Compositional analysis of seasonal variation in Danish residual household waste

Seasonal variations are considered one of the key factors affecting the generation and composition of residual waste. Despite this importance, attempts have not been made to characterize residual household waste consistently by accounting for seasonal variations in waste disposal patterns. To assess differences between seasons and within individual households, we collected residual household waste from the same 101 households in summer, autumn and winter. The waste bags were sorted individually, and residual household waste data (mass and composition) were generated for each household. In total, 3 t of waste were collected, weighed and manually sorted into nine (9) waste fractions. The result of mixed linear model indicated that for this study area, seasonal variations may introduce no significant difference to the mass and composition of residual household waste. However, residual waste generation within a household may change significantly between the seasons. The result also showed that while household size may significantly influence the generation of residual household, the difference in residual household waste composition was not significantly different between household sizes.

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An MFA-based optimization model for increased resource efficiency: Phosphorus flows in Denmark

Phosphorus (P) is present in large amounts in agricultural residues and organic wastes from human consumption, from which it can be recovered as fertiliser, reducing dependence on primary P. Crucial for a secondary resource is its ability to fulfil the functions of the resource intended to be substituted. This quality of secondary resources is not captured well by material flow analysis (MFA). A static MFA of the Danish anthropogenic P cycle was adapted for optimization via linear programming to minimize primary P imports. The MFA system was adapted to reflect typical nutrient availability from various secondary-P fertilisers, to allow for exchange of secondary-P fertilisers between regions (sewage sludge incineration ash and composted organic household waste), and to reflect the system's development over 3 annual time steps. Since P accumulating in agricultural soil gradually becomes available for plants over time, the outcome showed both a gradual decline of mineral P fertiliser inputs and net additions to soil P stocks stabilising at distinctly lower levels than evident from the static MFA. The optimization model's outcome, accounting for the dynamic aspects of transport and P availability to crops over time, suggests a substitution potential of over 80% (9.8 Gg primary P) by P recovered from sewage sludge and household biowaste, compared to 35% in the static MFA.
Challenge of material recycling at large public events

Large public events such as festivals, sports events or national celebrations tend to attract a considerable number of people. While some of the events are important sources of entertainment for the participants, such gatherings create a challenge to organize and maintain a functioning infrastructure. Sound waste management is one of the challenges. Some preliminary results presented here, concern waste material flows at a large public event, illustrated on the example of Roskilde Festival (Denmark). Roskilde Festival is a large annual event, which attracts more than 120,000 participants and generates more than 2000 tonnes of waste over eight days. In 2016, approximately 16% of the total waste generated was either recycled or sent to special treatment, the remaining (approximately 85%) ended up as residual waste and was sent to a waste-to-energy facility. While measures to promote material recycling at the festival have been implemented, our preliminary results suggest that there is currently large potential to recover additional materials for recycling and improve sustainability at large public events.

Challenges to a circular economy – the presence of impurities in wood waste for recycling

The combustion of wood chips and wood pellets for the production of renewable energy in Denmark increased from 5.7 PJ to 16 PJ during the period 2000-2015, and further increases are expected to occur within the coming years. In 2012, about 22,300 tonnes of wood ashes were generated in Denmark. Currently, these ashes are mainly landfilled, despite Danish legislation allowing their application onto forest and agricultural soils for fertilising and/or liming purposes. During this PhD work, 16 wood ash samples generated at ten different Danish combustion plants were collected and characterised for their composition and leaching properties. Despite the relatively large variations in the contents of
nutrients and trace metals, the overall levels were comparable to typical ranges reported in the literature for other wood combustion ashes, as well as with regards to leaching. In general, the composition of the ashes complied with Danish ash quality criteria, indicating that they may be applied onto forest soil. However, according to EU landfill waste acceptance criteria, the leachates corresponded to “non-hazardous” or “hazardous” waste, thereby suggesting that recirculation of the same ashes to forestry land may constitute an environmental issue as a result of leaching, especially with regards to Cr and Se.

The release of nutrients and contaminants from two selected wood ash samples (corresponding to one mixed ash sample and one fly ash sample) was estimated based on selected pH conditions and data for both short- and long-term leaching. Acidic conditions relevant for typical forest soils in Denmark indicated considerably higher releases of Cd, Mg, Zn and P compared with releases of the natural ash pH (more than two orders of magnitude difference). The leaching of Cl, K, Na and S was rather pH-independent, high during the initial leaching and most likely governed by the availability of these elements in the ash matrix. On the other hand, the leaching of Al, Ba, Ca, Cr, Mg, Sb, V and Zn was distributed over a wider liquid-to-solid (L/S) interval and differences of at least one order of magnitude were shown between the observed cumulative releases at L/S 10 L/kg and L/S 1000 L/kg. Relatively large fractions of P (i.e. 33 % and 48 % of the fly ash and mixed ash P contents, respectively) were observed to dissolve after extraction with neutral ammonium citrate, which indicated the potential use of wood ashes as a P supplement for the soil.

The release of major elements such as Al, Ba, Ca, Fe, Mg, Si, P and S was governed mainly by mineral solubility. The most likely minerals governing the release of these elements were found to be in general agreement with mineral phases identified in the literature for other wood combustion ashes, but also municipal solid waste incineration ashes. The leaching of trace elements, such as Cu, Cr, Pb and Zn, was described adequately as a combination of mineral solubility, adsorption onto Al/Fe (hydr-) oxides and complexation with dissolved organic matter.

The influence of common ash pre-treatments, such as hardening (also known as ageing or maturing) and granulation, on ash chemistry, liming potential and leaching behaviour was investigated through a series of laboratory experiments. Ash granules were relatively hard (barely breakable by finger-pinning) and demonstrated a reduced leaching compared to loose ashes, an effect that appeared to be related to the specific surface area granules. Ash granules may be used in actual field applications to minimise dust generation. Hardening affected the mineralogical structure of the ashes, but their overall acid neutralisation capacity remained practically constant. Column leaching tests showed that hardened ashes presented pH levels about two units lower than fresh ashes and a reduced leaching of alkalinity. The leaching of As, P, Sb and V increased after hardening, while the leaching of Ba, Ca, Pb and Zn was generally reduced to concentration levels below or close to limit of quantitation levels. Ash hardening was observed to be a relatively simple and fast treatment. Preferably, this process should be carried out under controlled conditions, before the ashes are applied, as this will minimise their overall reactivity as well as the leaching of most trace elements.

The effects of ash application on the mobility of nutrients and trace elements in soil pore water were evaluated through a series of column experiments. The two uppermost soil horizons of a Danish nutrient-poor forest soil were tested against three ash dosages, namely 3, 9 and 30 tonnes/ha. Ash application promoted the release of nutrients such as K and P during the entire duration of the experiment, corresponding to about eight field-scale years. A short-term release of Cl, K, Mg and S was also observed within the first 500 L/m² of infiltrating water (corresponding to fewer than two years on the field scale). While an overall increase in the leached amounts of As and Cu from the organic soil horizon were observed in the case of ash application (from 2.2 to 5.0-5.8 mg/m² for As and from 2.0 to 4.9-7.6 mg/m² for Cu), their concentration levels in the percolating soil solutions was generally within Danish groundwater quality criteria. Though the effects of both the 3 and 9 tonnes/ha dosages were limited and comparable, the use of 30 tonnes/ha indicated considerably larger amounts of K, Mg, S and Si within the first 500 L/m² (at least five times larger than the soil controls). Furthermore, because of the low mobility of many trace elements, such as Cd, Cr, Ni, Pb and Zn, potential accumulation of these elements on the forest floor should be evaluated. Consequently, such high dosages cannot be recommended based on these experiments.

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Characterization of waste from nanoenabled products: Occurrence, distribution, fate and nanoparticle release

In the last decades, benefits provided by nanotechnology have been utilised for example to increase the sustainability and functionality of consumer products. Engineered nanomaterials (ENMs) are widely used in consumer products across different applications, but their use in nanoproducts has not been regulated specifically - as is the case for other chemicals and substances. This has caused concern regarding the possible release and effects of ENMs during the life cycle of nanoproducts. Specifically knowledge regarding the end-of-life phase is limited. In order to assess the potential environmental exposure or risks associated with ENMs in waste from nanoproducts, it is necessary to investigate what ENMs are being used and to which extent, how they are treated at the end-of-life of the nanoproduct and, finally, what is the likelihood of them being released during waste treatment. This PhD project addressed these knowledge gaps by mapping and analysing available nano-enabled products, developing a method for categorising waste material fractions of nanoproducts and estimating their likely waste treatment. Furthermore, new experimental data regarding ENM release from nano-enabled products was provided, applying a standardised waste characterisation test. To investigate the abundance and distribution of nanoproducts, different product inventories exist, such as BUND, PEN CPI and The Nanodatabase. However, they are all limited by the lack of available quantitative information about ENM mass or particle number in the products. Overall, the most common product applications for ENMs are the “Health & Fitness” or “Home & Garden” sector, which was still the case, despite the increasing number of nanoproducts. The product inventories PEN CPI and The Nanodatabase are based on manufacturers’ claims regarding nanotechnology, which are often unsubstantial leading to many products being registered with an unknown ENM, such as 64% of all products registered on The Nanodatabase. It was discovered that out of all ENMs registered on The Nanodatabase nano-Ag was used in the greatest number of products and in a range of product applications (e.g. in cosmetics, textiles and food containers). By utilising The Nanodatabase product inventory, a method was developed for analysing the distribution of ENMs in waste, which involved the estimation of ENM fate in selected waste treatments based on their main matrix material. This information was included on The Nanodatabase to enable the online analysis of different waste treatment scenarios. The waste treatment analysis revealed that the most significant waste material fraction was “Plastic packaging” followed by “Electronic”, “Textile” and “Multi material” waste. “Plastic packaging” waste involved mainly the large number of products sold in plastic containers, meaning that the remaining ENM mass at the time of disposal is expected to be minor. Nano-Ag was widespread across the identified waste fractions, thereby corresponding with the wide use of the material in different product categories. Furthermore, titanium-, silicon- and carbon-based ENMs were also present in several different waste material fractions (i.e. “Electronic”, “Multi material”, “Unknown”, “Plastic, other” and “Plastic, packaging”), whereas nanophasate and bamboo charcoal were only found in “Batteries” and “Textile” waste, respectively. In terms of waste treatment, it was estimated that on average in the EU around 50% of nano-enabled products are recycled, 19% are incinerated and 26% landfilled. However, these percentages depend on the specific waste treatments available in the investigated region. It is also expected that more ENMs will eventually enter a landfill, since they may accumulate in sewage sludge or waste incineration ashes, both of which are often landfilled. Another prerequisite for ENM characterisation in a waste scenario is the ability to quantify the potential ENM release from a nanowaste matrix. Experimental characterisation of ENM release from nano-enabled products or waste matrices is scarce, and most studies are limited by analytical constraints to detect the ENMs, or have investigated an artificial or “spiked” waste matrix. These studies cannot identify the behaviour of ENMs released from a real nano-enabled product nor how realistic environmental conditions will influence this release. The main challenges facing experimental nanowaste characterisation relate to the complexity of the matrices (both the waste itself and the variety of ENM and product matrix combinations), the low concentration of ENMs present in the waste and, for some ENMs, the background quantities of natural particles being high making it near impossible to distinguish between engineered and natural entities. In this thesis, selected nanoproducts were investigated using a standardised waste characterisation test and the potential ENM release was characterised using nanospecific methods, namely single particle-ICP-MS, TEM/EDX and zeta potential. Since more than 50% of ENMs are expected to be landfilled on a global scale, a standardised batch leaching test was applied to characterise the potential release of nanoproducts. The case studies represented two different types of ENMs and product matrices: self-cleaning ceramic tiles with a nano-TiO2 coating and wood painted with nano-CuO wood protection paint. Different environmental conditions were mimicked i.e. high ionic strength (added CaCl2) and addition of organic matter. For both materials, the potential ENM release under these conditions was considered to be low, but they indicated that, there was an effect of media conditions on the particles released from a nano-enabled product. For nano-TiO2-coated tiles, total titanium release was approximately 0.01 µg/g material or below detection limit, slightly higher concentrations were found in leachates from nano-enabled tiles. Particle sizes and number concentrations were below calculated limits of detection (with the exception of one sample, “Ti CAL”) and the sp-ICP-MS analysis generally suffered interference from calcium. For wood painted with nano-CuO paint, presence of nano-Cu particles, of approximately 60-80nm in size, was confirmed using sp-ICP-MS. However, these findings are associated with uncertainty, and so additional tests are needed to assess quantitatively the nano-CuO release in terms of particle size and number concentration. While these two case studies showed limited release, it cannot be excluded that other matrix and ENM combinations may cause more significant releases. New approaches concerning nanowaste characterisation, both indirect and direct methods, were presented in this thesis, but further research is needed to develop and validate these methods. Future studies, assessing the potential release of ENMs from waste, should apply nano-enabled products and different product matrix combinations to take into account the transformations of the ENMs which may occur during the product life cycle. The development of analytical methods is promising e.g. the use of fingerprinting or other tracer techniques for ENMs, and sp-ICP-MS is becoming a routine analysis, though large challenges regarding matrix complexity and interferences still persist. Considering the large number of nanoproducts available, the potential release of ENMs from these products would have to be understood to perform a risk assessment of these products. Since ENMs are considered possible contaminants of the solid waste, it is important to include nano-specific characterisation tests in waste characterisation to ensure a safe disposal of the nanowaste.
Compositional data analysis of household waste recycling centres in Denmark

The Danish government has set a target of 50% recycling rates for household waste by 2022. To achieve this goal, the Danish municipalities should increase the source separation of household waste. While significant knowledge and experiences were locally gained, lessons learnt have not been extensively exploited country-wise, an important reason being that the influence of these changes has not been rigorously investigated and quantified, meaning that generalized conclusions could not be drawn so far. One of the reasons is that a consistent calculation method to assess and document the effect of these projects on the recycling rates does not exist. Thus, compositional data analysis technique was applied to analyze consistently waste data. Based on the waste composition obtained from a recycling center in Denmark, we analyzed the composition of waste treatment and disposal options. Zero and non-zero pattern was used to describe historical changes in the definition and components of waste fractions. Variation array was applied to determine the relationship between waste treatment and disposal options. As a result, compositional data analysis technique enables to analyze waste data regardless of the unit (mass or percentage).

Environmental assessment of presence of impurity materials and chemical pollutants in wood waste meant for recycling
Environmental Multiobjective Optimization of the Use of Biomass Resources for Energy

Bioenergy is often considered an important component, alongside other renewables, to mitigate global warming and to reduce fossil fuel dependency. Determining sustainable strategies for utilizing biomass resources, however, requires a holistic perspective to reflect a wider range of potential environmental consequences. To circumvent the limitations of scenario-based life cycle assessment (LCA), we develop a multiobjective optimization model to systematically identify the environmentally optimal use of biomass for energy under given system constraints. Besides satisfying annual final energy demand, the model constraints comprise availability of biomass and arable land, technology- and system-specific capacities, and relevant policy targets. Efficiencies and environmental performances of bioenergy conversions are derived using biochemical process models combined with LCA data. The application of the optimization model is exemplified by a case aimed at determining the environmentally optimal use of biomass in the Danish energy system in 2025. A multiobjective formulation based on fuzzy intervals for six environmental impact categories resulted in impact reductions of 13-43% compared to the baseline. The robustness of the optimal solution was analyzed with respect to parameter uncertainty and choice of environmental objectives.
Evaluation of Externality Costs in Life-Cycle Optimization of Municipal Solid Waste Management Systems

The development of sustainable solid waste management (SWM) systems requires consideration of both economic and environmental impacts. Societal life-cycle costing (S-LCC) provides a quantitative framework to estimate both economic and environmental impacts, by including "budget costs" and "externality costs". Budget costs include market goods and services (economic impact), whereas externality costs include effects outside the economic system (e.g., environmental impact). This study demonstrates the applicability of S-LCC to SWM life-cycle optimization through a case study based on an average suburban U.S. county of 500000 people generating 320000 Mg of waste annually. Estimated externality costs are based on emissions of CO2, CH4, N2O, PM2.5, PM10, NOx, SO2, VOC, CO, NH3, Hg, Pb, Cd, Cr (VI), Ni, As, and dioxins. The results indicate that incorporating S-LCC into optimized SWM strategy development encourages the use of a mixed waste material recovery facility with residues going to incineration, and separated organics to anaerobic digestion. Results are sensitive to waste composition, energy mix and recycling rates. Most of the externality costs stem from SO2, NOx, PM2.5, CH4, fossil CO2, and NH3 emissions. S-LCC proved to be a valuable tool for policy analysis, but additional data on key externality costs such as organic compounds emissions to water would improve future analyses.

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Future scenario development within life cycle assessment of waste management systems

Life Cycle Assessment (LCA) is an acknowledged tool for quantifying the sustainability of waste management solutions. However, the use of LCA for decision-making is hindered by the strong dependency of the LCA results on the assumptions regarding the future conditions in which the waste management solutions will operate. Future scenario methods from the management engineering field may provide valid approaches for formulating consistent assumptions on future conditions for the waste management system modelled with LCA. However, the standardized LCA procedure currently does not offer much guidance on how to model future scenarios in LCA.

This thesis highlights critical findings aiming at strengthening the role of LCA in decision support and strategic planning for
waste management. In particular, the thesis thoroughly investigated the future scenario methods, the existing guidance on modelling of future scenarios in LCA, all peer-reviewed articles in the literature combining future scenarios and LCA, across sectors, and the specific modelling mechanisms occurring in LCA when assessing future scenarios. For each of these aspects, the thesis investigated the specific needs of the waste management field. The quantitative modelling implications were tested within real-scale LCA models focusing on the management of residual waste in Denmark. In a wide range of scenarios, this thesis addressed the influence on the LCA model results of realistic technology and waste composition uncertainties, as well as the effects of implementing future energy scenarios and design-stage technologies. The thesis underlines that future scenarios can be used to formulate consistent assumptions for waste management systems. However, in order to obtain well-founded quantitative results with LCA, the implementation of future scenarios should comply with the following conditions:

Future scenarios should include important aspects identified within the case-specific LCA model. Important aspects can be identified from a preliminary LCA, but should always be evaluated again after implementing the future scenarios in LCA.

Identification of important aspects (such as parameters of the modelled technologies, waste composition, and framework conditions) ultimately governing the LCA results of the future scenarios should be regarded as a fundamental part of the future scenario process and be communicated to the final receivers of the LCA. The main outcome of this thesis is a systematic framework that can be used to assess future scenarios in LCAs of waste management systems. The framework combines approaches developed during the PhD study in order to systematically address the modelling implications of combining future scenarios and LCAs of waste management systems.

The study developed a systematic definition of importance of LCA model parameters based on their input uncertainty and their sensitivity on results with a Global Sensitivity Analysis (GSA) approach. Within LCAs of waste management systems, the GSA approach allowed quantifying the importance of the waste composition versus the more commonly tested technology parameters. Less than 10 waste composition parameters as well as 5-6 technology parameters, out of a total of 750 waste and technology parameters in the LCA model, were found important for the results across all tested impact categories. These findings were used to improve existing step-wise approaches for quantification of uncertainty in LCA.

Moreover, this PhD study provided a novel method to quantitatively determine the most robust waste management solution across several future scenarios combining results of uncertainty analysis and scenario analysis into a simple and conveyable score.

The systematic framework for future scenarios in LCA should start from a preliminary LCA carried out on the case-specific system and identifying the important aspects with the GSA approach. The future scenarios can be formulated with whichever future scenario technique in preference, including the important aspects identified in the preliminary LCA. Then, the future scenarios can be implemented in further LCAs. A subsequent determination of important parameters with GSA is fundamental for identifying the aspects of the model ultimately governing the future scenario results and any necessary revisions in the future scenarios or model data. Finally, sustainability on the long-term can be strengthened by the combined use of uncertainty and scenario analysis. This means that the LCA results can be communicated as probabilities of each individual waste solution being environmentally better compared to the others, together with a clear indication of which aspects and parameters critically affect the performance of the solution.

The proposed systematic framework can be adapted to LCAs carried out in all fields and can also be used to quantitatively carry out systematic scenario analyses on the assumptions of present-day LCAs.
LCA results associated with selection of waste composition data. Three archetypal waste management scenarios were modelled with the waste LCA model EASETECH based on detailed waste composition data from the literature. The influence from waste composition data on the LCA results was quantified with a step-wise Global Sensitivity Analysis (GSA) approach involving contribution, sensitivity, uncertainty and discernibility analyses. The waste composition data contributed significantly to the LCA results and the uncertainty associated with these results. The importance of 405 individual waste properties was evaluated in comparison with 345 technology parameters. Overall, less than 10 physico-chemical properties dominated the output uncertainty of the LCA results, although these properties had low sensitivity in the model. Moreover, the uncertainties associated with the physico-chemical properties were responsible for output uncertainties that spanned from impacts to benefits. The GSA approach applied in this study constitutes a valuable tool for systematically assessing the importance of waste composition and for consciously collecting and using waste composition data within LCAs of waste management systems.

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Let's Be Clear(er) about Substitution A Reporting Framework to Account for Product Displacement in Life Cycle Assessment: A Framework to Account for Substitution in LCA

The multifunctional character of resource recovery in waste management systems is commonly addressed through system expansion/substitution in life cycle assessment (LCA). Avoided burdens credited based on expected displacement of other product systems can dominate the overall results, making the underlying assumptions particularly important for the interpretation and recommendations. Substitution modeling, however, is often poorly motivated or inadequately described, which limits the utility and comparability of such LCA studies. The aim of this study is therefore to provide a structure for the systematic reporting of information and assumptions expected to contribute to the substitution potential in order to make substitution modeling and the results thereof more transparent and interpretable. We propose a reporting framework that can also support the systematic estimation of substitution potentials related to resource recovery. Key components of the framework include waste-specific (physical) resource potential, recovery efficiency, and displacement rate. End-use-specific displacement rates can be derived as the product of the relative functionality (substitutability) of the recovered resources compared to potentially displaced products and the expected change in consumption of competing products. Substitutability can be determined based on technical functionality and can include additional constraints. The case of anaerobic digestion of organic household waste illustrates its application. The proposed framework enables well-motivated substitution potentials to be accounted for, regardless of the chosen approach, and improves the reproducibility of comparative LCA studies of resource recovery.
To generate meaningful results, life cycle assessments (LCAs) require accurate technology data that are consistent with the goal and scope of the analysis. While literature data are available for many products and processes, finding representative data for highly site-specific technologies, such as waste treatment processes, remains a challenge. This study investigated representative life cycle inventory (LCI) modeling of waste treatment technologies in consideration of variations in technological level and climate. The objectives were to demonstrate the importance of representative LCI data.
modeling as a function of the specificity of the study, and to illustrate the necessity of iteratively refining the goal and scope of the study as data are developed. A landfill case study was performed where 52 discrete landfill data sets were built and grouped to represent different technology options and geographical sites, potential impacts were calculated, and minimum/maximum (min-max) intervals were generated for each group. The results showed decreasing min-max intervals with increasing specificity of the scope of study, which indicates that compatibility between the scope of study and LCI model is critical. Hereby, this study quantitatively demonstrates the influence of representative modeling on LCA results. The results indicate that technology variations and site-specific conditions (e.g., the influence of precipitation and cover permeability on landfill gas generation and collection) should be carefully addressed by a systematic analysis of the key process parameters. Therefore, a thorough understanding of the targeted waste treatment technologies is necessary to ensure that appropriate data choices are made within the boundaries of the defined scope of the study.

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Long-term leaching of nutrients and contaminants from wood combustion ashes

With increasing amounts of woody biomass being combusted for energy purposes worldwide, more wood ash is being generated and needs management. As an alternative to landfilling, residues may be utilised for liming and fertilising purposes on forest soils. Comprehensive evaluations of long-term leaching from these residues are needed in order to assess potential environmental impacts associated with their utilisation. Two Danish wood ash samples, one fly ash and one mixed ash (a combination of fly ash and bottom ash), were evaluated in long-term percolation column tests (up to L/S ~2000 L/kg), in order to quantify the release of major, minor and trace metal(loid)s. While columns of three different lengths were used, the leaching of individual elements could be described as a function of the L/S ratio – irrespective of the column length. At L/S 1000 L/kg, the cumulative releases of K, S, Na, Ca and Rb were at 40–100% of their respective solid contents, followed by Ba, Cr, Sb, Sr and V at 15–40% and Al, Mg, Zn, Cd, Co, Fe, Pb, Tl, Mn and P at<5%.

