes and the avoided emissions from the baseline scenario. In the scenario, only 15% of deinking sludge was utilized while the rest was landfilled. ADP increased by 21%, AP by 15%, and EP by 3.4%. On the other hand, GWP was reduced by 11%, and ODP by 25%. The decrease in GWP was mainly due to the avoided landfilling emissions. The reduction in ODP occurred due to the reduced cement consumption and the avoidance of emissions of halon, which is emitted during cement production and included in the GaBi database.

3.2.3. Sensitivity analysis

Sensitivity analysis was performed to estimate the importance of raw materials and fuel substitution rates on the research findings. The variation of raw materials and fuel substitution rates by 20% described the possible variation of deinking sludge properties, such as heating value and content of calcium oxides and other elements enabling deinking sludge utilization. The values for sensitivity analysis used in the study are presented in Table SI1.3 of Supplementary Information 1. Fig. 5 presents information on which resources have the greatest effect on the environment and which impact categories are more sensitive to substitution rate variation.

In Scenario 1, the change in the limestone substitution rate did not lead to a significant variation in the environmental impact results, with the greatest change being less than 0.2%, for GWP. A change in the petcoke substitution rate resulted in greater variation, namely, approximately 6% for ADP, AP, and EP. This finding mirrors that of Valderrama et al. (2013), who presented that fuel substitution results in greater environmental impact reduction than raw material substitution.

Substitution rate variation in Scenario 2 had little effect on most of the impact categories. The greatest change was in GWP, by 2.7%. The use of an alternative methodology for the substitution rate calculation based on the energy consumption resulted in GWP change of 5.1%. Scenario 3 showed least dependence on the substitution rate and the variation did not exceed 0.12% when the substitution rates of both limestone and clay were varied. Scenario 4 showed the greatest dependence of ODP on the substitution rate, 5%.

3.2.4. Comparison between scenarios

As was stated earlier, the systems assessed in the study are not directly comparable due to the different substitution rates and

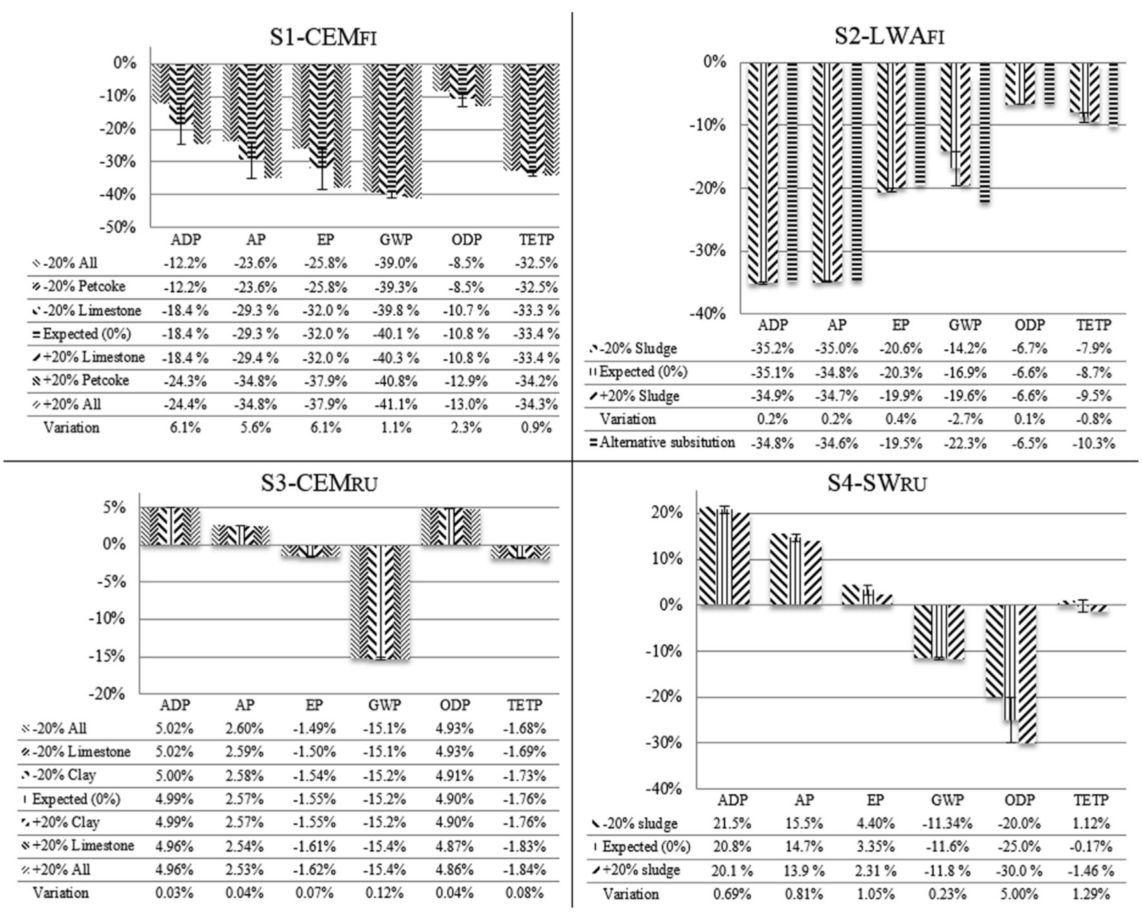


Fig. 5. Sensitivity analysis of substitution rates.

amounts of materials substituted. Thus, to enable comparison, the life cycle impact assessment results were normalized to the total impact caused by all systems studied. The comparative results of environmental impact changes are presented in Fig. 6.