Speciation calculations indicated that (i) the observed concentrations of Ca, Mg, Al, Ba, Si and sulphate from both ash types could be described through the dissolution/precipitation of a limited set of minerals and that (ii) leaching of silicates should be included in long-term assessment of alkalinity release from wood ashes. Non-equilibrium conditions were indicated by flow interruptions. However, the presence of non-equilibrium did not have significant effect on the calculated cumulative releases at high L/S ratios. Based on the assessment of cumulative releases at L/S 10 L/kg and L/S 1000 L/kg it is concluded that low L/S-based data may not provide sufficient background for prediction of long-term release from wood ash, in particular for Ba, Cr, Sb and V, and less critically also for As, Cd, Cu, Mo and Ni.
The optimal use of biomass from a global warming mitigation perspective depends upon numerous factors, including competition for land and other constraints. The goal of this study is identifying optimal uses of domestic biomass resources for the case of Denmark, with the objectives of minimizing global warming contribution and fossil energy resource consumption. For this purpose, consequential life cycle assessment of the different options for biomass was performed. Optimal solutions were identified, given specific national environmental targets, using linear programming. Results highlighted that utilizing the energy potential of manure and straw represents the primary opportunity for further global warming mitigation. For this purpose, co-digestion (for manure) and combustion with heat-and-power production (for straw) appear as the most promising technologies. The utilization of biomass (or biogas) for electricity/heat is generally preferred, as long as coal/oil is still used within the energy system. Yet, to fulfill environmental targets for renewable energy in the transport sector, the diversion of a significant share of biogas (and/or other biofuels) from these more beneficial uses is necessary. To completely phase out coal/oil, additional biomass (to current domestic resources) must be included, either through domestic energy crops cultivation or biomass/biofuel import; alternatively, natural gas could be used.
Recirculation of biomass ashes onto forest soils: Ash composition, mineralogy and leaching properties
In Denmark, increasing amounts of wood ashes are generated from biomass combustion for energy production. The utilisation of ashes on top of forest soil for liming purposes has been proposed as an alternative to landfilling. Danish wood ash samples were collected and characterised with respect to chemical composition, mineralogy and leaching properties (batch leaching at L/S 2 and 10L/kg, and pH-dependent leaching at 10L/kg). Large variations in the ash liming properties were observed (ANC7.5: 1.8-6.4meqH+/g), indicating that similar soil application dosages may result in different liming effects. High contents of Ca, Si, P, K and Mg were observed in all samples, while the highest contents of S and N were found in fly ashes and mixed ashes (combination of fly and bottom ashes). Similarly, the highest contents of some trace metals, e.g. Cd, Mo and Se, were observed for fly ash. Releases of major, minor and trace elements were affected significantly by pH: high releases of PO4 3-, Mg, Zn, Cu and Cd were found for acidic conditions relevant to forest soils, while the highest releases of Mo and Cr were observed in alkaline conditions. Mineral phases were selected based on XRD analyses and the existing literature, and they were applied as inputs for the geochemical modelling of pH-dependent leaching. Mineral dissolution was found adequate for a wide range of major elements and nutrients, while the description of trace elements could be done only for parts of the pH-range. Content and leaching of PAHs were observed below detection limits. The source-term release of Ca, K, Mg, Mn, and P in acidic conditions relevant to forest soils was higher than ten years of atmospheric deposition, in contrast to the relatively low release of Al, Fe and Na. The potential release of Cd was found to be the most critical element compared with soil quality criteria, whereas the maximum theoretical loads of Ba, Cd, Cr, Sr, Mo, Ni, Pb, Sb, Se, Sn and V were relatively low.
Recycling of plastic waste: Screening for brominated flame retardants (BFRs)

Flame retardants are chemicals vital for reducing risks of fire and preventing human casualties and property losses. Due to the abundance, low cost and high performance of bromine, brominated flame retardants (BFRs) have had a significant share of the market for years. Physical stability on the other hand, has resulted in dispersion and accumulation of selected BFRs in the environment and receiving biota. A wide range of plastic products may contain BFRs. This affects the quality of waste plastics as secondary resource: material recycling may potentially reintroduce the BFRs into new plastic product cycles and lead to increased exposure levels, e.g. through use of plastic packaging materials. To provide quantitative and qualitative data on presence of BFRs in plastics, we analysed bromophenols (tetrabromobisphenol A (TBBPA), dibromophenols (2,4- and 2,6-DBP) and 2,4,6-tribromophenol (2,4,6-TBP)), hexabromocyclododecane stereoisomers (α-, β-, and γ-HBCD), as well as selected polybrominated diphenyl ethers (PBDEs) in samples of household waste plastics, virgin and recycled plastics. A considerable number of samples contained BFRs, with highest concentrations associated with acrylonitrile butadiene styrene (ABS, up to 26,000,000 ng TBBPA/g) and polystyrene (PS, up to 330,000 ng ∑HBCD/g). Abundancy in low concentrations of some BFRs in plastic samples suggested either unintended addition in plastic products or degradation of higher molecular weight BFRs. The presence of currently restricted flame retardants (PBDEs and HBCD) identified in the plastic samples illustrates that circular material flows may be contaminated for extended periods. The screening clearly showed a need for improved documentation and monitoring of the presence of BFRs in plastic waste routed to recycling.

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Statistical analysis of solid waste composition data: Arithmetic mean, standard deviation and correlation coefficients
Data for fractional solid waste composition provide relative magnitudes of individual waste fractions, the percentages of which always sum to 100, thereby connecting them intrinsically. Due to this sum constraint, waste composition data represent closed data, and their interpretation and analysis require statistical methods, other than classical statistics that are suitable only for non-constrained data such as absolute values. However, the closed characteristics of waste composition data are often ignored when analysed. The results of this study showed, for example, that unavoidable animal-derived food waste amounted to $2.21 \pm 3.12\%$ with a confidence interval of $(-4.03, 8.45)$, which highlights the problem of the biased negative proportions. A Pearson's correlation test, applied to waste fraction generation (kg mass), indicated a positive correlation between avoidable vegetable food waste and plastic packaging. However, correlation tests applied to waste fraction compositions (percentage values) showed a negative association in this regard, thus demonstrating that statistical analyses applied to compositional waste fraction data, without addressing the closed characteristics of these data, have the potential to generate spurious or misleading results. Therefore, compositional data should be transformed adequately prior to any statistical analysis, such as computing mean, standard deviation and correlation coefficients.

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Waste prevention for sustainable resource and waste management

Although the 2Rs (reduce and reuse) are considered high-priority approaches, there has not been enough quantitative research on effective 2R management. The purpose of this paper is to provide information obtained through the International Workshop in Kyoto, Japan, on 11–13 November 2015, which included invited experts and researchers in several countries who were in charge of 3R policies, and an additional review of 245 previous studies. It was found that, regarding policy development, the decoupling between environmental pressures and economy growth was recognized as an essential step towards a sustainable society. 3R and resource management policies, including waste prevention, will play a crucial role. Approaches using material/substance flow analyses have become sophisticated enough to describe the fate of resources and/or hazardous substances based on human activity and the environment, including the final sink. Life-cycle assessment has also been developed to evaluate waste prevention activities. Regarding target products for waste prevention, food loss is one of the waste fractions with the highest priority because its countermeasures have significant upstream and downstream effects. Persistent organic pollutants and hazardous compounds should also be taken into account in the situation where recycling activities are globally widespread for the promotion of a material-cycling society.

General information

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Organisations: Department of Environmental Engineering, Residual Resource Engineering, Japan Environment Safety Corporation, Environment Policy Bureau, National Institute of Environmental Studies, Ehime University, TOWA Technology Corporation, German Federal Environment Agency, Technical University of Berlin, Politecnico di Milano, University of Toronto, National Institute of Environmental Research, Tsinghua University, National Taiwan University, Vietnam Academy of Science and Technology, University of New South Wales, Kyoto University
A global approach for sparse representation of uncertainty in Life Cycle Assessments of waste management systems

Purpose: Identification of key inputs and their effect on results from Life Cycle Assessment (LCA) models is fundamental. Because parameter importance varies greatly between cases due to the interaction of sensitivity and uncertainty, these features should never be defined a priori. However, exhaustive parametrical uncertainty analyses may potentially be complicated and demanding, both with analytical and sampling methods. Therefore, we propose a systematic method for
selection of critical parameters based on a simplified analytical formulation that unifies the concepts of sensitivity and
uncertainty in a Global Sensitivity Analysis (GSA) framework. Methods: The proposed analytical method based on the
calculation of sensitivity coefficients (SC) is evaluated against Monte Carlo sampling on traditional uncertainty assessment
procedures, both for individual parameters and for full parameter sets. Three full-scale waste management scenarios are
modelled with the dedicated waste LCA model EASETECH and a full range of ILCD recommended impact categories.
Common uncertainty ranges of 10 % are used for all parameters, which we assume to be normally distributed. The
applicability of the concepts of additivity of variances and GSA is tested on results from both uncertainty propagation
methods. Then, we examine the differences in discernibility analyses results carried out with varying numbers of sampling
points and parameters. Results and discussion: The proposed analytical method complies with the Monte Carlo results for
all scenarios and impact categories, but offers substantially simpler mathematical formulation and shorter computation
times. The coefficients of variation obtained with the analytical method and Monte Carlo differ only by 1 %, indicating that
the analytical method provides a reliable representation of uncertainties and allows determination of whether a
discernibility analysis is required. The additivity of variances and the GSA approach show that the uncertainty in results is
determined by a limited set of important parameters. The results of the discernibility analysis based on these critical
parameters vary only by 1 % from discernibility analyses based on the full set, but require significantly fewer Monte Carlo
runs. Conclusions: The proposed method and GSA framework provide a fast and valuable approximation for uncertainty
quantification. Uncertainty can be represented sparsely by contextually identifying important parameters in a systematic
manner. The proposed method integrates with existing step-wise approaches for uncertainty analysis by introducing a
global importance analysis before uncertainty propagation.

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Anthropogenic phosphorus flows in Denmark: Quantification and critical analysis
Phosphorus (P) is an essential plant nutrient mined from the earth’s crust as phosphate rock. It cannot be substituted, making it a crucial resource for food production. For the EU, future phosphate scarcity is a potential geopolitical and strategic threat. An increasing worldwide phosphate demand is coupled with dependence on imports from a limited number of suppliers outside the EU-28, so that the EU updated its list of critical raw materials in 2014 to include phosphate rock. As a plant nutrient, P is not destroyed by human use, but dissipated into the environment, where it is a pollutant contributing to eutrophication of water bodies and soils. The anthropogenic P is open on the global scale, with global shipments of animal feed, fertiliser, and food; and on the local scale, through the inefficient use of fertiliser or animal manure by application in excess of plant P demand, and losses in waste and wastewater treatment due to insufficient recycling.

The focus of this PhD project was on the resource aspect, as opposed to the pollution aspect, of P in Denmark. The overall goal was to quantify and evaluate the country’s anthropogenic P flows, i.e. those flows caused or significantly influenced by human action, based on a comprehensive material flow analysis (MFA). MFA is a method widely applied to establish resource budgets within a spatial – such as a country – and temporal system boundary, establish a material balance, and handle data uncertainties and data conflicts.

When looking at P from a resource efficiency perspective, the most important flows to consider are those linked to agriculture, as a consumer and producer of large P flows, and waste/wastewater management, as the key processes for treating the resulting P-containing wastes. Country-wide average values regarding these processes hold limited informative value. Moreover, it became clear at the outset of the study that there were distinct differences between the P flows across regions of the country, especially between the east, with the largest urban agglomeration, and the northwest. Apart from population and industrial density, a contrast also exists in agricultural practice, with animal husbandry concentrated in the west and northwest, and the east being dominated by crop production. For the agriculture and waste management processes, the MFA was divided into 3 “typical” regions between the northwest (North Jutland), the east (Zealand and the capital region), and a middle part with more mixed characteristics (Mid-Jutland and Southern Denmark); the regional subdivisions formed a part of a complete country-scale MFA. As is typical for a European country, the Danish P budget showed a strong dependence on P imports in fertilisers and animal feed; with food products being the dominant export of P. The regional contrasts in agricultural P budgets were pronounced as expected, with a slight P deficit in the east and the largest per-hectare surplus, due to large amounts of manure, in the northwest. Manure was shown to hold the most salient potential for P recovery, yet stays quite local and adds to the surplus in the country’s northwest, posing a environmental problem. In the waste management system, two streams were identified to hold significant potential for P
recovery. Sewage sludge, while already applied to land on a considerable scale, still holds potentially recoverable P not yet utilised today; and vegetable and animal kitchen and food waste from consumption currently not collected separately, with residues being lost to P recovery. These amounts are furthermore located in the east, with a slight P deficit in agricultural soils, suggesting themselves for substituting some fertiliser imports in the future. The total P quantities in these streams amounted to approximately 35% of concurrent mineral P imports.

Since MFA for regional resource budgets is often the groundwork for further analysis, the robustness and comparability of MFA studies’ outcomes when using them as sources of information is important. To this end, the MFA for Denmark was compared to a recent and methodically similar P MFA for Austria, and the effects of the structure of the data material and an MFA practitioner’s modelling choices on the outcomes identified and measured. It was demonstrated that the data available do, in fact, influence model layout. Moreover, the approach to assess uncertainty is subject to a certain degree of arbitrariness, and reflects the modeller’s belief in the quality of the data material. This, however, leads to incomparability of data quality between MFAs, as the comparison showed, since data uncertainties can be only evaluated against those in the same model. Lastly, data conflicts are normal in country-scale MFA; the extent of the necessary reconciliation of conflicting data provides a useful proxy measure for the quality of an MFA. Metadata matter; this comparison showed the quantitative effects of those aspects of MFAs not resulting from the real-world systems studied. The results thus gave a quantitative basis to requiring a transparent system definition and data characterisation in regional MFA beyond the case of P in Denmark.

A third part of this PhD project consisted of exploring the potentials for increased P recovery efficiency in the Danish anthroposphere based on the results of the initial MFA. An aspect of a secondary resource (recovered P fertiliser) is its ability to fulfil the functions of the resource substituted (mineral P fertiliser). For this purpose, the MFA system and values obtained in this study were adapted to reflect the typical values for availability of P from various material flows to crops, and to allow for transport of less bulky secondary-P material flows. An optimal distribution of recovered P flows (from sewage sludge and composted organic household waste) was then determined by formal optimization via linear programming. The outcome showed a gradual decline of both mineral P inputs, and net additions to soil P stocks, stabilising at a distinctly lower level than evident from the static MFA, due to P applied gradually becoming available for plants over time, showing a significantly higher (82%) potential for substituting mineral P imports than evident from the initial, static MFA (35%). While the potential improvements in closing the P cycle could be shown, this can, however, not be expected to change the reliance on imported P on one or another form.

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Composition of municipal solid waste in Denmark
In response to continuous pressure on resources, and the requirement for secure and sustainable consumption, public authorities are pushing the efficient use of resources. Among other initiatives, the prevention, reduction and recycling of solid waste have been promoted. In this context, reliable data for the material and resource content of waste flows are crucial to establishing baselines, setting targets and tracking progress on waste prevention, reduction and recycling goals. Waste data are also a critical basis for the planning, development and environmental assessment of technologies and waste management. These data are obtained through the characterisation of waste material. In the absence of standardised and commonly accepted waste sampling and sorting procedures, various approaches have been employed, albeit they limit both the comparability and the applicability of results. Thus, waste sampling and sorting procedures, as well as a consistent and transparent waste-naming system, have been developed.

Classical statistics are applied increasingly when analysing waste data, in order to draw conclusions that underpin the development of waste legislation and policy. The existing statistical techniques ignore the inherent properties of waste data, which are "closed data," because the percentage or the mass of individual fractions are positive and add up to a constant. This constant constraint affects statistical analysis seriously and results in erroneous interpretations. Therefore, compositional analysis techniques have been introduced to analyse waste data more appropriately.

Waste was sampled directly from source, in order to attribute the waste data accurately to the geographical areas and types of household generating the waste. Sampling and contamination errors were minimised by avoiding sieving and the
mass reduction of waste before manual sorting. Consequently, the waste was collected without compacting. Additionally, the entire sample was manually sorted into 10-50 waste fractions organised according to a three-level approach. This detailed waste fractions list facilitated the comparison of waste data with various objectives.

Analysis revealed that Danish residual household waste constitutes mainly food waste (42 – 45% mass per wet basis). Misplaced recyclable materials in residual waste bins, such as paper, board, glass, metal and plastic, amounted to 20% (mass per wet basis) of residual household waste. Moreover, special waste, such as hazardous waste, batteries and WEEE, was also misplaced in residual household bins, accounting for 0.4-0.8% of the total. Although the proportion of misplaced special waste was relatively small, these material fractions can have dire impacts on the environment when they are not disposed of appropriately.

Statistical analysis indicated that separating food waste residue from packaging during waste sorting was unnecessary, because this separation did not significantly influence overall waste composition, the percentage of food waste or packaging waste fractions. Furthermore, the difference in waste composition between municipalities was not significant. These results suggest that waste composition data obtained from one municipality could be applied to other municipalities in the same area (provided that municipalities share the same source segregation scheme), although socio-economic aspects between municipalities were not analysed.

Food waste consists of avoidable and unavoidable food waste. Here, “avoidable” food waste is defined as food that could be eaten but instead was thrown away regardless of the reason, whereas “unavoidable” food waste is food that would not be edible under normal circumstances (e.g. bones, banana peel, etc.). Food waste was estimated at 183 kg per household per year (86 kg per person per year), of which 103 kg per household (48 kg per person) per year was avoidable food waste and 80 kg per household (38 kg per person) per year was unavoidable food waste. These food waste fractions occurred in most of Danish households, which suggests that initiatives to reduce avoidable food waste should be combined with policies that promote the efficient treatment of unavoidable food waste, to ensure plant nutrient and resource recovery.

The mass of avoidable food waste discarded per household increased in line with household size. However, there was no statistical evidence that a household containing one person throws away more avoidable food waste per person than households containing more than one person. This suggests that campaigns and initiatives targeting food waste reduction should particularly aim at households containing more than one person. Additionally, the mass of avoidable and unavoidable food waste per household and per person discarded in Danish houses was significantly influenced neither by periodic variation nor by geographical variations.

Waste analysis from kitchens in office areas showed that food waste generation amounted to 23 kg per employee per year, of which 20 kg per employee was source-segregated. This suggests that only 11% of food waste was misplaced in residual waste, which itself amounted to 10 kg per employee per year and consisted of 29% paper, 23% plastic and 24% residual waste. Thus, sorting efficiency was estimated at 89% of food waste, accompanied by extremely high purity (99%). These results indicate that the 60% recycling target formulated by the Danish Government for food waste generated by the service sector should be achievable.

Composition of waste materials and recyclables

As the valorization of waste has become a main objective of modern waste management a variety of waste technologies were developed and the complexity of management systems increased. Maximizing environmental benefits in one part of the system may lead to burdens in another. Environmentally sound decisions in waste planning thus require a holistic and systematic assessment of environmental impacts of different waste management options. Such assessment requires reliable information on the physical and chemical waste properties to model the flows of waste materials and substances throughout the entire waste management system.

The aim of this PhD project was to improve the understanding of factors influencing the quality of waste composition data during waste characterization and application in the environmental assessment of waste management systems. Reviewing existing waste characterization studies revealed that a large variety of waste characterization approaches and analytical methods has been employed. The most frequently used approach was the chemical analysis of directly sampled waste materials which offers the highest flexibility for waste characterization studies. Direct waste analysis involves several steps to prepare the samples mechanically and/or chemically for final analysis. Not all sample preparation methods are equally well suited for specific waste characterization purposes. The correctness of results and practical
feasibility of sample preparation was strongly affected by the material type of the sample and the physico-chemical parameter to be analyzed. For example, studies examining mechanical sample preparation methods suggest that plastic fractions are especially prone to de-mixing effects and that differing mechanical properties within a sample (e.g. plastic and metal) can lead to biased results. In the experimental part of this PhD project the milling of plastics and metals was especially challenging and alternative methods for preparation and analysis should be investigated. Furthermore, chemical sample preparation by means of acid digestion was found to severely affect the element content resulting from chemical analysis. Although the suitability of standardized HF-containing methods can be generally confirmed, these methods led to considerable underestimations of the element content for some combinations of element and waste material. Appropriate selection of acid digestion methods thus needs to take the waste material and the elements to be analyzed into account.

The dataset obtained during this PhD project provides information on the performance for six relevant acid mixtures for nine different waste material fractions and 64 elements and can support the selection of appropriate acid digestion method for future waste characterization studies and the comparison of data across existing studies.

A consistent dataset for 73 physico-chemical parameters in 49 residual and 24 source-segregated Danish household waste fractions was obtained and is now available for future modelling and assessment of waste management systems. The analyzed fractions were selected based on material properties with relevance for potential recycling processes. The physico-chemical analysis revealed chemical differences between residual and source-segregated samples for several fractions. The results for parameters associated with organic matter confirmed the idea of cross-contaminated recyclables in residual waste, whereas the results for heavy metals and trace elements were more complex. For many fractions rather high metal contents were found to be intrinsic properties of the recyclables. For example, the Sb content in PET packaging was 250-270 mg/kgTS. In some cases metal contents in source-segregated fractions were higher than in the respective fractions from residual waste. Rare earth elements (RRE) were quantified in all analyzed material fractions and considerably high concentrations (e.g. the Ce content in ceramics was 72 mg/kgTS) were associated with mineral and soil-like materials. This “natural background” concentrations need to be considered when concluding on the origin of RRE which are typically associated with electronic/hazardous waste.

In general the use of primary physico-chemical waste characterization data for the environmental assessment of waste management systems is always preferable because many factors such as fraction definition and sampling point can be controlled. Anyhow, value ranges (as opposed to single values) should be considered due to the possibility of systematic bias (e.g. resulting from specific characterization methods) and “natural” variation. Commonly reported measurement uncertainties are not suitable to capture such effects. Thus secondary data should be considered when deriving uncertainty ranges and more research is necessary to quantify systematic effects of different characterization methods. Considering the extensive time and costs related to physico-chemical waste characterization it is likely that environmental assessment of waste management systems will continue to draw on secondary data from literature. For some parameters the values reported in literature were found to differ significantly. The wide range of values in literature for physico-chemical properties of individual waste materials were shown to severely affect the results of the life cycle assessment (LCA) of waste management systems, although the parameters had relatively low sensitivity. This emphasizes that sensitivity alone is not an appropriate indicator to identify critical parameters for LCA modelling. Using the literature value ranges for complete uncertainty analysis physico-chemical parameters contributed substantially to the output uncertainty of the modelling results and were in many cases more important than technology and scenario specific parameters. By selecting well-fitting data from literature the input value ranges could be potentially narrowed. Suggestions for physico-chemical data selection for environmental assessment and related uncertainty analysis are presented. At this point, however, low data availability and the large variety of used waste characterization methods limit the quantification and ranking of influencing factors via statistical data analysis of literature data. Nevertheless, it was found that the regional context of the data origin appeared to be less or equally important than other potential influencing factors (such as e.g. analytical methods, waste management system, natural variation, etc.). To consider the influence of such factors on secondary data but also primary data, LCA of waste management systems should always include a systematic uncertainty analysis for physico-chemical waste properties which needs to be based on both sensitivity and realistic uncertainty ranges for the individual physico-chemical parameters.
Environmental implications of the use of agro-industrial residues for biorefineries: application of a deterministic model for indirect land-use changes

Biorefining agro-industrial biomass residues for bioenergy production represents an opportunity for both sustainable energy supply and greenhouse gas (GHG) emissions mitigation. Yet, is bioenergy the most sustainable use for these residues? To assess the importance of the alternative use of these residues, a consequential life-cycle assessment (LCA) of 32 energy-focused biorefinery scenarios was performed based on eight selected agro-industrial residues and four conversion pathways (two involving bioethanol and two biogas). To specifically address indirect land-use changes (iLUC) induced by the competing feed/food sector, a deterministic iLUC model, addressing global impacts, was developed. A dedicated biochemical model was developed to establish detailed mass, energy, and substance balances for each biomass conversion pathway, as input to the LCA. The results demonstrated that even for residual biomass, environmental savings from fossil fuel displacement can be completely out-balanced by iLUC, depending on the feed value of the biomass residues. This was the case of industrial residues brewer's grain, beet residues, potato pulp, and whey. Overall, the GHGs from iLUC impacts were quantified to 4.1 t CO2-eq.ha-1demanded y-1 corresponding to 1.2-1.5 t CO2 t-1 dry biomass used for energy. Only bioenergy from straw and wild grass was shown to perform better than the alternative use, as no competition with the feed sector was involved. Biogas for heat-and-power production was the best performing pathway, in a short-term context. Focusing on transport fuels, bioethanol was generally preferable to biomethane considering conventional biogas upgrading technologies. Based on the results, agro-industrial residues cannot be considered burden-free simply because they are a residual biomass and careful accounting of alternative utilization is a pre-requisite to assess the sustainability of a given use. In this endeavor, the iLUC factors and biochemical model proposed herein can be used as templates and directly applied to any bioenergy consequential study involving demand for arable land.
Estimation of marginal costs at existing waste treatment facilities

This investigation aims at providing an improved basis for assessing economic consequences of alternative Solid Waste Management (SWM) strategies for existing waste facilities. A bottom-up methodology was developed to determine marginal costs in existing facilities due to changes in the SWM system, based on the determination of average costs in such waste facilities as function of key facility and waste compositional parameters. The applicability of the method was demonstrated through a case study including two existing Waste-to-Energy (WtE) facilities, one with co-generation of heat and power (CHP) and another with only power generation (Power), affected by diversion strategies of five waste fractions (fibres, plastic, metals, organics and glass), named “target fractions”. The study assumed three possible responses to waste diversion in the WtE facilities: (i) biomass was added to maintain a constant thermal load, (ii) Refused-Derived-Fuel (RDF) was included to maintain a constant thermal load, or (iii) no reaction occurred resulting in a reduced waste throughput without full utilization of the facility capacity. Results demonstrated that marginal costs of diversion from WtE were up to eleven times larger than average costs and dependent on the response in the WtE plant. Marginal cost of diversion were between 39 and 287€Mg⁻¹ target fraction when biomass was added in a CHP (from 34 to 303€Mg⁻¹ target fraction in the only Power case), between -2 and 300€Mg⁻¹ target fraction when RDF was added in a CHP (from -2 to 294€Mg⁻¹ target fraction in the only Power case) and between 40 and 303€Mg⁻¹ target fraction when no reaction happened in a CHP (from 35 to 296€Mg⁻¹ target fraction in the only Power case). Although average costs at WtE facilities were highly influenced by energy selling prices, marginal costs were not (provided a response was initiated at the WtE to keep constant the utilized thermal capacity). Failing to systematically address and include costs in existing waste facilities in decision-making may unintendedly lead to higher overall costs at societal level. To avoid misleading conclusions, economic assessment of alternative SWM solutions should not only consider potential costs associated with alternative treatment but also include marginal costs associated with existing facilities.
Food waste from Danish households: Generation and composition

Sustainable solutions for reducing food waste require a good understanding of food waste generation and composition, including avoidable and unavoidable food waste. We analysed 12 tonnes of residual household waste collected from 1474 households, without source segregation of organic waste. Food waste was divided into six fractions according to avoidability, suitability for home-composting and whether or not it was cooked, prepared or had been served within the
household. The results showed that the residual household waste generation rate was 434 ± 18 kg per household per year, of which 183 ± 10 kg per year was food waste. Unavoidable food waste amounted to 80 ± 6 kg per household per year, and avoidable food waste was 103 ± 9 kg per household per year. Food waste mass was influenced significantly by the number of occupants per household (household size) and the housing type. The results also indicated that avoidable food waste occurred in 97% of the households, suggesting that most Danish households could avoid or at least reduce how much they generate. Moreover, avoidable and unavoidable food waste was more likely to be found in houses containing more than one person than in households with only one occupant.
As a response to the growing pressure on the supply chains, developing a resource-efficient circular economy will be fundamental to satisfy the future demands for material resources. In this context, the Danish Government, in 2013, launched its Resource Strategy Plan, mandating that, by 2018 at least 60% of organic waste – that cannot be prevented or reduced – generated by service sector, should be source-segregated and collected separately. In order to establish the baseline of the current situation, and to allow for any evaluation of performance against target indicators, data on solid waste generation and composition are required.

The overall aim of this study was to quantify the potential for source-segregated organic waste as well as mixed waste from institutions.

This study was carried at the Department of Environmental Engineering at Technical University of Denmark. In the course of this study, two plastic waste bins of 60 L each were placed in the kitchens: organic waste bins and mixed waste bins. Organic waste and mixed waste from these kitchens were collected and weighed separately, on a daily basis, during 133 working days (29 weeks). However, waste was not sampled during weekends and public holidays, when the offices were officially closed. Furthermore, the composition of source-segregated organic waste was analysed to investigate its purity.

During the sampling period, the number of employees coming to work at the department was recorded. These data were used to investigate any relationship between mass of discarded waste (source-segregated organic and mixed waste) and the number of employee coming to work at the department.

The result showed that 20 to 60 days (e.g. working days) should be considered to obtain reliable data when sampling waste from an institution.

We found a significant correlation between mass of source-segregated organic waste and the number of employees coming to work at the department (0.70 with 95% HDI 0.6 and 0.78). Similarly, there was a significant correlation between mixed waste and number of employees (0.49 with 95% HDI 0.3 and 0.62).

The generate rates of source-segregated organic waste amounted to 23 ± 5 kg/employee/year, of which 20 ± 5 kg/employee/year was source-segregated, with a considerably high purity of 99%. Mixed waste amounted to 10 ± 5 kg/employee/year.

These results show that source-segregated organic waste from institutions offers promising potential. They also suggest that recycling target for source-segregated organic waste might be achievable with reasonable logistical ease in institution areas.
GHG emission factors for bioelectricity, biomethane, and bioethanol quantified for 24 biomass substrates with consequential life-cycle assessment

Greenhouse gas (GHG) emission savings from biofuels dramatically depend upon the source of energy displaced and the effects induced outside the energy sector, for instance land-use changes (LUC). Using consequential life-cycle assessment and including LUC effects, this study provides GHG emission factors (EFs) for bioelectricity, biomethane, and bioethanol produced from twenty-four biomasses (from dedicated crops to residues of different origin) under a fossil and a non-fossil energy system. Accounting for numerous variations in the pathways, a total of 554 GHG EFs were quantified. The results showed that, important GHG savings were obtained with residues and seaweed, both under fossil and non-fossil energy systems. For high-yield perennial crops (e.g. willow and Miscanthus), GHG savings were achieved only under fossil energy systems. Biofuels from annual crops and residues that are today used in the feed sector should be discouraged, as LUC GHG emissions exceeded any GHG savings from displacing conventional energy sources. (C) 2016 Elsevier Ltd. All rights reserved.
Influence of data choices in Life Cycle Assessment of waste management systems

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Integrated environmental and economic assessment of waste management systems
The Solid Waste Management (SWM) sector has evolved from a simple control of emissions towards a resource recovery sector while still being constrained by strict emission regulations. For that waste authorities are paying increased attention to the waste hierarchy as a set of priorities for solid waste treatment options to boost this shift towards higher resource recovery. In this hierarchy, waste prevention has the highest priority, followed by re-use and recycling options, and what cannot be recycled should be energy recovered; and, finally, the least favoured option is disposal in landfills. However, the waste hierarchy does not consider the local needs/conditions of each geographical area, and it cannot be used to identify sustainable SWM options by itself. Environmental impact assessment can help with this task as holistic decision-support
tool. Nevertheless, waste authorities need economic assessment of SWM systems alongside environmental impacts assessment to take budget constrains into account.

In light of the need for combined environmental and economic assessment of SWM, this PhD thesis developed a consistent and comprehensive method for integrated environmental and economic assessment of SWM technologies and systems. The method resulted from developing further the generic Life Cycle Costing (LCC) framework suggested by Hunkeler et al. (2008) and Swarr et al. (2011) to apply it on the field of SWM. The method developed includes: two modelling approaches (Accounting and Optimization), three cost approaches (Conventional, Environmental and Societal LCCs) and two goal perspectives (Planning and Analysis).

- The modelling approach describes how the scenarios are defined. The “Accounting approach” defines the technological pathway of each scenario before the study is performed, while in the “Optimization approach” the scenarios are the results of an optimization process.
- The cost approach describes cost principles and level of LCA integration. Conventional and Environmental LCCs are financial assessments, i.e. include marketed goods/services, but while Environmental LCCs include environmental impacts in a parallel LCA, Conventional LCCs do not. Societal LCC is a welfare economic assessment, i.e. includes marketed goods/services and effects outside the economic system (externality costs).
- The goal perspective differentiates between “Analysis” and “Planning” perspective. Analysis LCCs evaluate current status of a SWM system, while Planning LCCs focus on the consequences a change in a system with respect to the status quo.

The applicability of the LCC framework was tested through four case studies from which the following conclusions can be drawn:

- Organic source-segregation incurs financial and social costs mainly related to the cost of bags and bins used by households, as well as extra collection costs related to the additional collection scheme for organics collection as well as extra cost of residual waste collection (compared with mixed waste).
- The environmental benefits related to food waste prevention (due to avoided food production) could be overtaken by the environmental loads associated with the alternative consumptions purchased with the savings generated from the prevented (unpurchased) food. This could be avoided if prevention campaigns were accompanied by other policies aiming at reducing the impact of alternative consumption patterns. The inclusion of these income effects is especially critical when the alternatives being compared in an LCC have significant differences on the use of scarce resources such as income, land and time. In these cases, LCC studies should be supplemented by specific analysis of potential behavioural changes in consumption patterns (defining alternative consumptions) associated with the SWM systems being assessed.
- Recycling and prevention strategies can have significant economic consequences in existing waste facilities whose operation will have to be adjusted based on the waste changes. Marginal costs of diversion strategies in existing WtE facilities depend completely on the response in such facility. However, regardless of the response type, it was demonstrated that marginal costs of diversion are several times different than average costs. Hence, when performing Planning LCC the dynamics of the SWM system (including effects in existing waste facilities) should be taken into account to avoid misleading conclusions.
- Optimization of SWM using Societal LCC demonstrated that the social optimal solution results from balancing economic and externality costs. Contrary, optimizing using either economic costs or externality costs lead to socially suboptimal solutions.

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LCA of management strategies for RDF incineration and gasification bottom ash based on experimental leaching data
The main characteristics and environmental properties of the bottom ash (BA) generated from thermal treatment of waste may vary significantly depending on the type of waste and thermal technology employed. Thus, to ensure that the strategies selected for the management of these residues do not cause adverse environmental impacts, the specific properties of BA, in particular its leaching behavior, should be taken into account. This study focuses on the evaluation of potential environmental impacts associated with two different management options for BA from thermal treatment of Refuse Derived Fuel (RDF): landflling and recycling as a filler for road sub bases. Two types of thermal treatment were considered: incineration and gasification. Potential environmental impacts were evaluated by life-cycle assessment (LCA) using the EASETECH model. Both non-toxicity related impact categories (i.e. global warming and mineral abiotic resource
depletion) and toxic impact categories (i.e. human toxicity and ecotoxicity) were assessed. The system boundaries included BA transport from the incineration/gasification plants to the landfills and road construction sites, leaching of potentially toxic metals from the BA, the avoided extraction, crushing, transport and leaching of virgin raw materials for the road scenarios, and material and energy consumption for the construction of the landfills. To provide a quantitative assessment of the leaching properties of the two types of BA, experimental leaching data were used to estimate the potential release from each of the two types of residues. Specific attention was placed on the sensitivity of leaching properties and the determination of emissions by leaching, including: leaching data selection, material properties and assumptions related to emission modeling. The LCA results showed that for both types of BA, landfilling was associated with the highest environmental impacts in the non-toxicity related categories. For the toxicity related categories, the two types of residues behaved differently. For incineration BA the contribution of metal leaching to the total impacts had a dominant role, with the highest environmental loads resulting for the road scenario. For the gasification BA, the opposite result was obtained, due to the lower release of contaminants observed for this material compared to incineration BA. Based on the results of this study, it may be concluded that, depending on the type of BA considered, its leaching behavior may significantly affect the results of a LCA regarding its management strategies.

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Life cycle assessment modelling considering impurities in recyclable materials

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Life-Cycle Costing of Food Waste Management in Denmark: Importance of Indirect Effects
Prevention has been suggested as the preferred food waste management solution compared to alternatives such as conversion to animal fodder or to energy. In this study we used societal life-cycle costing, as a welfare economic assessment, and environmental life-cycle costing, as a financial assessment combined with life-cycle assessment, to evaluate food waste management. Both life-cycle costing assessments included direct and indirect effects. The latter are related to income effects, accounting for the marginal consumption induced when alternative scenarios lead to different household expenses, and the land-use-changes effect, associated with food production. The results highlighted that prevention, while providing the highest welfare gains as more services/goods could be consumed with the same income, could also incur the highest environmental impacts if the monetary savings from unpurchased food commodities were spent on goods/services with a more environmentally damaging production than that of the (prevented) food. This was not the case when savings were used, e.g., for health care, education, and insurances. This study demonstrates that income effects, although uncertain, should be included whenever alternative scenarios incur different financial costs. Furthermore, it highlights that food prevention measures should not only demote the purchase of un consumed food but also promote a low-impact use of the savings generated.

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This study provides a systematic approach for assessment of contaminants in materials for recycling. Paper recycling is used as an illustrative example. Three selected chemicals, bisphenol A (BPA), diethylhexyl phthalate (DEHP) and mineral oil hydrocarbons (MOHs), are evaluated within the paper cycle. The approach combines static material flow analysis (MFA) with dynamic material and substance flow modeling. The results indicate that phasing out of chemicals is the most effective measure for reducing chemical contamination. However, this scenario was also associated with a considerable lag phase (between approximately one and three decades) before the presence of chemicals in paper products could be considered insignificant. While improved decontamination may appear to be an effective way of minimizing chemicals in products, this may also result in lower production yields. Optimized waste material source-segregation and collection was the least effective strategy for reducing chemical contamination, if the overall recycling rates should be maintained at the current level (approximately 70% for Europe). The study provides a consistent approach for evaluating contaminant levels in material cycles. The results clearly indicate that mass-based recycling targets are not sufficient to ensure high quality material recycling.

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Physico-chemical characterisation of material fractions in household waste: Overview of data in literature

State-of-the-art environmental assessment of waste management systems rely on data for the physico-chemical composition of individual material fractions comprising the waste in question. To derive the necessary inventory data for different scopes and systems, literature data from different sources and backgrounds are consulted and combined. This study provides an overview of physico-chemical waste characterisation data for individual waste material fractions available in literature and thereby aims to support the selection of data fitting to a specific scope and the selection of uncertainty ranges related to the data selection from literature. Overall, 97 publications were reviewed with respect to employed characterisation method, regional origin of the waste, number of investigated parameters and material fractions and other qualitative aspects. Descriptive statistical analysis of the reported physico-chemical waste composition data was performed to derive value ranges and data distributions for element concentrations (e.g. Cd content) and physical parameters (e.g. heating value). Based on 11,886 individual data entries, median values and percentiles for 47 parameters in 11 individual waste fractions are presented. Exceptional values and publications are identified and discussed. Detailed datasets are attached to this study, allowing further analysis and new applications of the data.

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Physico-chemical characterisation of material fractions in residual and source-segregated household waste in Denmark

Physico-chemical waste composition data are paramount for the assessment and planning of waste management systems. However, the applicability of data is limited by the regional, temporal and technical scope of waste characterisation studies. As Danish and European legislation aims for higher recycling rates evaluation of source-segregation and recycling chains gain importance. This paper provides a consistent up-to-date dataset for 74 physico-chemical parameters in 49 material fractions from residual and 24 material fractions from source-segregated Danish household waste. Significant differences in the physico-chemical properties of residual and source-segregated waste fractions were found for many parameters related to organic matter, but also for elements of environmental concern. Considerable differences in potentially toxic metal concentrations between the individual recyclable fractions within one material type were observed. This indicates that careful planning and performance evaluation of recycling schemes are important to ensure a high quality of collected recyclables. Rare earth elements (REE) were quantified in all waste fractions analysed, with the highest concentrations of REE found in fractions with high content of mineral raw materials, soil materials and dust. The observed REE concentrations represent the background concentration level in non-hazardous waste materials that may serve as a reference point for future investigations related to hazardous waste management. The detailed dataset provided here can be used for assessments of waste management solutions in Denmark and for the evaluation of the quality of recyclable materials in waste.
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Quantification of chemical contaminants in the paper and board fractions of municipal solid waste
Chemicals are used in materials as additives in order to improve the performance of the material or the production process itself. The presence of these chemicals in recyclable waste materials may potentially affect the recyclability of the materials. The addition of chemicals may vary depending on the production technology or the potential end-use of the material. Paper has been previously shown to potentially contain a large variety of chemicals. Quantitative data on the presence of chemicals in paper are necessary for appropriate waste paper management, including the recycling and re-processing of paper. However, a lack of quantitative data on the presence of chemicals in paper is evident in the literature. The aim of the present work is to quantify the presence of selected chemicals in waste paper derived from households. Samples of paper and board were collected from Danish households, including both residual and source-segregated materials, which were disposed of (e.g., through incineration) and recycled, respectively. The concentration of selected chemicals was quantified for all of the samples. The quantified chemicals included mineral oil hydrocarbons, phthalates, phenols, polychlorinated biphenyls, and selected toxic metals (Cd, Co, Cr, Cu, Ni, and Pb). The results suggest large variations in the concentration of chemicals depending on the waste paper fraction analysed. Research on the fate of chemicals in waste recycling and potential problem mitigation measures should be focused on in further studies.

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Limited data availability and local differences of environmental treatment technologies lead to the use of sub-optimal data and choices of single datasets, where multiple data choices may be representative. The use of data not representing the entire coverage of an LCA study can cause a bias in the result interpretation and limit the robustness of the results. The objective of this study is to demonstrate the relationship between the number of discrete data options and the goal and scope of the study. The importance of the spread in LCA results and how this spread influences the LCA result interpretation is assessed. The objective is obtained by performing a landfill model case study and presenting and discussing results relative to the specificity of the coverage of the study (see conceptual approach in Figure 1).

The outcomes show a trend of decreasing LCA result ranges with increasing level of specification of the technological and geographical coverage of the study. For example, for global warming potential, the global maximum value is 2.6 times larger than the global minimum value and, for human toxicity, carcinogenic, the global maximum value is 45 times larger than the global minimum value. These ranges have the potential to significantly influence the LCA results, and are interpreted as potential magnitudes of errors introduced by the data choices. The results highlighted the pitfalls of
choosing specific data to represent a generic process, and vice-versa. The former will lead to precise, but inaccurate results, whereas in the latter the obtained data represent a lower level of knowledge than the initial goal and scope.

To conclude, a detailed description of the coverage of the study and understanding of the technologies are necessary for representative life cycle inventory modelling. This conclusions was described in a step-wise approach for representative data choices and modelling. The outcomes shed light on the potential spread caused by discrete data choices in the modelling of environmental treatment technologies.

Recycling of plastic waste: Presence of phthalates in plastics from households and industry

Plastics recycling has the potential to substitute virgin plastics partially as a source of raw materials in plastic product manufacturing. Plastic as a material may contain a variety of chemicals, some potentially hazardous. Phthalates, for instance, are a group of chemicals produced in large volumes and are commonly used as plasticisers in plastics manufacturing. Potential impacts on human health require restricted use in selected applications and a need for the closer monitoring of potential sources of human exposure. Although the presence of phthalates in a variety of plastics has been recognised, the influence of plastic recycling on phthalate content has been hypothesised but not well documented. In the present work we analysed selected phthalates (DMP, DEP, DPP, DiBP, DBP, BBzP, DEHP, DCHP and DnOP) in samples of waste plastics as well as recycled and virgin plastics. DBP, DiBP and DEHP had the highest frequency of detection in the samples analysed, with 360 μg/g, 460 μg/g and 2700 μg/g as the maximum measured concentrations, respectively. Among other, statistical analysis of the analytical results suggested that phthalates were potentially added in the later stages of plastic product manufacturing (labelling, gluing, etc.) and were not removed following recycling of household waste plastics. Furthermore, DEHP was identified as a potential indicator for phthalate contamination of plastics. Close monitoring of plastics intended for phthalates-sensitive applications is recommended if recycled plastics are to be used as raw material in production.
Semi-quantitative analysis of solid waste flows from nano-enabled consumer products in Europe, Denmark and the United Kingdom - Abundance, distribution and management

Many nano-enabled consumer products are known to be in the global market. At the same, little is known about the quantity, type, location etc. of the engineered nanomaterials (ENMs) inside the products. This limits the scientific investigations of potential environmental effects of these materials, and especially the knowledge of ENM behaviour and potential effects at the end-of-life stage of the products is scarce. To gain a better understanding of the end-of-life waste
treatment of nano-enabled consumer product, we provide an overview of the ENMs flowing into and throughout waste systems in Europe, Denmark and the United Kingdom. Using a nanoproduct inventory (nanodb.dk), we performed a four-step analysis to estimate the most abundant ENMs and in which waste fractions they are present. We found that in terms of number of products: (i) nano silver is the most used ENM in consumer products, and (ii) plastic from used product containers is the largest waste fraction also comprising a large variety of ENMs, though possibly in very small masses. Also, we showed that the local waste management system can influence the distribution of ENMs. It is recommended that future research focus on recycling and landfilling of nano-enabled products since these compartments represent hot spots for end-of-life nanoproducts.

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Size fractionation of waste-to-energy boiler ash enables separation of a coarse fraction with low dioxin concentrations

Polychlorinated dibenzo-p-dioxins and dibenzofurans (PCDD/F) formed in modern Waste-to-Energy plants are primarily found in the generated ashes and air pollution control residues, which are usually disposed of as hazardous waste. The objective of this study was to explore the occurrence of PCDD/F in different grain size fractions in the boiler ash, i.e. ash originating from the convection pass of the boiler. If a correlation between particle size and dioxin concentrations could be found, size fractionation of the ashes could reduce the total amount of hazardous waste. Boiler ash samples from ten sections of a boiler's convective part were collected over three sampling days, sieved into three different size fractions - 0.355 mm - and analysed for PCDD/F. The coarse fraction (>0.355 mm) in the first sections of the horizontal convection pass appeared to be of low toxicity with respect to dioxin content. While the total mass of the coarse fraction in this boiler was relatively small, sieving could reduce the amount of ash containing toxic PCDD/F by around 0.5 kg per tonne input waste or around 15% of the collected boiler ash from the convection pass. The mid-size fraction in this study covered a wide size range (0.09-0.355 mm) and possibly a low toxicity fraction could be identified by splitting this fraction into more narrow size ranges. The ashes exhibited uniform PCDD/F homologue patterns which suggests a stable and continuous generation of PCDD/F.
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The challenge of chemicals in material lifecycles

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The Effect of Data Structure and Model Choices on MFA Results: A Comparison of Phosphorus Balances for Denmark and Austria

Material Flow Analysis (MFA) studies for a particular substance often exist for several different countries or regions, but share a similar goal and scope. In direct comparisons of such regional resource budgets, the importance of the choices made in establishing an MFA system tends to be disregarded.

We identify and quantify the effects of choices made in system layout, data material and uncertainty assessment on the outcome of regional MFAs using two recent country-scale MFAs (of Denmark and Austria) of phosphorus as a case study. We highlight the differences in system boundaries and definition of flows and processes. We quantify types and choice of data sources; analyse the consistency of the data used by looking at the extent of data reconciliation, as a measure of model quality; quantify the effect of different approaches to uncertainty assessment; and show the influence of aggregating/disaggregating flows.

We show that differences in system layout are mostly attributable to varying goals and scope definitions. Direct comparison of uncertainties across studies is problematic: both studies draw on similar types of data sources, yet they show very different uncertainty assessments; the uncertainty assessment in MFA is always subjective to a certain extent. We demonstrate that reconciliation of conflicting data provides a useful measure to assess data consistency and model quality: data are more consistent (5% average change in reconciled data) in the Austrian than in the Danish (9%) case. We suggest an iterative approach to uncertainty assessment. Likewise, we demonstrate the effect of the aggregation of flows on model uncertainty.

These findings quantify and emphasise the importance of examining MFA studies’ metadata and suggest an approach to be followed when drawing on such studies as a source of information.

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The link between data choices and reality in life cycle assessment modelling of waste management technologies

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Waste material recycling: Assessment of contaminants limiting recycling
Materials and articles are constantly increasing in their complexity, promoted by demand for functionality, appearance and cost of consumer and industrial products. To satisfy these demands, a variety of chemicals and combinations of materials are used in products. On the other hand, material recycling has been recognised as a backbone of circular economy, with constant measures and initiatives being proposed in order to increase the recycling rates of materials being consumed. Material cycles are complex and dynamic systems where chemicals are added and removed in production, manufacturing,
consumption and waste management stages within a product's lifecycle (Figure 1). Hence, waste materials contain potentially hazardous chemicals that are unwanted in the new products made of the recycled raw materials. So far, the presence of such chemicals in materials for recycling has not been systematically investigated. This PhD project provided detailed quantitative data following a consistent approach to assess potential limitations for the presence of chemicals in relation to material recycling. Paper and plastics were used as illustrative examples of materials with well-established recycling schemes and great potential for increase in recycling, respectively.

The approach followed in the present work was developed and performed in four distinct steps. As step one, fractional composition of waste paper (30 fractions) and plastics (9 fractions) from households in Åbenrå municipality (Southern Denmark) was provided. In step two, a literature review concerning presence of chemicals in paper was performed. It was shown that approx. 10,000 individual chemicals may be present in paper products. Among the chemicals identified, approx. 150 were considered hazardous and approx. 50 were identified as particularly relevant with respect to paper recycling. Potential sources for chemicals in paper were evaluated. Printing and conversion were identified as the most important steps in relation to paper cycle, but chemicals added non-intentionally (NIAS) in a variety of steps (Figure 1) may also play a role.

Figure 1 Schematic representation of generic material and chemical cycles for a defined geographical boundary (e.g., Europe). Chemical loss implies evaporation, degradation, migration, etc., as well as removal through material (re) processing. NIAS: Non-Intentionally Added Substances [1].

Following, chemical analyses for quantification of a range of potential contaminants in paper (mineral oils, phenols, phthalates, polychlorinated biphenyls and toxic metals) and plastics (phthalates and brominated flame retardants) were done. The results indicated large variations in presence of chemical contaminants (from μg/kg to g/kg), depending on the contaminant in focus or the sub-fraction (e.g., books) of the material fraction being analysed (e.g., paper). Certain material fractions showed higher content of chemicals (e.g., bisphenols in thermal paper and flame retardants in polystyrene plastics), potentially detrimental to their recycling. Finally, a material flow analysis (MFA) approach revealed the potential for accumulation and spreading of contaminants in material recycling, on the example of the European paper cycle.

Assessment of potential mitigation measures indicated that prevention of chemical use, removal of chemicals in recycling and constrain chemicals to specific product flows were in decreasing order of effectiveness. The assessment also pointed out the potential trade-offs between material quantity (i.e. recycling rates) and quality (i.e. presence of contaminants) when mitigation measures are applied.