The most notable reduction in the environmental impact occurs when deinking sludge is utilized as described in S1-CEM$_{FI}$. GWP and AP were reduced by 12%–13%, which is the greatest impact reduction of the impact categories studied. Scenario 3 similarly allowed a significant reduction in GWP, by 12%, whereas the other scenarios only resulted in a slight decrease in GWP, by not more than 2.1%. In S3-CEM$_{RU}$, there was a slight negative impact of 2.6% and 1.5% on ADP and AP, respectively, whereas EP and TETP were reduced by 0.9% and 1.3%.

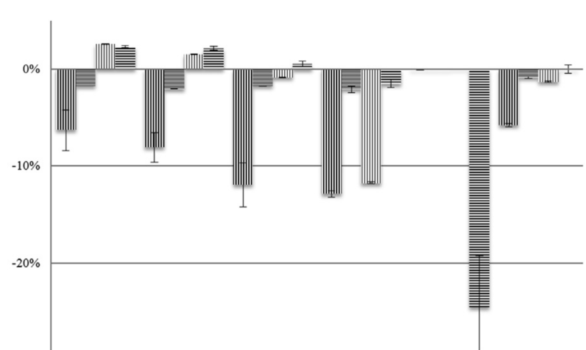
S2-LWA$_{FI}$ led to an overall reduction in the environmental impact, although the degree of the reduction was much smaller than in S1-CEM$_{FI}$, due to only partial utilization of the deinking sludge in the production process. The variation for all impact categories, with the exception of ODP, was between 0.9% and 2.1%. ODP changed by 0.01% due to the significant contribution of S4-SW$_{RU}$ to the overall ODP reduction in the system.

The implementation of S4-SW$_{RU}$ led to the greatest reduction in ODP, by 25%, clearly surpassing the reduction in ODP of the other scenarios which was in the order of 0.01–0.11%. The sensitivity analysis indicates that the reduction is highly dependent on the substitution rate used and the high value in Scenario 4 is primarily due to reduced cement production and consequent reduction in halon emissions. The effect on the rest impact categories varies from a 1.5% reduction in GWP to an increase in ADP, AP, and EP by 2.3%, 2.1%, and 0.5%, respectively.

4. Conclusions

This study conducted an LCA of five possible deinking sludge management approaches, four of which involved sludge utilization in the construction materials production, and one—landfill disposal—represented the current practice. The results of the study showed that the use of deinking sludge in a cement production plant as described in S1-CEM$_{FI}$ to substitute a part of petcoke and limestone resulted in the greatest reduction in the environmental impact in all the impact categories studied. GWP and EP were reduced by 13% and 12%. S2-LWA$_{FI}$ also gave an overall reduction of environmental impact, though to a lesser extent than S1-CEM$_{FI}$. The environmental impact reduced from 0.9% to 2.1% for all impact categories. S3-CEM$_{RU}$ led to a significant reduction in GWP by 12%, although ADP increased by 2.6%, the greatest increase in all the categories studied. S4-SW$_{RU}$ resulted in a large reduction in ODP, by 25%, which was due to the avoidance of cement production and related emissions of halon.

The study showed that the substitution of fuels led to a greater reduction in the environmental impact than the substitution of raw materials like limestone and clay. On the basis of the results, it can be concluded that the utilization of deinking sludge rather than its landfilling results in improved environmental quality supporting waste paper recycling as a part of a circular economy and cleaner production. The results could be used by decision-makers to improve overall environmental profile of the tissue production from recovered paper, as well as to help to identify the most environmentally-oriented deinking sludge utilization possibility.



	ADP	AP	EP	GWP	ODP	TETP
S1-CEM$_{FI}$	-6.3%	-8.0%	-12%	-13%	-0.11%	-5.8%
S2-LWA$_{FI}$	-1.7%	-2.1%	-1.8%	-2.1%	-0.01%	-0.89%
S3-CEM$_{RU}$	2.6%	1.5%	-0.86%	-12%	0.02%	-1.3%
S4-SW$_{RU}$	2.3%	2.1%	0.50%	-1.5%	-25%	-0.02%

Fig. 6. Normalized LCIA results.

Acknowledgements

The research was financially supported by the South-East Finland–Russia ENPI CBC 2007–2013 program through the EMIR project. The authors are grateful to SCA Hygiene Products Russia for providing deinking sludge samples and valuable information. The authors thank Peter Jones for his assistance with the English language.

Appendix A. Supplementary data

Supplementary data related to this article can be found at http://dx.doi.org/10.1016/j.jclepro.2015.10.022.

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