Applying Fuzzy and Probabilistic Uncertainty Concepts to the Material Flow Analysis of Palladium in Austria

Material flow analysis (MFA) is a widely applied tool to investigate resource and recycling systems of metals and minerals. Owing to data limitations and restricted system understanding, MFA results are inherently uncertain. To demonstrate the systematic implementation of uncertainty analysis in MFA, two mathematical concepts for the quantification of uncertainties were applied to Austrian palladium (Pd) resource flows and evaluated: (1) uncertainty ranges expressed by fuzzy sets and (2) uncertainty ranges defined by normal distributions given as mean values and standard deviations. Whereas normal distributions represent the traditional approach for quantifying uncertainties in MFA, fuzzy sets may offer additional benefits in relation to uncertainty quantification in cases of scarce information. With respect to the Pd case study, the fuzzy representation of uncertain quantities is more consistent with the actual data availability in cases of incomplete databases, and fuzzy sets serve to highlight the effect of uncertainty on resource efficiency indicators derived from the MFA results. For both approaches, data reconciliation procedures offer the potential to reduce uncertainty and evaluate the plausibility of the model results. With respect to Pd resource management, improved formal collection of end-of-life (EOL) consumer products is identified as a key factor in increasing the recycling efficiency. In particular, the partial export of EOL vehicles represents a substantial loss of Pd from the Austrian resource system, whereas approximately 70% of the Pd in the EOL consumer products is recovered in waste management. In conclusion, systematic uncertainty analysis is an integral part of MFA required to provide robust decision support in resource management.
Bisphenol A and its structural analogues in household waste paper

Bisphenol A (BPA) is an industrial chemical produced in large volumes. Its main use is associated with polycarbonate plastic, epoxy resins and thermal paper. In contrast to other applications, thermal paper contains BPA in its un-reacted form as an additive, which is subjected to migration. Receiving a significant amount of attention from the scientific community and beyond, due to its controversial endocrine-disrupting effects, the industry is attempting to substitute BPA in variety of applications. Alternative phenolic compounds have been proposed for use in thermal paper; however, information to what extent BPA alternatives have been used in paper is sparse. The aim of the present work was to quantify BPA and its alternatives (bisphenol S (BPS), bisphenol E (BPE), bisphenol B (BPB), 4-cumylphenol (HPP) and bisphenol F (BPF)) in waste paper and board from Danish households, thermal paper receipts, non-carbon copy paper and conventional printer paper. BPA was found in all waste paper samples analysed, while BPS was identified in 73% of them. Only BPB was not identified in any of the samples. BPA and BPS were found in the majority of the receipts, which contained no measurable concentrations of the remaining alternatives. Although receipts showed the highest concentrations of BPA and BPS, office paper, flyers and corrugated boxes, together with receipts, represented the major flux of the two compounds in waste paper streams.

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Capabilities for modelling of conversion processes in LCA

Life cycle assessment was traditionally used for modelling of product design and optimization. This is also seen in the conventional LCA software which is optimized for the modelling of single materials streams of a homogeneous nature that is assembled into a final product. There has therefore been little focus on the chemical composition of the functional flows, as flows in the models have mainly been tracked on a mass basis, as focus was on the function of the product and not the chemical composition of said product.

Conversely modelling environmental technologies, such as wastewater treatment and waste management, the material being addressed is of a very heterogeneous nature. Between treatment facilities receiving materials with different compositions, but also at the individual treatment facility where the temporal composition of a treated material varies considerably. To address this, EASETECH (Clavreul et al., 2014) was developed which integrates a matrix approach for the functional unit which contains the full chemical composition for different material fractions, and also the number of different material fractions present in the overall mass being handled. These chemical substances can then be traced through the different processes similar to substance flow assessment, but with the added options to address emissions and material and energy usage through each process step.

However, it was found that further capabilities were needed as in some technologies even the chemical substances themselves change through a process chain. A good example of this is bio-refinery processes where different residual biomass products are converted through different steps into the final energy product. Here it is necessary to know the stoichiometry of the different products going in, and being able to set constraints for a possible flow on basis of other flows, and also do return flows for some material streams. We have therefore developed a new editor for the EASETECH software, which allows the user to make specific process modules where the actual chemical conversion processes can be modelled and then integrated into the overall LCA model. This allows for flexible modules which automatically will adjust the material flows it is handling on basis of its chemical information, which can be set for multiple input materials at the same time. A case example of this was carried out for a bio-refinery process.
Capabilities For Modelling Of Conversion Processes In Life Cycle Assessment

Life cycle assessment was traditionally used for modelling of product design and optimization. This is also seen in the conventional LCA software which is optimized for the modelling of single materials streams of a homogeneous nature that is assembled into a final product. There has therefore been little focus on the chemical composition of the functional flows, as flows in the models have mainly been tracked on a mass basis, as emphasis was the function of the product and not the chemical composition of said product. Conversely, in modelling of environmental technologies, such as wastewater treatment and waste management, the material being addressed is of a very heterogeneous nature. This heterogeneity is seen both between treatment facilities receiving materials with different compositions, but also at the individual treatment facility where the temporal composition of a treated material varies considerably. To address this, EASETECH (Clavreul et al., 2014) was developed which integrates a matrix approach for the reference flow which contains the full chemical composition for different material fractions, and also the number of different material fractions present in the overall mass being handled. These chemical substances can then be traced through the different processes similarly to substance flow assessment, but with the added options to address emissions, material and energy usage through each process step. However, it was found that further capabilities were needed, when considering how the biochemical parameters change through a process chain. A good example of this is bio-refinery processes where different residual biomass products are converted through different steps into the final energy product. Here it is necessary to know the stoichiometry of the different products going in, and being able to set constraints for a possible flow on basis of other flows, and also do return flows for some material streams. We have therefore developed a new editor for the EASETECH software, which allows the user to make specific process modules where the actual chemical conversion processes can be modelled and then integrated into the overall LCA model. This allows for flexible modules which automatically will adjust the material flows and the conversion takes places in processes on basis of its chemical information, which can be set for multiple input materials at the same time. A case example of this was carried out for a bio-refinery process, and the result of this case studied will be used to exemplify the use of the new process editor.

Challenges in plastics recycling

Recycling of waste plastics still remains a challenging area in the waste management sector. The current and potential goals proposed on EU or regional levels are difficult to achieve, and even to partially fulfill them the improvements in collection and sorting should be considerable. A study was undertaken to investigate the factors affecting quality in
plastics recycling. The preliminary results showed factors primarily influencing quality of plastics recycling to be polymer cross contamination, presence of additives, non-polymer impurities, and polymer degradation. Deprivation of plastics quality, with respect to recycling, has been shown to happen throughout the plastics value chain, but steps where improvements may happen have been preliminary identified. Example of Cr in plastic samples analysed showed potential spreading and accumulation of chemicals ending up in the waste plastics. In order to assure a functional recycling scheme and maintain consumer and market acceptance of recycled plastics, transparency in data on quality of plastics and better monitoring should be induced.

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Chemical contamination of material cycles
Material recycling represents a backbone of sustainable society in the context of circular economy. Ideally, materials are converted into products, used by the consumers, and discarded, just to be recycled and converted into newly manufactured products. Furthermore, materials may also contain chemicals, which would be re-introduced into the loop once a product is recycled. Such chemicals may not be removed in the recycling process, persist, and contaminate the newly manufactured products. Chemical contamination could potentially put product consumers at unnecessary risk and jeopardize public acceptance of recycled material-based products. Paper and plastics are conventional materials used to manufacture a variety of products within main sectors of economy (i.e. packaging, transportation, construction, services, and other). A number of chemicals can be either intentionally or unintentionally added to these materials in the process of product manufacturing or final product conversion. Extend of chemical use, as well as their presence in paper and plastic products remains largely uninvestigated. The aim of this project is to obtain reliable quantitative data on presence of selected (potentially hazardous) chemicals in paper and plastic materials, and furthermore discuss the likely impacts of chemical contamination on material recycling. The work is part of the new Danish initiative focusing on Integrated Resource Management and Recovery (IRMAR, grant no. 11-116775). The outcomes of the work will provide crucial basis for future waste characterization activities, environmental and risk assessments of material recycling, as well as provide authorities, scientific community and society with a necessary basis for evaluating potential future limitations to recycling and address means of mitigating accumulation and spreading of chemicals in various materials.

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Chemicals in material cycles
Material recycling has been found beneficial in terms of resource and energy performance and is greatly promoted throughout the world. A variety of chemicals is used in materials as additives and data on their presence is sparse. The present work dealt with paper as recyclable material and diisobutyl phthalate (DiBP) as chemical in focus. The results showed variations, between 0.83 and 32 μg/g, in the presence of DiBP in Danish waste paper and board and potential accumulation due to recycling.

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Column leaching from biomass combustion ashes
The utilization of biomass combustion ashes for forest soil liming and fertilizing has been addressed in literature. Though, a deep understanding of the ash chemical composition and leaching behavior is necessary to predict potential benefits and environmental risks related to this practice. In this study, a fly ash sample from an operating Danish power plant based on wood biomass was collected, chemically characterized and investigated for its leaching release of nutrients and heavy metals. A column leaching test was employed. The strongly alkaline pH of all the collected eluates suggested the potential suitability of the ash as a liming material. Although high contents of nutrients were detected, differences in their leaching release were found. Heavy metals were detected within typical literature contents for Nordic countries ashes.

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Comparing Titanium Release from Ceramic Tiles using a waste material characterization test - Influence of Calcium and Organic Matter concentrations
Nanomaterials are beneficial in the building industry to enhance or add certain features to commonly used materials. One example is the use of nano-titanium dioxide in the surface coating of ceramic tiles, to make the tiles surface self-cleaning. At the end of life stage, ceramic tiles might be deposited in landfills for construction and demolition waste or other types of landfills, depending on the local waste management system. Hence, the potential release of nano-Ti under landfill conditions is relevant to investigate. In this study we used a standard waste material characterization method to assess if
nano-titanium dioxide coated ceramic tiles are suitable for depositing in a landfill or not. Specifically, we used compliance batch test method, which is a simple test evaluating the release from a solid material to an aqueous media during 24 hrs. If nano-Ti particles are released from solid waste material to the landfill leachate, it is expected that the calcium and organic matter content in the liquid will affect the stability of the nanoparticles. The concentration of calcium in the landfill percolate is expected to decrease the stability of the particles due to compression of the electric double layer surrounding the particle, causing increased particle agglomeration and settling. Natural organic matter might have both a stabilizing and destabilizing effect on the released nano-Ti particles depending on the concentration, since this will specifically influence the ability of the organic matter to fully cover the surface of the particles. We evaluated the titanium release from identical ceramic tiles - with and without a nano-titanium dioxide coating - and varied the concentrations of calcium chloride (100-500 mg/l) and humic acid (25-100 mg/l). The titanium release was quantified immediately after the 24 hrs. test using single particle ICPMS and Transmission Electron Microscopy imaging. The preliminary results suggest that nanoparticulate titanium is released from both tiles – with and without nano-titanium dioxide coating. The size distributions of the released particles are similar and show a high polydispersity. Further, the median size of the particles is generally above 100nm. However, the results suggest some effect of the humic acid on the particle size distribution, which needs to be investigated further. These results can aid the further development of models for environmental concentrations of nanomaterials, specifically concerning the life cycle of nano-enabled products.
Construction and demolition waste: Comparison of standard up-flow column and down-flow lysimeter leaching tests

Five samples of construction and demolition waste (C&DW) were investigated in order to quantify leaching of inorganic elements under percolation conditions according to two different experimental setups: standardised up-flow saturated columns (-1TS) for Al, As, Ba, Cd, Cu, Mg, Mn, Ni, P, Pb, Sb, Se, Si, Zn. Observed differences between tests are likely to be due to differences in pH related to crushing and exposure of fresh particle surfaces, as well as in equilibrium conditions. In the case of C&DW, the standardised column tests, which are more practical, are considered to acceptably describe cumulative releases at L/S 10 l·kg⁻¹TS in percolation scenarios. However, when the focus is on estimation of initial concentrations for (for example) risk assessment, data from standardised column tests may not be fully applicable, and data from lysimeters may be used for validation purposes. Se, Cr and, to a lesser extent, SO₄ and Sb were leaching from C&DW in critical amounts compared with existing limit values.
Data structure in MFA and its effects on results: a comparison of P in Denmark and Austria

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Food waste generation in office areas at DTU

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Environmental Impacts Assessment of Recycling of Construction and Demolition Waste

Construction and demolition waste (C&DW) is waste derived from the construction, demolition and renovation of buildings and civil infrastructure. With 900 million tons generated every year in Europe, it is the largest waste stream on the continent. C&DW is mainly constituted of mineral fractions, i.e. soil and stones, concrete, asphalt and masonry, and as such it has the potential to be used as aggregate in the construction sector. A typical application is in an unbound state as filler in road structures. This practice offers evident benefits in terms of resource savings, however it might lead to potential adverse impacts, especially related to the water-borne emission of pollutants, which need to be avoided. This requires first of all an estimation of their magnitude, and so the goal of this PhD is to provide an assessment of potential environmental impacts related to C&DW utilisation. C&DW is characterised by significant variability, especially in terms of leaching. Different levels of Ca, Ba, Cl-, Cr, K, Li, Mg, Na, Sr, Se, Si, SO4 and V are in evidence, depending on the ageing level (and therefore on the extent of carbonation) as well as the content of masonry. Both aspects may be optimised by appropriate measures within the C&DW waste management system, for instance by promoting source segregation of the concrete fraction stream or actively pursuing its carbonation. We found that leaching of Se, and to a lower extent Cr, Sb, SO4, Cl-, appears critical for C&DW in relation to existing national and European regulations. Cr mainly exists in C&DW leachates as anionic species, which may be interpreted as hexavalent species (mainly chromate). Despite being banned several decades ago, PCBs are still found in C&DW and in concrete raw materials, albeit in low, non-critical concentrations. This highlights their ubiquitous environmental presence. Several methods may be used to investigate leaching from granular C&DW, one of which is percolation tests. Compared to down-flow lysimeters with uncrushed C&DW, this study found that the use of standard up-flow columns, with materials below 4mm in particle size, may introduce differences especially in terms of pH, which in turn may affect the leaching of Al, As, Ba, Cu, DOC, Mg, Mn, P, Pb, Sb, Se, Si and Zn as a consequence of the crushing process, which results in the exposure of fresh, un-carbonated surfaces. However, when the scope involves quantifying cumulative release, standard up-flow columns may be considered appropriate, while for estimating early concentrations, relying on standard up-flow columns may be more problematic (e.g. Al, As, Cu, DOC, Mg, Mn, P, Pb, Sb, Se, Si and Zn), and the relationship between testing conditions and field conditions should be evaluated critically. Owing to its high toxicity and significant mobility, especially at high pH levels, Cr(VI) is one of the elements of concern found in C&DW leachates. Its fate in the sub-soil below road applications was assessed experimentally, and its vertical migration was then predicted through a model. Interactions with sub-soil particles, namely reduction to immobile Cr(III), are responsible for the retention of Cr(VI) in the first 70 cm of sub-soil below the C&DW sub-base. Temperate climates might inhibit the already slow reduction kinetics, resulting in Cr(VI) migration up to 2 m. The same case applies to situations characterised by high infiltration rates, such as unpaved roads, cracked asphalt cover or heavy rain events. By using holistic tools such as life cycle assessment (LCA) a general evaluation of the environmental consequences of C&DW utilisation system was provided. Although for most impact categories C&DW utilisation in road sub-bases does not provide environmental savings in absolute terms, it is generally less hazardous than when being landfilled (excluding toxicity impacts). On the other hand, landfilling appears better than C&DW utilisation when considering toxicity categories, owing to lower leaching in landfill scenarios over a 100-year time horizon. Oxyanions play a predominant role in leaching impacts, rather than cationic metals, and accurate modelling of Cr(VI) fate is essential to the results, while the heterogeneity of C&DW leachates does not play a crucial role in LCA results. C&DW carbonation leads to a trade-off between reducing global warming impacts and increasing toxic impacts related to the higher leaching of oxyanions. While leaching appears as the major problem relating to C&DW utilisation in LCA terms, uncertainties related to methodological aspects of leaching modelling in LCA should be acknowledged.
GHG emission factors of biofuels: A case study for Denmark

Biofuels are likely to play an increasingly important role in the transportation sector in the coming decades. To ensure the sustainability of the biofuel chain, regulatory criteria and reduction targets for greenhouse gases (GHG) emissions have been defined in different legislative frameworks (e.g. the European Renewable Energy Directive, RED). The provided calculation methods, however, leave room for interpretation regarding methodological choices, which could significantly affect the resulting emission factors. In this study, GHG reduction factors for a range of biofuels produced in a Danish biorefinery system were determined using five different emission allocation principles. The results show that emission savings ranged from -34 % to 71 %, indicating the need for a better definition of regulatory calculation principles. The calculated emission factors differed significantly from default values provided in the literature, suggesting that case-specific local conditions should be taken into consideration. A more holistic LCA-based approach proved useful in overcoming some of the issues inherent in the regulatory allocation principles. On this basis, indirect land use change (ILUC) emissions were shown to have the same magnitude as the direct emissions, thus indicating that the overall system should be included when assessing biofuel sustainability criteria.

GHG sustainability compliance of rapeseed-based biofuels produced in a Danish multi-output biorefinery system

Biofuels are likely to play an increasingly important role in the transportation sector in the coming decades. To ensure the sustainability of the biofuel chain, regulatory criteria and reduction targets for greenhouse gases (GHG) emissions have been defined in different legislative frameworks (e.g. the European Renewable Energy Directive, RED). The provided calculation methods, however, leave room for interpretation regarding methodological choices, which could significantly affect the resulting emission factors. In this study, GHG reduction factors for a range of biofuels produced in a Danish biorefinery system were determined using five different emission allocation principles. The results show that emission savings ranged from -34 % to 71 %, indicating the need for a better definition of regulatory calculation principles. The calculated emission factors differed significantly from default values provided in the literature, suggesting that case-specific local conditions should be taken into consideration. A more holistic LCA-based approach proved useful in overcoming some of the issues inherent in the regulatory allocation principles. On this basis, indirect land use change (ILUC) emissions were shown to have the same magnitude as the direct emissions, thus indicating that the overall system should be included when assessing biofuel sustainability criteria.
Life cycle assessment and residue leaching: The importance of parameter, scenario and leaching data selection

Residues from industrial processes and waste management systems (WMSs) have been increasingly reutilised, leading to landfilling rate reductions and the optimisation of mineral resource utilisation in society. Life cycle assessment (LCA) is a holistic methodology allowing for the analysis of systems and products and can be applied to waste management systems to identify environmental benefits and critical aspects thereof. From an LCA perspective, residue utilisation provides benefits such as avoiding the production and depletion of primary materials, but it can lead to environmental burdens, due to the potential leaching of toxic substances. In waste LCA studies where residue utilisation is included, leaching has generally been neglected. In this study, municipal solid waste incineration bottom ash (MSWI BA) was used as a case study into three LCA scenarios having different system boundaries. The importance of data quality and parameter selection in the overall LCA results was evaluated, and an innovative method to assess metal transport into the environment was applied, in order to determine emissions to the soil and water compartments for use in an LCA. It was found that toxic impacts as a result of leaching were dominant in systems including only MSWI BA utilisation, while leaching appeared negligible in larger scenarios including the entire waste system. However, leaching could not be disregarded a priori, due to large uncertainties characterising other activities in the scenario (e.g. electricity production). Based on the analysis of relevant parameters relative to leaching, and on general results of the study, recommendations are provided regarding the use of leaching data in LCA studies.
Life cycle assessment modelling considering uncertainty – the more robust Recommendation

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Life cycle assessment modelling of new technologies considering uncertainty

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Life cycle assessment of construction and demolition waste management

Life cycle assessment (LCA) modelling of construction and demolition waste (C&DW) management was carried out. The functional unit was management of 1 Mg mineral, source separated C&DW, which is either utilised in road construction as a substitute for natural aggregates, or landfilled. The assessed environmental impacts included both non-toxic and toxic impact categories. The scenarios comprised all stages of the end-of-life management of C&DW, until final disposal of all residues. Leaching of inorganic contaminants was included, as was the production of natural aggregates, which was avoided because of the use of C&DW. Typical uncertainties related to contaminant leaching were addressed. For most impact categories, utilisation of C&DW in road construction was preferable to landfilling; however, for most categories, utilisation resulted in net environmental burdens. Transportation represented the most important contribution for most nontoxic impacts, accounting for 60-95 per cent of these impacts. Capital goods contributed with negligible impacts. Leaching played a critical role for the toxic categories, where landfilling had lower impacts than utilisation because of the lower levels of leachate per ton of C&DW reaching the groundwater over a 100-year perspective. Leaching of oxyanions (As, V and Sb) was critical with respect to leaching. Typical experimental uncertainties in leaching data did not have a pivotal influence on the results; however, accounting for Cr immobilisation in soils as part of the impact assessment was critical for modelling the leaching impacts. Compared with the overall life cycle of building and construction materials, leaching emissions were shown to be potentially significant for toxicity impacts, compared with contributions from production of the same materials, showing that end-of-life impacts and leaching should not be disregarded when assessing environmental impacts from construction products and materials. CO2 uptake in the C&DW corresponding to 15 per cent carbonation could out-balance global warming impacts from transportation; however, carbonation would also likely result in increased toxicity impacts due to higher leaching of oxyanions. (C) 2015 Elsevier Ltd. All rights reserved.
Life cycle assessment of resource recovery from municipal solid waste incineration bottom ash

Bottom ash, the main solid output from municipal solid waste incineration (MSWI), has significant potential for the recovery of resources such as scrap metals and aggregates. The utilisation of these resources ideally enables natural resources to be saved. However, the quality of the recovered scrap metals may limit recycling potential, and the utilisation of aggregates may cause the release of toxic substances into the natural environment through leaching. A life cycle assessment (LCA) was applied to a full-scale MSWI bottom ash management and recovery system to identify environmental break-even points beyond which the burdens of the recovery processes outweigh the environmental benefits from valorising metals and mineral aggregates. Experimental data for the quantity and quality of individual material fractions were used as a basis for LCA modelling. For the aggregates, three disposal routes were compared: landfilling, road sub-base and aggregate in concrete, while specific leaching data were used as the basis for evaluating toxic impacts. The recovery and recycling of aluminium, ferrous, stainless steel and copper scrap were considered, and the importance of aluminium scrap quality, choice of marginal energy technologies and substitution rates between primary
and secondary aluminium, stainless steel and ferrous products, were assessed and discussed. The modelling resulted in burdens to toxic impacts associated with metal recycling and leaching from aggregates during utilisation, while large savings were obtained in terms of non-toxic impacts. However, by varying the substitution rate for aluminium recycling between 0.35 and 0.05 (on the basis of aluminium scrap and secondary aluminium alloy market value), it was found that the current recovery system might reach a breakeven point between the benefits of recycling and energy expended on sorting and upgrading the scrap. (C) 2014 Elsevier Ltd. All rights reserved.
Life cycle assessment of shredder residue management

This report provides a life-cycle assessment (LCA) of the treatment of shredder residue (SR) in Denmark. The LCA was conducted for the Environmental Protection Agency by DTU Environment in the period March-July 2014, as part of a service agreement between the Danish Environmental Protection Agency and the Technical University of Denmark on research-based services in the field of waste management. The report is part of a larger survey on improved resource recovery of waste, focusing on the environmental as well as socio-economic consequences of different treatment scenarios for shredder waste, impregnated wood waste, wood waste for recycling and district heating pipes. The LCA was conducted using the EASETECH LCA model developed by DTU Environment for the environmental assessment of waste management systems and environmental technologies. The LCA was conducted in accordance with the LCA principles outlined in DS/EN ISO standards 14040 and 14044. A critical review was carried out by external LCA experts from the Danish Technological Institute. A reference group consisting of Danish stakeholders with interests in SR management were asked to comment on the report as well. All critical comments from reference group and LCA reviewer were followed and the report was changed accordingly.

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Life cycle assessment of thermal Waste-to-Energy technologies: Review and recommendations

Life cycle assessment (LCA) has been used extensively within the recent decade to evaluate the environmental performance of thermal Waste-to-Energy (WtE) technologies: incineration, co-combustion, pyrolysis and gasification. A critical review was carried out involving 250 individual case-studies published in 136 peer-reviewed journal articles within 1995 and 2013. The studies were evaluated with respect to critical aspects such as: (i) goal and scope definitions (e.g. functional units, system boundaries, temporal and geographic scopes), (ii) detailed technology parameters (e.g. related to waste composition, technology, gas cleaning, energy recovery, residue management, and inventory data), and (iii)
modeling principles (e.g. energy/mass calculation principles, energy substitution, inclusion of capital goods and uncertainty evaluation). Very few of the published studies provided full and transparent descriptions of all these aspects, in many cases preventing an evaluation of the validity of results, and limiting applicability of data and results in other contexts. The review clearly suggests that the quality of LCA studies of WtE technologies and systems including energy recovery can be significantly improved. Based on the review, a detailed overview of assumptions and modeling choices in existing literature is provided in conjunction with practical recommendations for state-of-the-art LCA of Waste-to-Energy.

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This paper provides a detailed and comprehensive cost model for the economic assessment of solid waste management systems. The model was based on the principles of Life Cycle Costing (LCC) and followed a bottom-up calculation approach providing detailed cost items for all key technologies within modern waste systems. All technologies were defined per tonne of waste input, and each cost item within a technology was characterised by both a technical and an economic parameter (for example amount and cost of fuel related to waste collection), to ensure transparency, applicability and reproducibility. Cost items were classified as: (1) budget costs, (2) transfers (for example taxes, subsidies and fees) and (3) externality costs (for example damage or abatement costs related to emissions and disamenities).

Technology costs were obtained as the sum of all cost items (of the same type) within a specific technology, while scenario costs were the sum of all technologies involved in a scenario. The cost model allows for the completion of three types of LCC: a Conventional LCC, for the assessment of financial costs, an Environmental LCC, for the assessment of financial costs whose results are complemented by a Life Cycle Assessment (LCA) for the same system, and a Societal LCC, for socio-economic assessments. Conventional and Environmental LCCs includes budget costs and transfers, while Societal LCCs includes budget and externality costs. Critical aspects were found in the existing literature regarding the cost assessment of waste management, namely system boundary equivalency, accounting for temporally distributed emissions and impacts, inclusions of transfers, the internalisation of environmental impacts and the coverage of shadow prices, and there was also significant confusion regarding terminology. The presented cost model was implemented in two case study scenarios assessing the costs involved in the source segregation of organic waste from 100,000 Danish households and the subsequent co-digestion of organic waste with animal manure. Overall, source segregation resulted in higher financial costs than the alternative of incinerating the organic waste with the residual waste: 1.6 M€/year, of which 0.9 M€/year was costs for extra bins and bags used by the households, 1.0 M€/year for extra collections and -0.3.
ME/year saved on incineration.

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Sound waste management and optimisation of resource recovery require reliable data on solid waste generation and composition. In the absence of standardised and commonly accepted waste characterisation methodologies, various approaches have been reported in literature. This limits both comparability and applicability of the results. In this study, a waste sampling and sorting methodology for efficient and statistically robust characterisation of solid waste was introduced. The methodology was applied to residual waste collected from 1442 households distributed among 10 individual sub-areas in three Danish municipalities (both single and multi-family house areas). In total 17 tonnes of waste were sorted into 10-50 waste fractions, organised according to a three-level (tiered approach) facilitating comparison of the waste data between individual sub-areas with different fractionation (waste from one municipality was sorted at "Level III", e.g. detailed, while the other two were sorted only at "Level I"). The results showed that residual household waste mainly contained food waste (42 +/- 5%, mass per wet basis) and miscellaneous combustibles (18 +/- 3%, mass per wet basis). The residual household waste generation rate in the study areas was 3-4 kg per person per week. Statistical analyses revealed that the waste composition was independent of variations in the waste generation rate. Both, waste composition and waste generation rates were statistically similar for each of the three municipalities. While the waste generation rates were similar for each of the two housing types (single-family and multi-family house areas), the individual percentage composition of food waste, paper, and glass was significantly different between the housing types. This indicates that housing type is a critical stratification parameter. Separating food leftovers from food packaging during manual sorting of the sampled waste did not have significant influence on the proportions of food waste and packaging materials, indicating that this step may not be required. (C) 2014 Elsevier Ltd. All rights reserved.
Occurrence and temporal variation of danish household food waste

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Phosphorus in Denmark: national and regional anthropogenic flows

Substance flow analyses (SFA) of phosphorus (P) have been examined on a national or supra-national level in various recent studies. SFA studies of P on the country scale or larger can have limited informative value; large differences between P budgets exist within countries and are easily obscured by country-wide average values. To quantify and evaluate these imbalances we integrated a country-scale and regional-scale model of the Danish anthropogenic P flows and stocks. We examine three spatial regions with regard to agriculture, as the main driver for P use, and waste management, the crucial sector for P recovery. The regions are characterised by their differences in agricultural practice, population and industrial density. We show considerable variation in P flows within the country. First, these are driven by agriculture, with mineral fertiliser inputs varying between 3 and 5 kg ha\(^{-1}\) yr\(^{-1}\), and animal feedstuff inputs between 5 and 19 kg ha\(^{-1}\) yr\(^{-1}\). We identified surpluses especially in areas with a larger proportion of animal husbandry, owing to additional application of manure in excess of crop P demand. However, redistribution of the large amounts of P in manure is not feasible owing to transport limitations. Second, waste management, closely linked to population and industrial density is the driver behind differences in recoverable P flows. Current amounts of potentially recoverable P cannot change the reliance on primary P. The most immediate P re-use potential exists in the areas around the eastern urban agglomerations, from more complete recovery of sewage sludge (with unrecovered P amounts of up to 33% of P in current mineral fertiliser imports) and the biowaste fraction in municipal solid waste currently not collected separately (24% of P in current mineral fertiliser imports), since this region shows both the highest proportion of crop production and fertiliser use and lowest soil P budget.

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Scopus rating (2011): SJR 1.119 SNIP 1.848 CiteScore 2.62
ISI indexed (2011): ISI indexed yes
Web of Science (2011): Indexed yes
BFI (2010): BFI-level 1
Preparing the ground for an operational handling of long-term emissions in LCA

Currently, there is no meaningful methodology for the estimation of environmental impacts from long-term heavy metal emissions in a life cycle assessment (LCA) context, when an assessment of landfill and mining technologies is performed. In this paper, the aims are to investigate the main issues hindering the standardisation of a methodology to account for potential impacts from long-term metal emissions, and to describe the characteristics of a robust framework for an operational impact assessment methodology. In order to demonstrate the issues around potential impacts from long-term emissions in LCA and derive a scientific basis for developing an adequate LCA methodology to address these impacts, a two-part review on long-term metal emissions is performed that (a) identifies a suitable time-dependent life cycle inventory (LCI) while underlining the problems in existing emission prediction attempts and (b) describes the existing LCA approaches for accounting of toxic potential impacts from these emissions while explaining the reason that the identified proposals have not been adopted from the LCA community. These approaches are then compared upon the basis of a common LCI and their differences are highlighted. A suitable dynamic LCI is identified for landfill emissions, which calculates Ni, Zn, Cd and Pb emissions as a function of time, based on assumed developments of the leachate pH. The results of the application of the different impact assessment methods on that LCI differ by up to 8 orders of magnitude. Therefore, the decision-making process supported by an LCA becomes very confusing. None of the approaches consider future changes in the receiving environment and are accompanied with any uncertainty considerations. In order to move towards a robust environmental assessment of long-term emissions, it is necessary to (i) represent future potential impacts more accurately by estimating time-dependent characterisation factors (CFs) corresponding to changing environmental conditions, (ii) develop more robust estimations by addressing uncertainty and (iii) refer to actual potential impacts, by taking into account the current and future background concentrations.

General information
State: Published
Organisations: Department of Management Engineering, Quantitative Sustainability Assessment, Department of Environmental Engineering, Residual Resource Engineering, ELSA-PACT
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Quantifying uncertainty in sustainability assessments: from feedstock to end-of-life

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Poster presentation
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Recent LCA Developments In Waste Management
Based on 10 years of experience we briefly present key issues which should receive special attention when waste LCA is performed. Attention paid to the importance of good data on waste composition, the contribution of environmental impacts from capital goods, assessing the value of recovered materials, nutrients and energy, the representativity of external life cycle inventory data bases, how we adress uncertainty and important factors in defining future scenarios.

General information
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Organisations: Department of Environmental Engineering, Residual Resource Engineering
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Resource recovery from residual household waste: An application of exergy flow analysis and exergetic life cycle assessment
Exergy is based on the Second Law of thermodynamics and can be used to express physical and chemical potential and provides a unified measure for resource accounting. In this study, exergy analysis was applied to four residual household waste management scenarios with focus on the achieved resource recovery efficiencies. The calculated exergy efficiencies were used to compare the scenarios and to evaluate the applicability of exergy-based measures for expressing resource quality and for optimizing resource recovery. Exergy efficiencies were determined based on two approaches: (i) exergy flow analysis of the waste treatment system under investigation and (ii) exergetic life cycle assessment (LCA) using the Cumulative Exergy Extraction from the Natural Environment (CEENE) as a method for resource accounting. Scenario efficiencies of around 17-27% were found based on the exergy flow analysis (higher
efficiencies were associated with high levels of material recycling), while the scenario efficiencies based on the exergetic LCA lay in a narrow range around 14%. Metal recovery was beneficial in both types of analyses, but had more influence on the overall efficiency in the exergetic LCA approach, as avoided burdens associated with primary metal production were much more important than the exergy content of the recovered metals. On the other hand, plastic recovery was highly beneficial in the exergy flow analysis, but rather insignificant in exergetic LCA. The two approaches thereby offered different quantitative results as well as conclusions regarding material recovery. With respect to resource quality, the main challenge for the exergy flow analysis is the use of exergy content and exergy losses as a proxy for resource quality and resource losses, as exergy content is not per se correlated with the functionality of a material. In addition, the definition of appropriate waste system boundaries is critical for the exergy efficiencies derived from the flow analysis, as it is constrained by limited information available about the composition of flows in the system as well as about secondary production processes and their interaction with primary or traditional production chains. In the exergetic LCA, resource quality could be reflected by the savings achieved by product substitution and the consideration of the waste’s upstream burden allowed for an evaluation of the waste’s resource potential. For a comprehensive assessment of resource efficiency in waste LCA, the sensitivity of accounting for product substitution should be carefully analyzed and cumulative exergy consumption measures should be complimented by other impact categories.

**General information**

State: Published
Organisations: Department of Environmental Engineering, Residual Resource Engineering, Vienna University of Technology, Ghent University
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BFI (2011): BFI-level 1
Scopus rating (2011): SJR 1.698 SNIP 2.085 CiteScore 2.99
ISI indexed (2011): ISI indexed yes
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Role of data quality in assessment of the sustainability of technologies

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Organisations: Department of Environmental Engineering, Residual Resource Engineering
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Poster presentation
Publication: Research - peer-review › Conference abstract in proceedings – Annual report year: 2015

Seasonal variation of household food waste in Denmark
This paper analysed the influence of seasonal variation in the generation of the Danish household food waste. Residual household waste was sampled and manually sorted into six food waste fractions. Vegetable food wastes were the main fraction contributing to the household food waste. Statistical analysis showed a significant relationship between avoidable food waste and household size. However, there were no significant seasonal differences in the amount of avoidable food waste.

General information
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Soil retention of hexavalent chromium released from construction and demolition waste in a road-base-application scenario

We investigated the retention of Cr(VI) in three subsoils with low organic matter content in laboratory experiments at concentration levels relevant to represent leachates from construction and demolition waste (C&DW) reused as unbound material in road construction. The retention mechanism appeared to be reduction and subsequent precipitation as Cr(III) on the soil. The reduction process was slow and in several experiments it was still proceeding at the end of the six-month experimental period. The overall retention reaction fit well with a second-order reaction governed by actual Cr(VI) concentration and reduction capacity of the soil. The experimentally determined reduction capacities and second-order kinetic parameters were used to model, for a 100-year period, the one-dimensional migration of Cr(VI) in the subsoil under a layer of C&DW. The resulting Cr(VI) concentration would be negligible below 7–70 cm depth. However, in rigid climates and with high water infiltration through the road pavement, the reduction reaction could be so slow that Cr(VI) might migrate as deep as 200 cm under the road. The reaction parameters and the model can form the basis for systematically assessing under which scenarios Cr(VI) from C&DW could lead to an environmental issue for ground- and receiving surface waters.
Source segregation of food waste in office areas: Factors affecting waste generation rates and quality
Existing legislation mandates that the amount of waste being recycled should be increased. Among others, in its Resource Strategy Plan, the Danish Government decided that at least 60% of food waste generated by the service sector, including in office areas, should be source-sorted and collected separately by 2018. To assess the achievability of these targets, source-sorted food waste and residual waste from office areas was collected and weighed on a daily basis during 133 working days. Waste composition analyses were conducted every week to investigate the efficiency of the source-sorting campaign and the purity of the source-sorted food waste. The moisture content of source-sorted food waste and residual waste fractions, and potential methane production from source-sorted food waste, was also investigated. Food waste generation equated to 23. ± 5. kg/employee/year, of which 20. ± 5. kg/employee/year was source-sorted, with a considerably high purity of 99%. Residual waste amounted to 10. ± 5. kg/employee/year and consisted mainly of paper (29. ± 13%), plastic (23. ± 9%) and missorted food waste (24. ± 16%). The moisture content of source-sorted food waste was significantly higher (8%) than missorted food waste, and the methane potential of source-sorted food waste was 463. ± 42. mL CH4/g VS. These results show that food waste in office areas offers promising potential for relatively easily collectable and pure source-sorted food waste, suggesting that recycling targets for food waste could be achieved with reasonable logistical ease in office areas.

General information
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Authors: Edjabou, V. M. E. (Intern), Boldrin, A. (Intern), Scheutz, C. (Intern), Astrup, T. F. (Intern)
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Publication date: 2015
Understanding uncertainty propagation in life cycle assessments of waste management systems

Uncertainty analysis in Life Cycle Assessments (LCAs) of waste management systems often results obscure and complex, with key parameters rarely determined on a case-by-case basis. The paper shows an application of a simplified approach to uncertainty coupled with a Global Sensitivity Analysis (GSA) perspective on three alternative waste management systems for Danish single-family household waste. The approach provides a fast and systematic method to select the most important parameters in the LCAs, understand their propagation and contribution to uncertainty.

Waste paper for recycling: Overview and identification of potentially critical substances

Paper product manufacturing involves a variety of chemicals used either directly in paper and pulp production or in the conversion processes (i.e. printing, gluing) that follow. Due to economic and environmental initiatives, paper recycling
rates continue to rise. In Europe, recycling has increased by nearly 20% within the last decade or so, reaching a level of almost 72% in 2012. With increasing recycling rates, lower quality paper fractions may be included. This may potentially lead to accumulation or un-intended spreading of chemical substances contained in paper, e.g. by introducing chemicals contained in waste paper into the recycling loop. This study provides an overview of chemicals potentially present in paper and applies a sequential hazard screening procedure based on the intrinsic hazard, physical-chemical and biodegradability characteristics of the substances. Based on the results, 51 substances were identified as potentially critical (selected mineral oils, phthalates, phenols, parabens, as well as other groups of chemicals) in relation to paper recycling. It is recommended that these substances receive more attention in waste paper.

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Scopus rating (2010): SJR 1.555 SNIP 1.78
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BFI (2008): BFI-level 2
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Web of Science (2008): Indexed yes
Scopus rating (2007): SJR 1.035 SNIP 1.767
Web of Science (2007): Indexed yes
Waste to energy the carbon perspective
Waste to energy plants are key treatment facilities for municipal solid waste in Europe. The technology provides efficient volume reduction, mass reduction and hygienisation of the waste. However, the technology is highly disputed in some countries. It is crucial to understand the role of waste to energy with respect to potential contributions to CO₂ emissions and savings.

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Organisations: Department of Environmental Engineering, Residual Resource Engineering
Authors: Christensen, T. H. (Intern), Damgaard, A. (Intern), Astrup, T. F. (Intern)
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Main Research Area: Technical/natural sciences

Bioenergy from crops and biomass residues: a consequential life-cycle assessment including land-use changes
Biofuels are promising means to reduce fossil fuel depletion and mitigate greenhouse-gas (GHG) emissions. However, recent studies questioned the environmental benefits earlier attributed to biofuels, when these involve land-use changes (direct/indirect, i.e., dLUC/iLUC) (1-5). Yet, second generation biofuels produced from residual biomass promise important environmental savings. However, since these residues are today in-use for specific purposes (e.g., feeding), a detailed modelling of the consequences (e.g., on the feed-market) induced by their diversion to energy should be performed to represent the actual environmental impacts.

This study quantified the GHG emissions associated with a number of scenarios involving bioenergy production (as...
combined-heat-and-power, heating, and transport biofuel) from energy crops, industrial/agricultural residues, algae, and the organic fraction of municipal solid waste. Four conversion pathways were considered: combustion, fermentation-to-ethanol, fermentation-to-biogas, and thermal gasification. A total of 80 bioenergy scenarios were assessed. Consequential life-cycle assessment (CLCA) was used to quantify the environmental impacts. CLCA aimed at identifying all the consequences associated with the establishment of bioenergy systems compared with the reference (current use of fossil and biomass resource). The modelling was facilitated with the LCA-model EASETECH. The functional unit was 1 unit-energy produced (i.e., 1 kWh electricity, 1 MJ heat or 1 MJ transport-biofuel, depending on the energy-service provided by the individual scenarios). The benefits derived from the use of the co-products were included.

Results revealed that iLUC GHG emissions were the major contributor to the total GHG impact (up to ca. 50%). For energy crops, the impact from iLUC was in the range 1.5-3.5 kg CO2-eq. kg-1 crop. Overall, bioenergy production from municipal solid waste and agricultural/industrial residues should be prioritized over cultivation of energy crops. This holds true as long as these residues are not today used as animal feed. Results also demonstrated that algae represent an interesting alternative to terrestrial energy crops.

This study provides GHG emission factors for a wide number of bioenergy scenarios. The aim is to inform decision/policy makers on the environmental consequences of producing biofuels from different sources, and for a variety of energy-services. Further, a new LCA-model (EASETECH) for bioenergy assessment is presented.

Bioenergy, material, and nutrients recovery from household waste: Advanced material, substance, energy, and cost flow analysis of a waste refinery process

Energy, materials, and resource recovery from mixed household waste may contribute to reductions in fossil fuel and resource consumption. For this purpose, legislation has been enforced to promote energy recovery and recycling. Potential solutions for separating biogenic and recyclable materials are offered by waste refineries where a bioliquid is produced from enzymatic treatment of mixed waste. In this study, potential flows of materials, energy, and substances within a waste refinery were investigated by combining sampling, analyses, and modeling. Existing material, substance, and energy flow analysis was further advanced by development of a mathematical optimization model for determination of the theoretical recovery potential. The results highlighted that the waste refinery may recover ca. 56% of the dry matter input as bioliquid, yielding 6.2GJ biogas-energy. The potential for nitrogen, phosphorous, potassium, and biogenic carbon recovery was estimated to be between 81% and 89% of the input. Biogenic and fossil carbon in the mixed household waste input was determined to 63% and 37% of total carbon based on 14C analyses. Additional recovery of metals and plastic was possible based on further process optimization. A challenge for the process may be digestate quality, as digestate may represent an emission pathway when applied on land. Considering the potential variability of local revenues for energy outputs, the costs for the waste refinery solution appeared comparable with alternatives such as direct incineration. © 2014 Elsevier Ltd.
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Bioenergy production from agri-industrial biomass residues: a consequential LCA

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Composition and leaching of construction and demolition waste: Inorganic elements and organic compounds
Thirty-three samples of construction and demolition waste collected at 11 recycling facilities in Denmark were characterised in terms of total content and leaching of inorganic elements and presence of the persistent organic pollutants PCBs and PAHs. Samples included (i) "clean" (i.e. unmixed) concrete waste, (ii) mixed masonry and concrete, (iii) asphalt and (iv) freshly cast concrete cores; both old and newly generated construction and demolition waste was included. PCBs and PAHs were detected in all samples, generally in non-critical concentrations. Overall, PAHs were comparable to background levels in urban environments. "Old" and "new" concrete samples indicated different PCB congener profiles and the presence of PCB even in new concrete suggested that background levels in raw materials may be an issue. Significant variability in total content of trace elements, even more pronounced for leaching, was observed indicating that the number of analysed samples may be critical in relation to decisions regarding management and utilisation of the materials. Higher leaching of chromium, sulphate and chloride were observed for masonry-containing and partly carbonated samples, indicating that source segregation and management practices may be important. Generally, leaching was in compliance with available leaching limits, except for selenium, and in some cases chromium, sulphate and antimony. © 2014 Elsevier B.V.

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Scopus rating (2013): SJR 1.822 SNIP 2.458 CiteScore 5.09
ISI indexed (2013): ISI indexed yes
Composition of municipal solid waste in Denmark

Data for the composition of municipal solid waste is a critical basis for any assessment of waste technologies and waste management systems. The detailed quantification of waste fractions is absolutely needed for a better technological development of waste treatment. The current waste composition data in Denmark are among the most detailed in the world. However, these data are more than 10 years old, and the following issues remain very important: (1) sampling approach, (2) representativeness of samples, (3) data uncertainties, (4) time and geographical variation. Moreover, in the absence of standardised and commonly accepted waste characterization methodologies, various approaches have been reported in literature. This limits both comparability and applicability of the results. The purpose of this study was to introduce a consistent methodology that reduces uncertainties and ensures data comparability to characterize municipal solid waste. This methodology was applied to residual waste collected from 1,442 households in three municipalities in Denmark. The main fractions contributing to the residual household waste were food waste and miscellaneous waste. Statistical analysis suggested that housing type is a critical stratification parameter for characterization of residual household waste.
EASETECH – A LCA model for assessment of environmental technologies

EASETECH is a new model for the environmental assessment of environmental technologies developed in collaboration between DTU Environment and DTU Compute. EASETECH is based on experience gained in the field of waste management modelling over the last decade and applies the same concepts to systems with different kinds of material flows, such as sludge, wastewater, biomass for energy production and treatment of contaminated soil. The primary aim of EASETECH is to perform life cycle assessment (LCA) of complex systems handling heterogeneous material flows. The main novelties of the model compared to other LCA software are as follows. The focus is put on material flow modelling. This means that each material flow is characterized as a mix of material fractions with different properties. Flows in terms of mass and composition are computed throughout the integrated system including rejects, slags, ashes and products as a basis for the LCA calculations. These flows are handled as a matrix of waste fractions and material properties, and each fraction can be handled independently or grouped based on general similarity (e.g. PE bottle and plastic waste) in different processes. This is very important because different materials have different chemical compositions, and the optimal treatment for one material fraction might be suboptimal for another fraction. It is therefore critical that the starting point of the modelling process is a composition matrix where each material fraction is specified in terms of chemical, as well as fraction-specific parameters (e.g. water content, heating value).

Emissions from cycling of thermal power plants in electricity systems with high penetration of wind power: Life cycle assessment for Ireland

The increase of renewable sources in the power sector is an important step towards more sustainable electricity production. However, introducing high shares of variable renewables, such as wind and solar, cause dispatchable power plants to vary their output to fulfill the remaining electrical demand. The environmental impacts related to potential future energy systems in Ireland for 2025 with high shares of wind power were evaluated using life cycle assessment (LCA), focusing on cycling emissions (due to part-load operation and start-ups) from dispatchable generators. Part-load operations significantly affect the average power plant efficiency, with all units seeing an average yearly efficiency noticeably less than optimal. In particular, load following units, on average, saw an 11% reduction. Given that production technologies are typically modeled assuming steady-state operation at full load, as part of LCA of electricity generation, the efficiency reduction would result in large underestimation of emissions, e.g. up to 65% for an oil power plant. Overall, cycling emissions accounted for less than 7% of lifecycle CO2, NOx and SO2 emissions in the five scenarios considered: while not overbalancing the benefits from increasing wind energy, cycling emissions are not negligible and should be systematically included (i.e. by using emission factors per unit of fuel input rather than per unit of power generated). As the ability to cycle is an additional service provided by a power plant, it is also recommended that only units with similar roles (load following, mid merit, or base load) should be compared. The results showed that cycling emissions increased with the installed wind capacity, but decreased with the addition of storage. The latter benefits can, however, only be obtained if base-load electricity production shifts to a cleaner source than coal. Finally, the present study indicates that, in terms of emission reductions, the priority for Ireland is to phase out coal-based power plants. While investing in new storage...
capacity reduces system operating costs at high wind penetrations and limits cycling, the emissions reductions are
somewhat negated when coupled with base load coal. © 2014.
Environmental exposure assessment framework for nanoparticles in solid waste

Information related to the potential environmental exposure of engineered nanomaterials (ENMs) in the solid waste management phase is extremely scarce. In this paper, we define nanowaste as separately collected or collectable waste materials which are or contain ENMs, and we present a five-step framework for the systematic assessment of ENM exposure during nanowaste management. The framework includes deriving EOL nanoproducts and evaluating the physicochemical properties of the nanostructure, matrix properties and nanowaste treatment processes as well as transformation processes and environment releases, eventually leading to a final assessment of potential ENM exposure. The proposed framework was applied to three selected nanoproducts: nanosilver polyester textile, nanoTiO2 sunscreen lotion and carbon nanotube tennis racquets. We found that the potential global environmental exposure of ENMs associated with these three products was an estimated 0.5–143 Mg/year, which can also be characterised qualitatively as medium, medium, low, respectively. Specific challenges remain and should be subject to further research: (1) analytical techniques for the characterisation of nanowaste and its transformation during waste treatment processes, (2) mechanisms for the release of ENMs, (3) the quantification of nanowaste amounts at the regional scale, (4) a definition of acceptable limit values for exposure to ENMs from nanowaste and (5) the reporting of nanowaste generation data.

General information

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Environmental impacts of future low-carbon electricity systems: Detailed life cycle assessment of a Danish case study
The need to reduce dependency on fossil resources and to decrease greenhouse gas (GHG) emissions is driving many countries towards the implementation of low-carbon electricity systems. In this study the environmental impact of a future (2030) possible low-carbon electricity system in Denmark was assessed and compared with the current situation (2010) and an alternative 2030 scenario using life cycle assessment (LCA). The influence on the final results of the modeling approach used for (i) electricity import, (ii) biomass resources, and (iii) the cogeneration of heat and power was discussed. The results showed that consumption of fossil resources and global warming impacts from the Danish electricity sector could be reduced significantly compared with 2010. Nevertheless, a reduction in GHG may be at the expense of other environmental impacts, such as the increased depletion of abiotic resources. Moreover, the results were very dependent upon biomass origin: when agricultural land was affected by biomass import, and land use changes and transportation were included, GHG emissions from imported biomass were comparable to those from fossil fuels. The results were significantly influenced by the modeling approach regarding the import of electricity, biomass provision, and the allocation between heat and power in cogeneration plants. As the importance of all three aspects is likely to increase in the future, transparency in LCA modeling is critical. Characterized impacts for Danish power plants in 2010 and 2030 (including corresponding electricity supply mixes) were provided, thus enabling future LCA studies to include appropriately impacts from the Danish electricity sector.

General information
State: Published
Environmentally Sustainable Construction Products and Materials – Assessment of release

The construction sector consumes yearly about half of all natural resources extracted in Europe and their transformation into building products has huge energy demands. Therefore the focus of today’s environmental policy is on the building end-of-life scenarios and material efficiency.

Here waste prevention and recycling/reuse play a key role by providing huge energy, water and material savings. These issues are also specifically addressed in the Construction Products Regulation (CPR2011), where health and safety aspects related to use of construction products cover the entire lifecycle.

Meanwhile the building sector is moving from new buildings towards maintenance and renovation. This trend will probably further increase by the energy conservation activities that will be required to achieve the 20-20-20 goals outlined by EC resulting in a need of renovation of a huge amount of buildings. Until today hardly any construction product is designed keeping recycling/reuse in mind, the “Design for the Environment” concept is one of the key steps towards increased recycling and reuse and thereby towards minimal environmental impacts.

This project has been carried out by VTT with cooperation with the Danish partners SBi, DTU and DHI and the Swedish partners SGI and IVL.

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Estimating household food waste in Denmark: case study of single family households

Food waste prevention remains the first priority in the European Waste Framework Directive, which aimed to halve the amount of food wasted within the EU Member States by 2025. Thus, reliable data on food waste composition and quantity are crucial for assessing the current food waste situation and determine potential improvements. In Denmark, although many sorting campaigns involving household waste has been conducted, little attention has been placed on food waste.
Comparison of recent studies made for examples in Austria, and the UK suggests that quantity and material composition of food waste vary significantly among the studies and differ from one country to another. Here, we provide a consistent methodology for characterization of household food waste, so that data comparability and source information are ensured. In this study, residual household waste was sampled and manually sorted from more than 211 single-family houses in Denmark. The residual waste from each household was collected and sorted separately to obtain a representative variation of the quantity and composition of food waste among households. The main fractions contributing to the household food waste were avoidable vegetable food waste and non-avoidable vegetable food waste. Furthermore, avoidable vegetable and animal food waste were the primary source of household food waste. Statistical analysis found a positive linear relationship between household size and the amount of the household food waste suggesting the amount of household food waste increases with the number of occupants per household.

General information
State: Published
Organisations: Department of Environmental Engineering, Residual Resource Engineering, Econet A/S
Authors: Edjabou, V. M. E. (Intern), Petersen, C. (Ekstern), Scheutz, C. (Intern), Astrup, T. F. (Intern)
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Estimation of ENM release from EOL consumer products in solid waste streams in Europe

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Organisations: Department of Environmental Engineering, Residual Resource Engineering, Environmental Chemistry
Authors: Heggelund, L. R. (Intern), Boldrin, A. (Intern), Hansen, S. F. (Intern), Astrup, T. F. (Intern)
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Feed or bioenergy production from agri-industrial residues?: An overview of the GHG emissions including indirect land-use change impacts

Second generation biofuels produced from “residual” biomasses are considered promising ways of producing bioenergy. However, many studies tend to forget that these biomasses are today used for specific purposes, (e.g. feeding). This means that their use for energy would induce cascading consequences on the food/feed market, or on the carbon balance of the soil. The first are commonly called indirect land-use changes (iLUC), as they cause an increase in the international demand of a food/feed product, finally inducing an expansion of cropland into other ecosystems. Failing to account for these consequences may lead to misrepresent the actual environmental impacts.

This study quantified, by use of consequential life cycle assessment (cLCA), the environmental impacts associated with a number of bioenergy scenarios involving selected agri-industrial residues. Three relevant conversion pathways were considered: combustion, fermentation to ethanol, and to biogas. The iLUC impacts were quantified and included in the assessment.

The LCA results revealed that, for all scenarios, GHG emissions from indirect land-use changes were the major contributor to the total GHG impact (up to ca. 40-60% of the total induced GHG emissions). All in all, the use of biomasses that are today used as animal feed (e.g. beet molasses) induced significant GHG emissions through LUC. These were quantified at between 1-3.5 t CO2/t dry residue depending upon the nutritional value. The recommendation is to avoid the use for bioenergy of those substrates having a significant nutritional value.
Conversely, the energy use of substrates having low nutritional value (e.g. straw) may provide considerable GHG savings.

**Impact Assessment of Abiotic Resources in LCA: Quantitative Comparison of Selected Characterization Models**

Resources have received significant attention in recent years resulting in development of a wide range of resource depletion indicators within life cycle assessment (LCA). Understanding the differences in assessment principles used to derive these indicators and the effects on the impact assessment results is critical for indicator selection and interpretation of the results. Eleven resource depletion methods were evaluated quantitatively with respect to resource coverage, characterization factors (CF), impact contributions from individual resources, and total impact scores. We included 2247 individual market inventory data sets covering a wide range of societal activities (ecoinvent database v3.0). Log-linear regression analysis was carried out for all pairwise combinations of the 11 methods for identification of correlations in CFs (resources) and total impacts (inventory data sets) between methods. Significant differences in resource coverage were observed (9–73 resources) revealing a trade-off between resource coverage and model complexity. High correlation in CFs between methods did not necessarily manifest in high correlation in total impacts. This indicates that also resource coverage may be critical for impact assessment results. Although no consistent correlations between methods applying similar assessment models could be observed, all methods showed relatively high correlation regarding the assessment of energy resources. Finally, we classify the existing methods into three groups, according to method focus and modeling approach, to aid method selection within LCA.
Influences of ammonia contamination on leaching from air-pollution-control residues

Application of selective non-catalytic reduction systems at municipal solid waste incinerators (MSWIs) often involves over-stoichiometric injection of ammonia into flue gases. Un-reacted ammonia may be deposited on fly ash particles and can ultimately influence the leaching behaviour of air-pollution-control (APC) residues. Batch tests were conducted to investigate the impacts of ammonia levels on leaching of a range of metals (sodium, potassium, calcium, aluminium, chromium, iron, lead, cadmium, copper, nickel and zinc), as well as chloride and dissolved organic carbon (DOC). Specific conductivity was also identified to reflect the soluble components. The results showed that with ammonia concentrations rising from a background level of 4 to 26,400 mg l\(^{-1}\), the specific conductivity increased by 2-7 times as pH varied from alkaline to acidic values. DOC release was also significantly enhanced with high ammonia levels of 1400 mg l\(^{-1}\) or higher at pH > 9; however at these high ammonia concentrations, the role of DOC in cadmium, copper, nickel and zinc leaching was negligible. Based on the experimental data, chloride, sodium and potassium were leached at high concentrations regardless of pH and ammonia concentrations. For aluminium, chromium, iron and lead, ammonia had little impact on their leaching behaviour. With respect to cadmium, copper, nickel and zinc, high ammonia concentrations significantly increased leaching in the pH range of 8-12 due to the formation of metal-ammonia complexes, which was also proved in

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\[ \text{Publication: Research - peer-review › Journal article – Annual report year: 2014} \]
the speciation calculations. However, the overall results suggest that typical levels of ammonia injection in MSWIs are not likely to affect metal leaching from APC residues.

**General information**

**State:** Published

**Organisations:** Department of Environmental Engineering, Residual Resource Engineering, Tongji University

**Authors:** Guan, Z. (Ekstern), Chen, D. (Ekstern), Astrup, T. F. (Intern)

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- Web of Science (2006): Indexed yes
- Scopus rating (2005): SJR 0.449 SNIP 0.729
- Web of Science (2005): Indexed yes
- Scopus rating (2004): SJR 0.48 SNIP 0.787
Integrated Resource Management and Recovery

A significant part of the environmental consequences related to activities in society is associated with our consumption of resources. Modern products become more and more complex and rely on more complex sets of resources than before. This emphasizes the need for continuous access to high quality resources, i.e. security of supply, but also the need for efficient recovery of the same resources after the use-phase of the products. While this recovery may appear simple, considerable challenges exist. Management and recovery of resources in waste materials, or in general residual streams in society, depends on the quality of these resources and technological abilities to extract resources from mixed materials, e.g. mobile phones, solar cells, or mixed domestic waste. The “effort” invested in recovery of secondary resources should not be more than the "benefit" associated with the secondary resources. Over the recent decades, DTU Environment has worked extensively both with resource recovery technologies and life cycle assessment (LCA) models (www.EASETECH.dk) dedicated to evaluating resource management and recovery systems. Advanced sustainability assessments of resource recovery and utilization have been carried out e.g. in relation to household and industrial waste systems, biomass residues from agriculture and forestry, energy producing technologies as well as entire energy systems. The presentation provides an introduction to key challenges in relation to sustainability assessment of resource recovery as well as examples of recent research.

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Authors: Astrup, T. F. (Intern)
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LCA of electricity systems with high wind power penetration

Electricity systems are shifting from being based on fossil fuels towards renewable sources to enhance energy security and mitigate climate change. However, by introducing high shares of variable renewables - such as wind and solar - dispatchable power plants are required to vary their output to fulfill the remaining electrical demand, potentially increasing their environmental impacts [1,2]. In this study the environmental impacts of potential short-term future electricity systems in Ireland with high shares of wind power (35-50% of total installed capacity) were evaluated using life cycle assessment (LCA). Cycling emissions from dispatchable generators due to part-load operation and start-ups [3] were included for the first time in LCA.

Part-load operations significantly affected the average power plant efficiency, with all units seeing an average yearly efficiency 1-11% lower than optimal. Given that similar penalties were seen for power plant with the same role in the system (i.e. load following, mid merit, and base load), it is suggested that only power plants within the same category should be compared. Since power production technologies are typically modeled in LCA assuming steady-state operation at full load [4], the efficiency reduction would result in a large underestimation of emissions, especially for load following power plants.

With regards to the entire electricity system, cycling emissions accounted for less than 10% of lifecycle CO2, NOx and...
SO2 emissions in the scenarios considered: while not outweighing the benefits from increasing wind energy, cycling emissions are not negligible and should thus be systematically included (i.e., by using emission factors per unit of fuel input rather than per unit of power generated). Cycling emissions increased with the installed wind capacity, and decreased with the addition of storage. However, a consequence of adding storage was the increased use of base load coal power plants, ultimately leading to an increase in total emissions from the Irish electricity system. Consequently, the present study indicates that while investing in new storage capacity reduces system operating costs at high wind penetrations and limits cycling, the emissions reductions may be negated when coupled with base load coal.

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Organisations: Department of Environmental Engineering, Residual Resource Engineering, University College Dublin
Authors: Turconi, R. (Intern), O’Dwyer, C. O. (Ekstern), Flynn, D. (Ekstern), Astrup, T. F. (Intern)
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LCA of metal recovery from waste incineration bottom ash

General information
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Organisations: Department of Environmental Engineering, Residual Resource Engineering, Afatek
Authors: Allegrini, E. (Intern), Boldrin, A. (Intern), Kallesøe, J. (Ekstern), Astrup, T. F. (Intern)
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Leaching from biomass combustion ash

The use of biomass combustion ashes for fertilizing and liming purposes has been widely addressed in scientific literature. Nevertheless, the content of potentially toxic compounds raises concerns for a possible contamination of the soil. During this study, five ash samples generated at four different Danish incineration plants were collected and analyzed for their chemical composition and leaching behavior. Batch leaching tests at Liquid-to-Solid ratio 2 l/kg were carried out. Although high total contents of nutrients (i.e., K and P) were detected, only K showed to be easily dissolvable in water. The content of the selected heavy metals (i.e., Cr, Ni, Pb, and Cd) complied with the Danish Statutory Order on the use of bio-ash for agricultural purposes; however, critical releases of Cr were detected in the leachate extracts, especially in the fly ash. High alkaline pHs were measured in all eluates.

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Organisations: Department of Environmental Engineering, Residual Resource Engineering
Authors: Maresca, A. (Intern), Astrup, T. F. (Intern)
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Life Cycle Assessment of Electricity Systems

Electricity systems represent a major source of global pollutants. Whilst currently relying heavily on fossil fuels, electricity systems are progressively shifting towards renewable sources to mitigate climate change and enhance energy security. The main goal of this PhD project was to develop a systematic framework for the life cycle assessment (LCA) of electricity systems, which aimed at providing:

- Scientifically sound recommendations for decision-making processes, leading to more sustainable energy systems;
- Accurate and transparent LCA data for electricity supply, thereby increasing the robustness of LCA results for a multitude of products producing or consuming electricity throughout the lifecycle. The main findings in relation to: (i) electricity generation, (ii) power transmission and distribution and (iii) low-carbon electricity systems are reported in the following paragraphs.

A great deal of variability was found in the literature regarding LCA of electricity generation in terms of modelling methodology and power plant characteristics, both of which strongly affected the results of the LCA. Major issues for individual electricity generation technologies were identified and discussed. For example, electricity used during the manufacturing of the power plant, reference year and data collection approach (process-chain or input-output analysis) strongly affected the impacts of hydro, wind and solar power. This information needs to be documented, to ensure comparability between studies. Based on information gathered from the literature, typical emission factor ranges for each technology were provided. Results showed that emission factors per unit of energy input should be used for thermal conversion processes (as opposed to emission factors per unit of electricity produced), as the efficiency may vary depending on the operation of the plant within the power system. The choice of LCA approach used to solve multi-functionality for combined heat and power plants strongly influenced how the environmental impact of electricity produced at such plants was estimated. When it is not possible to expand the assessment’s system boundaries, exergy allocation should be used, as it is more consistent with the general principles of LCA. Lastly, land use changes (LUC) were found to increase greenhouse gas (GHG) emissions from energy crops to levels comparable to those of fossil fuels; consequently, it might be preferable to use energy crops for purposes other than producing electricity. Transmission and distribution of electricity are often not included in LCA of power systems. An LCA of the Danish transmission and distribution systems was performed, showing that the distribution network makes a significant contribution to the impacts of electricity delivered to customers. In the future, because of the implementation of smart grids and low-carbon electricity systems, these results might change radically. It is thus recommended to include transmission and distribution in future LCA studies, while developing data on smart grids should be a priority for future research.

The environmental impacts of low-carbon electricity systems were assessed by combining LCA with power system modelling. Possible scenarios for the island of Ireland in 2025 and Denmark in 2030, with high amounts of wind power, were developed using Unit Commitment and Economic Dispatch, including wind and demand forecasts. This approach allows for assessing the influence of the fluctuating nature of wind on other electricity sources – this was not found in the LCA literature on renewable-based electricity systems, as it is based mostly on aggregated modelling. The results showed that an increase in wind power causes greater emissions from other power plants in the electricity system (which need to ‘cycle’ – adjust their production – more frequently); however, considering the entire electricity system, increasing wind power penetration reduces the overall emissions. Electricity storage limits the amount of cycling but environmental benefits are related to the base load fleet in the system, i.e. having coal as base load causes an increase in emissions. Electricity imports and exports are likely to increase with the expansion of wind power: transparent LCA modelling and adequate data for neighboring countries’ power systems are hence important for reliable and usable results.

Focusing on the Danish electricity system, it was found that using energy crops for electricity production did not lead to GHG reductions, owing to LUC-related impacts. Conversely, it will be possible to reduce GHG significantly, by increasing power production from residual biomass and wind and decreasing electricity production based on fossil fuels.

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Organisations: Residual Resource Engineering, Department of Environmental Engineering
Authors: Turconi, R. (Intern), Astrup, T. F. (Intern)
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Life cycle assessment of the Danish electricity distribution network

Purpose
This article provides life cycle inventory data for electricity distribution networks and a life cycle assessment (LCA) of the Danish transmission and distribution networks. The aim of the study was to evaluate the potential importance of environmental impacts associated with distribution, in current and future electricity systems.

Methods
The functional unit was delivery of 1 kWh of electricity in Denmark. The focus of the assessment was distribution of electricity, and the related impacts were compared to the generation and transmission of electricity, in order to evaluate the importance of electricity distribution in Denmark. The 2010 Danish electricity distribution network was modeled, including power lines (50, 10, 0.4 kV), transformers (50/10 and 10/0.4 kV), and relevant auxiliary infrastructure (e.g., cable ditches, poles, and substations). Two types of 50 kV power lines (underground and overhead) and 0.4 kV (copper and aluminum) were modeled.

Results and discussion
Electricity transmission and distribution provided nonnegligible impacts, related mainly to power losses. Impacts from electricity distribution were larger than those from transmission because of higher losses and higher complexity and material consumption. Infrastructure provided important contributions to metal depletion and freshwater eutrophication (copper and aluminum for manufacturing of the cables and associated recycling being the most important). Underground 50-kV lines had larger impacts than overhead lines, and 0.4-kV aluminum lines had lower impacts than comparable copper lines.

Conclusions
A new specific dataset for infrastructure in the distribution network was provided and used to evaluate the role of electricity distribution in Denmark. Both transmission and distribution provided nonnegligible impacts. It was argued that the impacts from electricity distribution are likely to increase in the future, owing to more renewables and decentralized electricity generation, and that impacts from infrastructure may become significant compared to electricity generation itself. It was recommended that impacts from electricity distribution and related infrastructure are included in relevant LCA studies. The data provided here make this possible.

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Authors: Turconi, R. (Intern), Simonsen, C. G. (Ekstern), Byriel, I. P. (Ekstern), Astrup, T. F. (Intern)
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Scopus rating (2013): SJR 1.666 SNIP 1.979 CiteScore 3.35
ISI indexed (2013): ISI indexed yes
To ensure sustainability of solid waste management, there is a need for cost assessment models which are consistent with environmental and social assessments. However, there is a current lack of standardized terminology and methodology to evaluate economic performances and this complicates the performance of new studies as well as the understanding of similarities and singularities between the different types of cost assessment applied in literature. This investigation develops a systematic framework for performing various types of cost assessments with different cost perspectives. Most of the cost assessments in literature can be classified into: 1) Conventional Life Cycle Costing (LCC), 2) Environmental LCC and 3) Societal LCC. While the first two LCCs are financial assessments, the third one is asocio-economic assessment. The three LCCs included marketed goods, but they handle differently nonmarketed goods (i.e. externalities). While non-marketed goods are beyond the scope of the Conventional LCC, the Environmental LCC included environmental externalities in a parallel LCA and the Societal LCC internalizes all the externalities into monetary terms. Different cost perspectives can be applied in each LCC, e.g. waste generator, waste operator and public finances and the perspective often defines the system boundaries of the study, e.g. waste operators often focus on her/his own cost, i.e. technology based, whereas waste generators and public finances often focus on the entire waste system, i.e. system based. Figure 1 illustrates the proposed modeling framework that distinguishes between: a) budget cost, b) externality costs and 3) transfers and defines unit costs of each technology (per ton of input waste). Unit costs are afterwards combined with a mass balance to calculate the technology cost. Later, the costs of individual technologies can be...
combined to calculate the system or scenario costs. In the technology definition, each cost item is defined with a unit cost per item, which is calculated with two types of parameters: 1) economic (e.g. unit prices and depreciation periods) and 2) technical (e.g. usage rate and consumptions of commodities). The investigation provides an overview of which cost items should be included in each pair of LCC perspective and common calculations to estimate technical parameters for main waste technologies. The applicability of the cost assessment model is illustrated with a fictive case study focusing on source segregation of organic waste in Denmark.

**Long-term sampling of CO₂ from waste-to-energy plants: ¹⁴C determination methodology, data variation and uncertainty**

A dedicated sampling and measurement method was developed for long-term measurements of biogenic and fossil-derived CO₂ from thermal waste-to-energy processes. Based on long-term sampling of CO₂ and ¹⁴C determination, plant-specific emission factors can be determined more accurately, and the annual emission of fossil CO₂ from waste-to-energy plants can be monitored according to carbon trading schemes and renewable energy certificates. Weekly and monthly measurements were performed at five Danish waste incinerators. Significant variations between fractions of biogenic CO₂ emitted were observed, not only over time, but also between plants. From the results of monthly samples at one plant, the annual mean fraction of biogenic CO₂ was found to be 69% of the total annual CO₂ emissions. From weekly samples, taken every 3 months at the five plants, significant seasonal variations in biogenic CO₂ emissions were observed (between 56% and 71% biogenic CO₂). These variations confirmed that biomass fractions in the waste can vary considerably, not only from day to day but also from month to month. An uncertainty budget for the measurement method itself showed that the expanded uncertainty of the method was ± 4.0 pmC (95% confidence interval) at 62 pmC. The long-term sampling method was found to be useful for waste incinerators for determination of annual fossil and biogenic CO₂ emissions with relatively low uncertainty.
Mapping ENM from consumer products in solid waste flows in Denmark

To address the challenges regarding management of waste from ENM-enabled consumer products, we mapped the flow of these products available online in Denmark and the EU. To do this, we used the Nanodatabase (www.nanodb.dk). A representative sample of products from the database was analyzed, and placed into suitable waste material fractions. Subsequently, the distribution of ENM in the individual waste fractions, by number of products, was found. Overall, the results showed that nanosilver was present in seven of the eight identified waste material fractions, whereas other ENMs (e.g. CNTs and silicon) were only present in one or two fractions. Furthermore, the waste material fraction "dirty plastic" was the most diversified, containing five different ENMs. To our knowledge this type of analysis has not previously been performed, and the results hold promise for gaining a better understanding of managing nanowaste.

General information
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Material recycling: Presence of chemicals and their influence on the circular economy concept

Linear production concept (extract-convert-use-discard) applied from the times of industrial revolution has created a lot of skepticism in the world of limited resources that we live in. As basis to tackle the issue of resource scarcity, circular economy concept has been proposed. The backbone of the concept is the pursuit of sustainability through re-use and recycling of products and materials once they have served their purpose. Once such materials (e.g. paper, plastics) are recycled, chemicals that they contain are reintroduced, spread or even accumulate in the newly manufactured products (Figure 1). As an example, paper and board products alone contain up to 10,000 different chemicals. While only small fraction is being regulated, most of them have not been identified in relevant materials or even lack hazard assessment. The overall goal of the project is to provide a basis for systematically addressing the recyclability of waste materials with respect to the presence of substances. The outcomes of the work will provide crucial basis for future waste characterization activities, environmental and risk assessments of material recycling, as well as provide authorities, scientific community and society with a necessary basis for evaluating potential future limitations to recycling and address means of mitigating accumulation and spreading of chemicals in various materials.

Optimal acid digestion for multi-element analysis of different waste matrices

Informed planning and assessment of waste management systems requires accurate data on physical and chemical characteristics of the waste materials. For many parameters analytical standard methods already exist; however, most of these methods do not account for the specific properties of the distinct waste materials and recyclables. The purpose of this study is to evaluate the performance of different standardized microwave assisted acid digestion methods on waste samples and subsequent multi-element analysis. Six acid digestion methods were applied on a Paper & Cardboard and Composite waste matrix preparing four replicates per method. The digestates were subsequently analyzed for 20 elements using ICP-MS and ICP-OES. The measurement results were statistically evaluated using ANOVA and a ranking procedure. The ANOVA shows a significant difference between the digestion methods for 12 elements in the Paper & Cardboard matrix and for 10 elements in the Composite matrix. The ranking procedure points to different methods to be the most optimal digestion methods in the tested waste matrices. The recovery rates can vary by more than 90% among the tested digestion methods depending on the individual element. The selection of an appropriate method is therefore crucial.
Phosphorus in Denmark: national and regional anthropogenic flows

General information
State: Published
Organisations: Department of Environmental Engineering, Residual Resource Engineering
Authors: Klinglmair, M. (Intern), Scheutz, C. (Intern), Astrup, T. F. (Intern)
Number of pages: 1
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Main Research Area: Technical/natural sciences
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Publication: Research - peer-review › Poster – Annual report year: 2014

Polychlorinated biphenyls (PCBs) in waste paper from danish household waste

General information
State: Published
Organisations: Department of Environmental Engineering, Residual Resource Engineering, Environmental Chemistry
Authors: Pivnenko, K. (Intern), Eriksson, E. (Intern), Astrup, T. F. (Intern)
Number of pages: 1
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MSW, Household solid waste, Waste paper, Paper recycling, POPs
Electronic versions:
Pivnenko_v1.0.pdf
Source: PublicationPreSubmission
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Quality and generation rate of solid residues in the boiler of a waste-to-energy plant

The Danish waste management system relies significantly on waste-to-energy (WtE) plants. The ash produced at the energy recovery section (boiler ash) is classified as hazardous waste, and is commonly mixed with fly ash and air pollution control residues before disposal. In this study, a detailed characterization of boiler ash from a Danish grate-based mass burn type WtE was performed, to evaluate the potential for improving ash management. Samples were collected at 10 different points along the boiler's convective part, and analysed for grain size distribution, content of inorganic elements, polychlorinated dibenzo-p-dioxins and dibenzofurans (PCDD and PCDF), and leaching of metals. For all samples, PCDD and PCDF levels were below regulatory limits, while high pH values and leaching of e.g. Cl were critical. No significant differences were found between boiler ash from individual sections of the boiler, in terms of total content and leaching, indicating that separate management of individual ash fractions may not provide significant benefits. © 2014 Elsevier B.V.

General information
State: Published
Organisations: Department of Environmental Engineering, Residual Resource Engineering, Umeå University, Babcock & Wilcox Velund A/S
Authors: Allegrini, E. (Intern), Boldrin, A. (Intern), Jansson, S. (Ekstern), Lundtorp, K. (Ekstern), Astrup, T. F. (Intern)
Pages: 127-136
Publication date: 2014
Main Research Area: Technical/natural sciences

Publication information
Journal: Journal of Hazardous Materials
Quantification of the resource recovery potential of municipal solid waste incineration bottom ashes.

Municipal solid waste incineration (MSWI) plays an important role in many European waste management systems. However, increasing focus on resource criticality has raised concern regarding the possible loss of critical resources through MSWI. The primary form of solid output from waste incinerators is bottom ashes (BAs), which also have important resource potential. Based on a full-scale Danish recovery facility, detailed material and substance flow analyses (MFA and SFA) were carried out, in order to characterise the resource recovery potential of Danish BA: (i) based on historical and experimental data, all individual flows (representing different grain size fractions) within the recovery facility were quantified, (ii) the resource potential of ferrous (Fe) and non-ferrous (NFe) metals as well as rare earth elements (REE) was determined, (iii) recovery efficiencies were quantified for scrap metal and (iv) resource potential variability and recovery efficiencies were quantified based on a range of ashes from different incinerators. Recovery efficiencies for Fe and NFe reached 85% and 61%, respectively, with the resource potential of metals in BA before recovery being 7.2%ww for Fe and 2.2%ww for NFe. Considerable non-recovered resource potential was found in fine fraction (below 2mm), where approximately 12% of the total NFe potential in the BA were left. REEs were detected in the ashes, but the levels were two or three orders of magnitude lower than typical ore concentrations. The lack of REE enrichment in BAs indicated that the post-incineration recovery of these resources may not be a likely option with current technology. Based on these results, it is recommended to focus on limiting REE-containing products in waste for incineration and improving pre-incineration sorting initiatives for these elements.

General information
State: Published
Organisations: Department of Environmental Engineering, Residual Resource Engineering, Afatek
Authors: Allegrini, E. (Intern), Maresca, A. (Intern), Olsson, M. E. (Intern), Holtze, M. S. (Ekstern), Boldrin, A. (Intern), Astrup, T. F. (Intern)
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BFI (2017): BFI-level 2
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BFI (2016): BFI-level 2
Scopus rating (2016): CiteScore 4 SJR 1.354 SNIP 2.044
Web of Science (2016): Indexed yes
BFI (2015): BFI-level 2
Scopus rating (2015): SJR 1.739 SNIP 2.256 CiteScore 4.33
Web of Science (2015): Indexed yes
BFI (2014): BFI-level 2
Scopus rating (2014): SJR 1.777 SNIP 2.482 CiteScore 3.43
Web of Science (2014): Indexed yes
BFI (2013): BFI-level 1
Scopus rating (2013): SJR 1.822 SNIP 2.435 CiteScore 3.39
ISI indexed (2013): ISI indexed yes
Web of Science (2013): Indexed yes
BFI (2012): BFI-level 1
Scopus rating (2012): SJR 1.611 SNIP 2.184 CiteScore 2.91
ISI indexed (2012): ISI indexed yes
Web of Science (2012): Indexed yes  
BFI (2011): BFI-level 1  
Scopus rating (2011): SJR 1.698 SNIP 2.085 CiteScore 2.99  
ISI indexed (2011): ISI indexed yes  
Web of Science (2011): Indexed yes  
BFI (2010): BFI-level 1  
Scopus rating (2010): SJR 1.555 SNIP 1.78  
Web of Science (2010): Indexed yes  
BFI (2009): BFI-level 1  
Scopus rating (2009): SJR 1.502 SNIP 1.899  
Web of Science (2009): Indexed yes  
BFI (2008): BFI-level 2  
Scopus rating (2008): SJR 1.378 SNIP 2.13  
Web of Science (2008): Indexed yes  
Scopus rating (2007): SJR 1.035 SNIP 1.767  
Web of Science (2007): Indexed yes  
Scopus rating (2006): SJR 1.046 SNIP 1.749  
Web of Science (2006): Indexed yes  
Scopus rating (2005): SJR 1.059 SNIP 1.65  
Scopus rating (2004): SJR 1.289 SNIP 1.939  
Web of Science (2004): Indexed yes  
Scopus rating (2003): SJR 0.847 SNIP 1.269  
Web of Science (2003): Indexed yes  
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Scopus rating (2000): SJR 0.271 SNIP 0.451  
Scopus rating (1999): SJR 0.262 SNIP 0.479  
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MSWI, Bottom ashes, Non-ferrous metals, Recovery efficiency, REE, Critical elements  
DOIs:  
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Source: Findit  
Source-ID: 267952053  
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Resource recovery from waste incineration residues

General information
State: Published  
Organisations: Department of Environmental Engineering, Residual Resource Engineering  
Authors: Allegrini, E. (Intern), Astrup, T. F. (Intern), Boldrin, A. (Intern)  
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Publication: Research › Ph.D. thesis – Annual report year: 2014

Systematic Evaluation of Uncertainty in Material Flow Analysis
Material flow analysis (MFA) is a tool to investigate material flows and stocks in defined systems as a basis for resource management or environmental pollution control. Because of the diverse nature of sources and the varying quality and availability of data, MFA results are inherently uncertain. Uncertainty analyses have received increasing attention in recent
MFA studies, but systematic approaches for selection of appropriate uncertainty tools are missing. This article reviews existing literature related to handling of uncertainty in MFA studies and evaluates current practice of uncertainty analysis in MFA. Based on this, recommendations for consideration of uncertainty in MFA are provided. A five-step framework for uncertainty handling is outlined, reflecting aspects such as data quality and goal/scope of the MFA. We distinguish between descriptive (quantification of material turnover in a region) and exploratory MFA (identification of critical parameters and system behavior). Whereas mathematically simpler concepts focusing on data uncertainty characterization are appropriate for descriptive MFAs, statistical approaches enabling more-rigorous evaluation of uncertainty and model sensitivity are needed for exploratory MFAs. Irrespective of the level of sophistication, lack of information about MFA data poses a major challenge for meaningful uncertainty analysis. The step-wise framework suggested here provides a systematic way to consider available information and produce results as precise as the data warrant.

General information
State: Published
Organisations: Department of Environmental Engineering, Residual Resource Engineering, Vienna University of Technology
Authors: Laner, D. (Ekstern), Rechberger, H. (Ekstern), Astrup, T. F. (Intern)
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Web of Science (2016): Indexed yes
BFI (2015): BFI-level 1
Scopus rating (2015): SJR 1.44 SNIP 1.689 CiteScore 3.82
Web of Science (2015): Indexed yes
BFI (2014): BFI-level 1
Scopus rating (2014): SJR 1.628 SNIP 1.706 CiteScore 3.07
Web of Science (2014): Indexed yes
BFI (2013): BFI-level 2
Scopus rating (2013): SJR 1.171 SNIP 1.405 CiteScore 2.47
ISI indexed (2013): ISI indexed yes
Web of Science (2013): Indexed yes
BFI (2012): BFI-level 2
Scopus rating (2012): SJR 1.03 SNIP 1.529 CiteScore 2.24
ISI indexed (2012): ISI indexed yes
Web of Science (2012): Indexed yes
BFI (2011): BFI-level 2
Scopus rating (2011): SJR 1.031 SNIP 1.228 CiteScore 2.13
ISI indexed (2011): ISI indexed yes
BFI (2010): BFI-level 2
Scopus rating (2010): SJR 0.891 SNIP 1.329
Web of Science (2010): Indexed yes
BFI (2009): BFI-level 2
Scopus rating (2009): SJR 1.192 SNIP 1.411
BFI (2008): BFI-level 2
Scopus rating (2008): SJR 1.226 SNIP 1.624
Web of Science (2008): Indexed yes
Biogenic carbon in combustible waste: Waste composition, variability and measurement uncertainty

Obtaining accurate data for the contents of biogenic and fossil carbon in thermally-treated waste is essential for determination of the environmental profile of waste technologies. Relations between the variability of waste chemistry and the biogenic and fossil carbon emissions are not well described in the literature. This study addressed the variability of...
biogenic and fossil carbon in combustible waste received at a municipal solid waste incinerator. Two approaches were compared: (1) radiocarbon dating (14C analysis) of carbon dioxide sampled from the flue gas, and (2) mass and energy balance calculations using the balance method. The ability of the two approaches to accurately describe short-term day-to-day variations in carbon emissions, and to which extent these short-term variations could be explained by controlled changes in waste input composition, was evaluated. Finally, the measurement uncertainties related to the two approaches were determined. Two flue gas sampling campaigns at a full-scale waste incinerator were included: one during normal operation and one with controlled waste input. Estimation of carbon contents in the main waste types received was included. Both the 14C method and the balance method represented promising methods able to provide good quality data for the ratio between biogenic and fossil carbon in waste. The relative uncertainty in the individual experiments was 7–10% (95% confidence interval) for the 14C method and slightly lower for the balance method.

**General information**

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Organisations: Department of Environmental Engineering, Residual Resource Engineering, FORCE Technology, Vienna University of Technology


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Scopus rating (2016): CiteScore 1.76 SJR 0.655 SNIP 1.036

BFI (2015): BFI-level 1

Scopus rating (2015): SJR 0.617 SNIP 0.899 CiteScore 1.53

Web of Science (2015): Indexed yes

BFI (2014): BFI-level 1

Scopus rating (2014): SJR 0.741 SNIP 1.085 CiteScore 1.28

Web of Science (2014): Indexed yes

BFI (2013): BFI-level 1

Scopus rating (2013): SJR 0.588 SNIP 0.951 CiteScore 1.17

ISI indexed (2013): ISI indexed yes

Web of Science (2013): Indexed yes

BFI (2012): BFI-level 1

Scopus rating (2012): SJR 0.886 SNIP 1.046 CiteScore 1.4

ISI indexed (2012): ISI indexed yes

Web of Science (2012): Indexed yes

BFI (2011): BFI-level 1

Scopus rating (2011): SJR 1.027 SNIP 0.865 CiteScore 1.33

ISI indexed (2011): ISI indexed yes

Web of Science (2011): Indexed yes

BFI (2010): BFI-level 1

Scopus rating (2010): SJR 0.666 SNIP 0.975

Web of Science (2010): Indexed yes

BFI (2009): BFI-level 1

Scopus rating (2009): SJR 0.877 SNIP 1.257

Web of Science (2009): Indexed yes

BFI (2008): BFI-level 1

Scopus rating (2008): SJR 0.49 SNIP 0.933
The electricity sector is among the main sources of greenhouse gas (GHG) emissions; today, those are mainly due to combustion of fossil fuels, but with increasing renewable sources the importance of infrastructures both in electricity generation and in transmission and distribution (T&D) will likely grow. Several studies are available on renewable energy technologies, but only a few on transmission of electricity, and none on its distribution. This study provides life cycle inventory data for electricity distribution networks, and a life cycle GHG accounting of the Danish T&D networks. The purpose was to evaluate the potential importance of environmental impacts associated with T&D in current and future electricity systems. Including the emissions from electricity T&D is needed to provide a full carbon footprint of electricity systems, and is essential to properly assess the environmental consequences of potential changes in an electricity system. So far, the basis for such assessments has not been available.

The functional unit of this study was the delivery of one kWh of electricity in Denmark. The 2010 Danish electricity T&D networks were modeled, including power lines, transformers, and relevant auxiliary infrastructures.

Electricity T&D provided respectively 29 and 17 gCO2e/kWh, mainly related to power losses. Emissions from distribution were larger than those from transmission, because of higher losses and higher complexity and material consumption. Large differences were found between overhead and underground lines (i.e. for 50 kV lines, 3.2 and 17 kgCO2e/km respectively)

A new specific dataset for infrastructures in the distribution network was provided and used to evaluate the role of electricity distribution in Denmark. Both T&D provided non-negligible emissions. In the future, due to more renewables and decentralized electricity generation, emissions from T&D may become significant compared to electricity generation itself. Consequently, it is recommended that emission from electricity T&D are included in relevant GHG studies.
Challenges in LCA-based decision making involving heavy metals long-term emissions from landfills

General information
State: Published
Organisations: Department of Management Engineering, Quantitative Sustainability Assessment, Department of Environmental Engineering, Residual Resource Engineering
Authors: Bakas, I. (Intern), Astrup, T. F. (Intern), Hauschild, M. Z. (Intern), Rosenbaum, R. K. (Intern)
Number of pages: 2
Publication date: 2013

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Publisher: CISA Publisher
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Electronic versions:
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Source-ID: u::9631
Publication: Research - peer-review › Conference abstract in proceedings – Annual report year: 2013

Characterisation of plastic packaging waste for recycling: problems related to current approaches
Informed decisions regarding new recycling schemes require waste characterisation studies which provide in addition to data on waste amounts and the share of recyclable fractions, accurate data on physico-chemical characteristics of the waste materials considering the material specific input criteria of recycling processes. A lack of information in current waste characterisation practise on polymer resin composition, black coloured material content and the influence of surface adherent material on physico-chemical characteristics of plastic packaging waste were identified. These shortcomings were addressed by a resin type-based sorting analysis and a washing test for plastic packaging material from Danish household waste. Preliminary results show that, for a quarter of the hand sorted material, no resin type could be identified and that Polypropylene and Polyethylene terephthalate were the dominating resin types in plastic packaging. The suggested washing procedure caused a decrease of 70% of the ash content of the plastic material. The analysed metals and nutrients were reduced by up to 24%

General information
State: Published
Organisations: Department of Environmental Engineering, Residual Resource Engineering
Authors: Götze, R. (Intern), Astrup, T. F. (Intern)
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Publisher: CISA Publisher
Main Research Area: Technical/natural sciences
Source: dtu
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Characterization of household food waste in Denmark
This paper presents a methodology and the results of compositional analysis of food waste from Danish families living in single-family houses. Residual household waste was sampled and manually sorted from 211 single-family houses in the suburb of Copenhagen. The main fractions contributing to the household food waste were avoidable vegetable food waste and non-avoidable vegetable food waste. Statistical analysis found a positive linear relationship between household size and the amount of the household food waste.

General information
State: Published
Organisations: Department of Environmental Engineering, Residual Resource Engineering, Econet A/S
Authors: Edjabou, V. M. E. (Intern), Petersen, C. (Ekstern), Scheutz, C. (Intern), Astrup, T. F. (Intern)
EASETECH - A Dedicated Waste Management LCA-Model

General information
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Organisations: Department of Environmental Engineering, Residual Resource Engineering
Authors: Christensen, T. H. (Intern), Damgaard, A. (Intern), Astrup, T. F. (Intern), Butera, S. (Intern)
Number of pages: 1
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Publisher: CISA Publisher
Main Research Area: Technical/natural sciences
EASETECH, LCA, Uncertainty, Energy
Source: dtu
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EASETECH Energy: Life Cycle Assessment of current and future Danish power systems
A new life cycle assessment (LCA) model software has been developed by DTU Environment, to facilitate detailed LCA of energy technologies. The model, EASETECH Energy, is dedicated to the specific technologies needed to assess energy production and energy systems and provides an unprecedented flexibility with respect to LCA modeling of these technologies. To illustrate the functionality of the model, preliminary results from a LCA of the Danish power system in 2010 as well as two future scenarios for 2030 are presented. In addition to providing a general overview of the environmental profile of a renewable based power system, specific focus is placed on the typical challenges encountered when performing an LCA of a power system. Further, the key characteristics of EASETECH Energy that can expedite the set-up of multiple scenarios and enhance transparency in the modelling are explained.

General information
State: Published
Organisations: Department of Environmental Engineering, Residual Resource Engineering
Authors: Turconi, R. (Intern), Damgaard, A. (Intern), Bisinella, V. (Intern), Astrup, T. F. (Intern)
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Life cycle assessment, LCA, Energy system, Environmental impacts, EASETECH, Bioenergy, Biomass to energy
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Energy and environmental analysis of a rapeseed biorefinery conversion process
The need for biofuels is steadily increasing as a result of political strategies and the need for energy security. Biorefineries have the potential to improve the sustainability of biofuels through further recovery of valuable bioproducts and bioenergy. A life cycle assessment (LCA)-based environmental assessment of a Danish biorefinery system was carried out to thoroughly analyze and optimize the concept and address future research. The LCA study was based on case-specific mass and energy balances and inventory data, and was conducted using consequential LCA approach to take into account market mechanisms determining the fate of products, lost opportunities and marginal productions. The results show that introduction of enzymatic transesterification and improved oil extraction procedure result in environmental benefits compared to a traditional process. Utilization of rapeseed straw seems to have positive effects on the greenhouse gases (GHG) footprint of the biorefinery system, with improvements in the range of 9 % to 29 %, depending on the considered alternative. The mass and energy balances showed the potential for improvement of straw treatment processes (hydrothermal pre-treatment and dark fermentation) as well as minor issues related to enzymes utilization in different bio-processes.
Environmental assessment of energy production from waste and biomass

Optimal utilization of biomass and waste for energy purposes offers great potentials for reducing fossil fuel dependency and resource consumption. The common understanding is that bioenergy decreases greenhouse gas (GHG) emissions as the carbon released during energy conversion has previously been captured during growth of the plants. This, however, neglects that using the land for energy crops implies that the same land cannot be used for other purposes, including food cropland, forestry, grassland, etc. This may induce cascading effects converting natural biomes into arable land with associated impacts. Waste, such as municipal solid waste, does not involve land use change impacts. However, existing and emerging waste treatment technologies offer different environmental benefits and drawbacks which should be evaluated in order to recommend appropriate technologies in selected scenarios. To evaluate the environmental and energy performance of bioenergy and wasteto-energy systems life cycle assessment was used in this thesis. This was supported by other tools such as material, substance, energy flow analysis and energy system analysis. The primary objective of this research was to provide a consistent framework for the environmental assessment of innovative bioenergy and waste-to-energy systems including the integration of LCA with other tools (mentioned earlier). The focus was on the following aspects:

- Evaluation of potential future energy scenarios for Denmark. This was done by integrating the results of energy system analysis into life cycle assessment scenarios.
- Identification of the criticalities of bioenergy systems, particularly in relation to land use changes.
- Identification of potentials and criticalities associated with innovative waste refinery technologies. This was done by assessing a specific pilot-plant operated in Copenhagen, Denmark. The waste refining treatment was compared with a number of different state-of-the-art technologies such as incineration, mechanical-biological treatment and landfilling in bioreactor.

The results highlighted that production of liquid and solid biofuels from energy crops should be limited when inducing indirect land use changes (iLUC). Solid biofuels for use in combined heat and power plants may perform better than liquid biofuels due to higher energy conversion efficiencies. The iLUC impacts stood out as the most important contributor to the induced GHG emissions within bioenergy systems. Although quantification of these impacts is associated with high uncertainty, an increasing number of studies are documenting the significance of the iLUC impacts in the bioenergy life cycle. With respect to municipal solid waste, state of the art incineration, MBT and waste refining (with associated energy and material recovery processes) may all provide important and comparable GHG emission savings. The waste
composition (e.g. amount of organic and paper) and properties (e.g. LHV, water content) play a crucial role in affecting the final ranking. When assessing the environmental performance of the waste refinery, a detailed knowledge of the waste composition is recommendable as this determines the energy outputs and thereby the assessment results. The benefits offered by the waste refinery compared with incinerators and MBT plants are primarily related to the optimized electricity and phosphorous recovery. However, recovery of nutrients and phosphorous might come at the expenses of increased N-eutrophication and emissions of hazardous substances to soil. The first could be significantly mitigated by post-treating the digestate left from bioliquid digestion (e.g. composting). Compared with waste refining treatment, efficient source-segregation of the organic waste with subsequent biological processing may decrease digestate/compost contamination and recover phosphorous similarly to the waste refinery process. However, recent studies highlighted how this strategy often fails leading to high mass/energy/nutrients losses as well as to contamination of the segregated organic waste with unwanted impurities. All in all, more insight should be gained into the magnitude of iLUC impacts associated with energy crops. Their quantification is the key factor determining a beneficial or detrimental GHG performance of bioenergy systems based on energy crops. If energy crops are introduced, combined heat and power production should be prioritized based on the results of this research. Production of liquid biofuels for transport should be limited as the overall energy conversion efficiency is significantly lower thereby leading to decreased GHG performances. On this basis, recovery of energy, materials and resources from waste such as residual agricultural/forestry biomass and municipal/commercial/industrial waste should be seen as the way ahead. Highly-efficient combustion and incineration offer robust energy and environmental performances. Innovative waste refineries may achieve similar performances from a GHG perspective and, in addition, may recover nutrients. In the perspective of future energy systems with increased shares of fluctuating energy sources (e.g. wind energy) the flexibility of the energy conversion process should also be considered in the environmental assessment. The storability of the produced energy carrier along with the regulation ability and the capacity of switching among outputs may offer substantial benefits to the surrounding energy system. In this perspective, waste refineries producing storable biogas and solid fuel may offer increased flexibility compared with base load incinerators.

## General information

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Publication: Research › Ph.D. thesis – Annual report year: 2013

## Exergy analysis of aluminum recovery from municipal solid waste incineration

Two main challenges, associated with the recovery of aluminum from state-of-the-art municipal solid waste (MSW) incineration plants, are yield as well as quality losses of metallic aluminum due to particle surface oxidation and presence of impurities. Yet, in the framework of life cycle assessment (LCA) a direct measure for expressing the quality of primary and secondary resources is missing. In view of a possible solution, exergy has been proposed as a concept to evaluate the quality of resources. In this paper, LCA and exergy analyses for two waste treatment approaches are conducted in parallel to each other, with a goal to evaluate the added value of exergy for LCA studies in the resource recovery context. The functional unit is the treatment of 1 ton MSW. Two alternative approaches for recovering aluminum from MSW directed to a waste-to-energy plant are considered. A) MSW is treated in a two-step system consisting of a waste-to-energy process and a consequent bottom ash treatment. B) An aluminum-pre-sorting step takes place prior to the thermal treatment. In case of B, an additional exergy is spent on pre-sorting, but, in return, a metal of higher quality is obtained. The discussion of exergy analysis in the LCA framework represents an important contribution to address resource quality in environmental assessment of thermal waste treatment.

## General information

State: Published
Organisations: Department of Environmental Engineering, Vienna University of Technology
Authors: Vyzinkarova, D. (Intern), Allegrini, E. (Intern), Laner, D. (Ekstern), Astrup, T. F. (Intern)
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Main Research Area: Technical/natural sciences
Exergy losses of resource recovery from a waste-to-energy plant

Metal resources recovered from waste incineration bottom ash (BA) are of lower quality as compared to primary resources, but to date no framework for expressing the quality losses exists. Exergy is a concept that may have the potential to evaluate the resource quality in waste management. In this study, focusing on recovery from waste-to-energy plants with basic and advanced BA treatment, the goal is to give an indication about quality of selected recovered resources (Fe, Al, and Cu) by means of exergy analysis. Metal flows are modeled through both incineration scenarios, and then chemical exergy values are assigned to all flows, allowing for quantifying various types of exergy losses. The exergy losses determined here are those caused by (1) oxidative changes in the thermal process (irreversible exergy destruction), (2) material losses (low recovery efficiencies), and (3) mixing of metals. The results indicate that exergy losses due to mixing are insignificant as compared to chemical exergies of metals in all flows. Total exergy losses for Fe, Al, and Cu recovery in the two WtE systems range from 38% to 90%.

Influence of ammonia on leaching behaviors of incineration fly ash and its geochemical modeling

Incineration fly ash could be contaminated with NH3 that was slipped from the ammonia-based selective non-catalytic reduction (SNCR) process and from evaporation of municipal solid wastes' leachate involved in the wastes. This research was conducted to investigate the impacts of ammonia on leaching of dissolved organic carbon (DOC) and metals from incineration fly ash in the pH range of 3.66-12.44 with an active ammonia spike. A geochemical modeling software Visual MINTEQ was adopted to calculate the chemical speciation of metals under the leaching conditions to reveal the mechanism behind the impacts. It was proved that at pH>9, the leaching of DOC increased significantly in the presence of high concentrations of ammonia (≥1357 mg·L-1), but there was little effect when the ammonia level in eluates was not higher than 537 mg·L-1. At pH12, for Cd, Cu, Ni and Zn, their leaching species were predominantly in the form of hydroxide complexes. Under the ammonia concentration of 3253 mg·L-1, the Visual MINTEQ modeling results were compared with the experimental data, and it was proved that the leaching of Al, Pb and Zn was mainly controlled by precipitation/dissolution modeling, while Cd, Cu and Ni were controlled by precipitation/dissolution and surface complexation/precipitation processes; Visual MINTEQ modeling could well describe the leaching behaviors of Al, Cu, Pb and Zn from incineration fly ash.
Integrated resource management and recovery (IRMAR): a new danish initiative

DTU Environment has launched the IRMAR initiative in collaboration with internationally leading partners to improve the scientific basis for integrated assessment of both the quality of resources in waste and the environmental aspects of resource recovery. Today, the basis for prioritization between individual resources is not available: which resources should be recovered from waste and which waste streams should be prioritised for this recovery? Which final resource quality should be achieved? The answers to these questions are less simple than they may appear. With IRMAR, we offer a critical analysis of existing resource assessment approaches (e.g. exergy, statistical entropy, resource indicators, criticality, etc.). On this basis, we develop a consistent framework for integrated assessment of resource recovery and implement this in our EASETECH waste LCA model. The entire concept is demonstrated based on a range of full-scale case studies in collaboration with the waste industry.

LCA af genbrug af mursten

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State: Published
Organisations: Department of Environmental Engineering, Residual Resource Engineering
Authors: Møller, J. (Intern), Damgaard, A. (Intern), Astrup, T. F. (Intern)
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Life cycle assessment (LCA) of electricity generation technologies: Overview, comparability and limitations

Electricity generation is a key contributor to global emissions of greenhouse gases (GHG), NOx and SO2 and their related environmental impact. A critical review of 167 case studies involving the life cycle assessment (LCA) of electricity generation based on hard coal, lignite, natural gas, oil, nuclear, biomass, hydroelectric, solar photovoltaic (PV) and wind was carried out to identify ranges of emission data for GHG, NOx and SO2 related to individual technologies. It was shown that GHG emissions could not be used as a single indicator to represent the environmental performance of a system or technology. Emission data were evaluated with respect to three life cycle phases (fuel provision, plant operation, and infrastructure). Direct emissions from plant operation represented the majority of the life cycle emissions for fossil fuel technologies, whereas fuel provision represented the largest contribution for biomass technologies (71% for GHG, 54% for NOx and 61% for SO2) and nuclear power (60% for GHG, 82% for NOx and 92% for SO2); infrastructures provided the highest impact for renewables. These data indicated that all three phases should be included for completeness and to avoid problem shifting. The most critical methodological aspects in relation to LCA studies were identified as follows: definition of the functional unit, the LCA method employed (e.g., IOA, PCA and hybrid), the emission allocation principle and/or system boundary expansion. The most important technological aspects were identified as follows: the energy recovery efficiency and the flue gas cleaning system for fossil fuel technologies; the electricity mix used during both the manufacturing and the construction phases for nuclear and renewable technologies; and the type, quality and origin of feedstock, as well as the amount and type of co-products, for biomass-based systems. This review demonstrates that the variability of existing LCA results for electricity generation can give rise to conflicting decisions regarding the environmental consequences of implementing new technologies.
Life Cycle Assessment of a brown seaweed-based third-generation biorefinery process

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Life cycle assessment of biofuel production from brown seaweed in Nordic conditions
The use of algae for biofuel production is expected to play an important role in securing energy supply in the next decades. A consequential lifecycle assessment (LCA) and an energy analysis of seaweed-based biofuel production were carried out in Nordic conditions to document and improve the sustainability of the process. Two scenarios were analyzed for the brown seaweed (Laminaria digitata), namely, biogas production (scenario 1) and bioethanol + biogas production (scenario 2). Potential environmental impact categories under investigation were Global Warming, Acidification and Terrestrial Eutrophication. The production of seaweed was identified to be the most energy intensive step. Scenario 1 showed better performance compared to scenario 2 for all impact categories, partly because of the energy intensive bioethanol separation process and the consequently lower overall efficiency of the system. For improved environmental performance, focus should be on optimization of seaweed production, bioethanol distillation, and management of digestate on land.
LCA was used to assess the environmental impacts from recycling of C&DW in road construction. The scenario comprised all stages in the end of life of C&D concrete, including recovery of materials, as well as avoided production of the substituted goods. Results show the importance of transportation of the material, especially when considering global warming, acidification and human toxicity categories. Ecotoxicity is dominated by leaching of pollutants from the concrete material, where Cr and Sb play a major role. Compared to landfilling of the same waste stream, reuse in road construction provides lower burdens for global warming, acidification and human toxicity categories, while ecotoxicity impacts are much larger, due to the larger leached amounts and the absence of any collection and treatment system.

Material resources, energy, and nutrient recovery from waste: are waste refineries the solution for the future?
Waste refineries focusing on multiple outputs of material resources, energy carriers, and nutrients may potentially provide more sustainable utilization of waste resources than traditional waste technologies. This consequential life cycle assessment (LCA) evaluated the environmental performance of a Danish waste refinery solution against state-of-the-art
waste technology alternatives (incineration, mechanical-biological treatment (MBT), and landfilling). In total, 252 scenarios were evaluated, including effects from source-segregation, waste composition, and energy conversion pathway efficiencies. Overall, the waste refinery provided global warming (GW) savings comparable with efficient incineration, MBT, and bioreactor landfilling technologies. The main environmental benefits from waste refining were a potential for improved phosphorus recovery (about 85%) and increased electricity production (by 15-40% compared with incineration), albeit at the potential expense of additional toxic emissions to soil. Society's need for the outputs from waste, i.e., energy products (electricity vs transport fuels) and resources (e.g., phosphorus), and the available waste composition were found decisive for the selection of future technologies. On the basis of the results, it is recommended that a narrow focus on GW aspects should be avoided as most waste technologies may allow comparable performance. Rather, other environmental aspects such as resource recovery and toxic emissions should receive attention in the future.

General information
State: Published
Organisations: Department of Environmental Engineering, Residual Resource Engineering
Authors: Tonini, D. (Intern), Martinez-Sanchez, V. (Intern), Astrup, T. F. (Intern)
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Mechanical–biological treatment: Performance and potentials. An LCA of 8 MBT plants including waste characterization

In the endeavour of avoiding presence of biodegradable waste in landfills and increasing recycling, mechanical–biological treatment (MBT) plants have seen a significant increase in number and capacity in the last two decades. The aim of these plants is separating and stabilizing the quickly biodegradable fraction of the waste as well as recovering recyclables from mixed waste streams. In this study the environmental performance of eight MBT-based waste management scenarios in Spain was assessed by means of life cycle assessment. The focus was on the technical and environmental performance of the MBT plants. These widely differed in type of biological treatment and recovery efficiencies. The results indicated that the performance is strongly connected with energy and materials recovery efficiency. The recommendation for upgrading and/or commissioning of future plants is to optimize materials recovery through increased automation of the selection and to prioritize biogas-electricity production from the organic fraction over direct composting. The optimal strategy for refuse derived fuel (RDF) management depends upon the environmental compartment to be prioritized and the type of marginal electricity source in the system. It was estimated that, overall, up to ca. 180—190 kt CO2-eq. y−1 may be saved by optimizing the MBT plants under assessment.

General information
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Organisations: Department of Environmental Engineering, University of Salamanca
Authors: Montejo, C. (Ekstern), Tonini, D. (Intern), Márquez, M. D. C. (Ekstern), Astrup, T. F. (Intern)
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Metal recovery from municipal solid waste incineration bottom ash (MSWIBA): state of the art, potential and environmental benefits

Incineration has a central role in the waste management system in Denmark (e.g. 52% of the household waste) resulting in approximately 726,000t of solid residues each year. However, the targets imposed by the Danish Waste Strategy and the increasing discussions about resource in waste raise an issue on resource losses through waste incineration. In this framework, this study provides actual data on the state of the art of the recovery of resource in MSWIBA in Denmark (i.e. metals), on the potential for further recovery and on the environmental benefits or burdens assessed through the Life Cycle Assessment (LCA) methodology.
Presence of potentially critical substances in waste paper

The paper industry accounts for a significant share of the chemicals consumed by the industrial sector. Most of the chemicals used are additives, i.e. chemical substances added during pulp and paper preparation and final product manufacturing (conversion and printing) in order to facilitate the process itself as well as the quality or functionality of the final product. Such additives may be re-introduced to the paper production process once waste paper is recycled, leading to their accumulation and spreading in newly manufactured paper and board products. This study aimed at identification of the critical additives potentially present in paper products and quantification of a selected group of additives (Mineral Oil Hydrocarbons) in waste paper and board source segregated from Danish municipal solid waste.
Pyrolysis and gasification of meat-and-bone-meal: Energy balance and GHG accounting

Meat-and-bone-meal (MBM) produced from animal waste has become an increasingly important residual fraction needing management. As biodegradable waste is routed away from landfills, thermo-chemical treatments of MBM are considered promising solution for the future. Pyrolysis and gasification of MBM were assessed based on data from three experimental lab and pilot-scale plants. Energy balances were established for the three technologies, providing different outcomes for energy recovery: bio-oil was the main product for the pyrolysis system, while syngas and a solid fraction of biochar were the main products in the gasification system. These products can be used – eventually after upgrading – for energy production, thereby offsetting energy production elsewhere in the system. Greenhouse gases (GHG) accounting of the technologies showed that all three options provided overall GHG savings in the order of 600–1000kg CO2-eq. per Mg of MBM treated, mainly as a consequence of avoided fossil fuel consumption in the energy sector. Local conditions influencing the environmental performance of the three systems were identified, together with critical factors to be considered during decision-making regarding MBM management.
Stability and leaching of cobalt smelter fly ash

The leaching behaviour of fly ash from a Co smelter situated in the Zambian Copperbelt was studied as a function of pH (5–12) using the pH-static leaching test (CEN/TS 14997). Various experimental time intervals (48h and 168h) were evaluated. The leaching results were combined with the ORCHESTRA modelling framework and a detailed mineralogical investigation was performed on the original FA and leached solid residues. The largest amounts of Co, Cu, Pb and Zn were leached at pH 5, generally with the lowest concentrations between pH 9 and 11 and slightly increased concentrations at pH 12. For most elements, the released concentrations were very similar after 48h and 168h, indicating near-equilibrium conditions in the system. Calcite, clinopyroxenes, quartz and amorphous phases predominated in the fly ash. Various metallic sulfides, alloys and the presence of Cu, Co and Zn in silicates and glass were detected using SEM/EDS and/or TEM/EDS. The leaching of metals was mainly attributed to the dissolution of metallic particles. Partial dissolution of silicate and glass fractions was assumed to significantly influence the release of Ca, Mg, Fe, K, Al and Si as well as Cu, Co and Zn. The formation of illite was suggested by the ORCHESTRA modelling to be one of the main solubility-controlling phases for major elements, whereas Ca and Zn were controlled by CoO and zincite, respectively. Sorption of metals on hydrous ferric oxides was assumed to be an important attenuation mechanism, especially for the release of Pb and Cu. However, there is a high risk of Co, Cu, Pb and Zn mobility in the acidic soils around the smelter facility. Therefore, potential local options for "stabilisation" of the fly ash were evaluated on the basis of the modelling results using the PHREEQC code.

General information
Assessment of leaching from Construction & Demolition Waste concrete

Construction and demolition waste features two very important properties when considering its management options: the large amounts, and the low environmental hazardousness. Therefore, concrete waste can be recycled relatively easily: most common end-of-life option is utilization as unbound aggregates in road sub-bases, where it substitutes for natural aggregates such as gravel and crushed rocks. However, leaching of heavy metals may occur in such uncontrolled environmental conditions, and become a limiting factor for utilization. Therefore, proper assessment of leaching is crucial. Different approaches exist, often implying unrealistic or not relevant conditions if compared to real life utilization scenarios.

A modified version of the CEN/TS 14405 column percolation test has been implemented on four crushed concrete samples, with the purpose of analysing the release of chromium, one of the elements of biggest concern. Main differences from the standard test include particles size, non saturated conditions and downflow intermittent watering.

The results of these experiments will be utilized to assess the actual potential for soil and groundwater pollution in a broader perspective.

Bioenergy production from perennial energy crops: A consequential LCA of 12 bioenergy scenarios including land use changes

In the endeavor of optimizing the sustainability of bioenergy production in Denmark, this consequential life cycle assessment (LCA) evaluated the environmental impacts associated with the production of heat and electricity from one hectare of Danish arable land cultivated with three perennial crops: ryegrass (Lolium perenne), willow (Salix viminalis) and Miscanthus giganteus. For each, four conversion pathways were assessed against a fossil fuel reference: (I) anaerobic co-digestion with manure, (II) gasification, (III) combustion in small-to-medium scale biomass combined heat and power (CHP) plants and IV) co-firing in large scale coal-fired CHP plants. Soil carbon changes, direct and indirect land use changes as well as uncertainty analysis (sensitivity, MonteCarlo) were included in the LCA. Results showed that global warming was the bottleneck impact, where only two scenarios, namely willow and Miscanthus co-firing, allowed for an improvement as compared with the reference (-82 and -45 t CO2-eq. ha-1, respectively). The indirect land use changes impact was quantified as 310 ± 170 t CO2-eq. ha-1, representing a paramount average of 41% of the induced greenhouse gas emissions. The uncertainty analysis confirmed the results robustness and highlighted the indirect land use changes uncertainty as the only uncertainty that can significantly change the outcome of the LCA results. © 2012 American Chemical Society.
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Scopus rating (2013): SJR 2.956 SNIP 2.103 CiteScore 5.52
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Scopus rating (2012): SJR 3.146 SNIP 2.056 CiteScore 5.17
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BFI (2010): BFI-level 2
Scopus rating (2010): SJR 2.964 SNIP 1.729
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BFI (2009): BFI-level 2
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Biomass waste – the way ahead

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Organisations: Department of Environmental Engineering, Residual Resource Engineering, Aalborg University, University of Applied Sciences
Authors: Poulsen, T. G. (Ekstern), Astrup, T. F. (Intern), Ragossnig, A. M. (Ekstern)
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Scopus rating (2009): SJR 0.877 SNIP 1.257
SUMMARY: Biomass and waste are expected to play a key role in future energy systems based on large shares of renewable energy resources. The LCA model EASETECH Energy was developed specifically for modelling large and complex energy systems including various technologies and several processing steps. The model allows simultaneous balancing of mass and energy flows of the system under assessment, and is equipped with advanced tools for sensitivity/uncertainty analysis. EASETECH Energy was used to assess the environmental footprint of the Danish energy system in 2050 (based on 100% renewables) and compare it to the
current situation. The results show that the future Danish energy systems will have a rather different environmental footprint than the current one.

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Global warming potential impact of bioenergy systems

Reducing dependence on fossil fuels and mitigation of GHG emissions is a main focus in the energy strategy of many Countries. In the case of Denmark, for instance, the long-term target of the energy policy is to reach 100% renewable energy system. This can be achieved by drastic reduction of the energy demand, optimization of production/distribution and substitution of fossil fuels with biomasses. However, a large increase in biomass consumption will finally induce conversion of arable and currently cultivated land into fields dedicated to energy crops production determining significant environmental consequences related to land use changes. In this study the global warming potential impact associated with six alternative bioenergy systems based on willow and Miscanthus was assessed by means of life-cycle assessment. The results showed that bioenergy production may generate higher global warming impacts than the reference fossil fuel system, when the impacts from indirect land use changes are accounted for. In a life-cycle perspective, only highly-efficient co-firing with fossil fuel achieved a (modest) GHG emission reduction.

LCA of biomass-based energy systems: a case study for Denmark

Decrease of fossil fuel consumption in the energy sector is an important step towards more sustainable energy production. Environmental impacts related to potential future energy systems in Denmark with high shares of wind and biomass energy were evaluated using life-cycle assessment (LCA). Based on the reference year 2008, energy scenarios for 2030 and 2050 were assessed. For 2050 three alternatives for supply of transport fuels were considered: (1) fossil fuels, (2) rapeseed based biodiesel, and (3) Fischer–Tropsch based biodiesel. Overall, the results showed that greenhouse gas emissions per PJ energy supplied could be significantly reduced (from 68 to 17 Gg CO2-eq/PJ) by increased use of wind and residual biomass resources as well as by electrifying the transport sector. Energy crops for production of biofuels and the use of these biofuels for heavy terrestrial transportation were responsible for most environmental impacts in the 2050 scenarios, in particular upstream impacts from land use changes (LUCs), fertilizer use and NOx emissions from the
transport sector were critical. Land occupation (including LUC effects) caused by energy crop production increased to a range of 600–2100 × 10^6 m²/PJ depending on the amounts and types of energy crops introduced. Use of fossil diesel in the transport sector appeared to be environmentally preferable over biodiesel for acidification, aquatic eutrophication and land occupation. For global warming, biodiesel production via Fischer–Tropsch was comparable with fossil diesel.
Life-cycle assessment of a waste refinery process for enzymatic treatment of municipal solid waste

Decrease of fossil fuel dependence and resource saving has become increasingly important in recent years. From this perspective, higher recycling rates for valuable materials (e.g. metals) as well as energy recovery from waste streams could play a significant role substituting for virgin material production and saving fossil resources. This is especially important with respect to residual waste (i.e. the remains after source-separation and separate collection) which in Denmark is typically incinerated. In this paper, a life-cycle assessment and energy balance of a pilot-scale waste refinery for the enzymatic treatment of municipal solid waste (MSW) is presented. The refinery produced a liquid (liquefied organic materials and paper) and a solid fraction (non-degradable materials) from the initial waste. A number of scenarios for the energy utilization of the two outputs were assessed. Co-combustion in existing power plants and utilization of the liquid fraction for biogas production were concluded to be the most favourable options with respect to their environmental impacts (particularly global warming) and energy performance. The optimization of the energy and environmental performance of the waste refinery was mainly associated with the opportunity to decrease energy and enzyme consumption.

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Life Cycle Assessment of electricity generation: overview and methodological issues

Electricity production is currently responsible for a large share of global Greenhouse Gas (GHG), NOx and SO2 emissions, and their related environmental impacts. This study provides a critical review of the status of research on life cycle assessment (LCA) of electricity generation. NREL [1-6] recently suggested a harmonization of GHG emissions of single technologies: these studies certainly broaden the level of understanding of the variables that might lead to different results when performing LCA, but focusing on GHG may not lead towards environmental sustainability. Additionally, the present study focuses on the comparability between different technologies, identifying and quantifying the possible mistakes that can occur when comparing two technologies whose environmental assessments have been performed with conflicting assumptions.

Nine different power generation technologies were examined: hard coal, lignite, natural gas, oil, nuclear, biomass, hydroelectric, solar photovoltaic and wind. More than 150 published studies were selected and analyzed to investigate whether "typical" GHG, NOx and SO2 emission factors for each technology could be identified. For a better overview of the sources of emissions, those were divided among three life cycle phases: fuel provision, operation of the plant and infrastructure.

It was possible to estimate typical emission factors for all technologies except for biomass, where methodological and technical aspects result in very variable outcomes. Within these ranges, we identified direct emissions at the plant as the main contributor to the total GHG emissions for fossil fuels, with thermal efficiency being the most determining parameter. Nevertheless, with high thermal efficiency fuel provision becomes increasingly important (e.g. natural gas combined cycle). Different results were found concerning NOx and SO2. Concerning renewable energy sources, infrastructures were identified as the main contributor to all emissions. However, when considering renewables the emissions often covered a wide interval even within the same technology; this was mainly due to geographical factors and date and type of data used.

We therefore suggest not to limit studies to GHG, and, to ensure comparability between studies, to transparently report emission factors for electricity production stating clearly the functional unit of the study, the efficiency for fossil technologies and the temporal and geographical scope for renewables.
Carbon in solid waste: is it a problem?

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Scopus rating (2011): SJR 1.027 SNIP 0.865 CiteScore 1.33
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CO₂ emission factors for waste incineration: Influence from source separation of recyclable materials

CO₂ loads from combustible waste are important inputs for national CO₂ inventories and life-cycle assessments (LCA). CO₂ emissions from waste incinerators are often expressed by emission factors in kg fossil CO₂ emitted per GJ energy content of the waste. Various studies have shown considerable variations between emission factors for different incinerators, but the background for these variations has not been thoroughly examined. One important reason may be variations in collection of recyclable materials as source separation alters the composition of the residual waste incinerated. The objective of this study was to quantify the importance of source separation for determination of emission factors for incineration of residual household waste. This was done by mimicking various source separation scenarios and based on waste composition data calculating resulting emission factors for residual waste routed to incineration. Emission factors ranged from 27 to 40 kg CO₂/GJ. The results appeared most sensitive towards variations in waste composition and water content. Recycling rates and lower heating values could not be used as simple indicators of the resulting emission factors for residual household waste; however the fossil carbon ratio of the waste after source separation was found to be appropriately correlated with the emission factor. Based on the results, it is recommended to carefully evaluate the source separation and collection systems behind reported literature values when comparing different studies and when using the values for environmental assessment purposes.

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State: Published
Organisations: Department of Environmental Engineering, Residual Resource Engineering
Authors: Larsen, A. W. (Intern), Astrup, T. (Intern)
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  Web of Science (2016): Indexed yes
Coherent Energy and Environmental System Analysis

This report presents a summary of results of the strategic research project “Coherent Energy and Environmental System Analysis” (CEESA) which was conducted in the period 2007-2011 and funded by the Danish Strategic Research Council together with the participating parties.

The project was interdisciplinary and involved more than 20 researchers from 7 different university departments or research institutions in Denmark. Moreover, the project was supported by an international advisory panel.

The results include further development and integration of existing tools and methodologies into coherent energy and environmental analysis tools as well as analyses of the design and implementation of future renewable energy systems.
For practical reasons, the work has been carried out as an interaction between five work packages, and a number of reports, papers and tools have been reported separately from each part of the project. A list of the separate work package reports is given at the end of this foreword while a complete list of all papers and reports can be found at the end of the report as well as at the following website: www.ceesa.dk.

This report provides a summary of the results of the different project parts in a coherent way by presenting tools and methodologies as well as analyses of the design and implementation of renewable energy systems – including both energy and environmental aspects.

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Environmental performance of an innovative waste refinery based on enzymatic treatment
Decrease of fossil fuel dependence and global warming mitigation has become increasingly important issues during the last decades. With respect to waste management higher recycling rates for valuable materials as well as energy recovery from waste streams could play a significant role substituting for virgin material and saving fossil resources. In this paper a life-cycle assessment of a pilot-scale waste refinery for the enzymatic treatment of municipal solid waste (MSW) is presented. The refinery produced a liquid (liquefied organic materials and paper) and a solid fraction (non-degradable materials) from the waste. The waste refinery was compared to alternative treatments such as incineration, bioreactor landfill and mechanical-biological treatment followed by utilization of the RDF (refuse-derived fuel) for energy. The performance of the waste refinery turned out to be comparable with incineration, but for most environmental categories, landfilling turned out to be the worst option with respect to most categories (especially energy-related such as GW). The refinery treatment has large margins of improvement with respect to the environmental performance. These are mainly associated with the opportunity for decreases in heat and enzyme consumption.

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Incinerator performance: effects of changes in waste input and furnace operation on air emissions and residues

Waste incineration can be considered a robust technology for energy recovery from mixed waste. Modern incinerators are generally able to maintain relatively stable performance, but changes in waste input and furnace operation may affect emissions. This study investigated how inorganic air emissions and residue composition at a full-scale incinerator were affected by known additions of specific waste materials to the normal municipal solid waste (MSW) input. Six individual experiments were carried out (% ww of total waste input): NaCl (0.5%), shoes (1.6%), automobile shredder waste (14%), batteries (0.5%), poly(vinyl chloride) (5.5%) and chromate-cupper-arsenate impregnated wood (11%). Materials were selected based on chemical composition and potential for being included or excluded from the waste mix. Critical elements in the waste materials were identified based on comparison with six experiments including ‘as-large-as-possible’ changes in furnace operation (oxygen levels, air supply and burnout level) only using normal MSW as input. The experiments showed that effects from the added waste materials were significant in relation to: air emissions (in particular As, Cd, Cr, Hg, Sb), element transfer coefficients, and residue composition (As, Cd, Cr, Cu, Hg, Mo, Ni, Pb, S, Sb, Zn). Changes in furnace operation could not be directly linked to changes in emissions and residues. The results outlined important elements in waste which should be addressed in relation to waste incinerator performance. Likely ranges of element transfer coefficients were provided as the basis for sensitivity analysis of life-cycle assessment (LCA) results involving waste incinerator technologies

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Organisations: Residual Resource Engineering, Department of Environmental Engineering, Technical University of Denmark
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BFI (2011): BFI-level 1
Scopus rating (2011): SJR 1.027 SNIP 0.865 CiteScore 1.33
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Every year around 50 millions Mg solid waste are incinerated in Europe. Large differences exist in different regions, mainly regarding energy recovery, flue gas treatment and management of solid residues. This paper aims to identify and quantify those differences, providing a Life Cycle Assessment of two incinerator systems that are representative of conditions in Northern and Southern Europe. The two case studies are Aarhus (Denmark) and Milan (Italy). The results show that waste incineration appears more environmentally friendly in the Danish case than in the Italian one, due to the higher energy recovery and to local conditions, e.g. substitution of electricity and heat in the area. Focusing on the incineration process, Milan incinerator performs better than Aarhus, since its upstream impacts (related to the production of chemicals used in flue gas cleaning) are more than compensated by lower emissions at the stack. Consequently a more efficient flue gas cleaning as it is in the Italian case appears to be more environmentally friendly than the Danish one.
Leaching From Biomass Gasification Residues
The aim of the present work is to attain an overall characterization of solid residues from biomass gasification. Besides the determination of chemical and physical properties, the work was focused on the study of leaching behaviour. Compliance and pH-dependence leaching tests coupled with geochemical modelling were carried out both on fresh and aged samples. The results showed that the material is comparable to residues from wood combustion and the leaching behaviour was dominated by Ca-containing minerals and solid solutions. Heavy metals were detected in very low concentrations in the bulk composition, and DOC complexation and sorption mechanisms were found to have a great influence on their release. Like wood combustion residues, the analysed ashes could be relevant for recycling in agriculture or forestry because of the potential as liming agent and source of macroelements. However, the high reactivity turned out to limit this utilization option, even after ageing processes.

Leaching from waste incineration bottom ashes treated in a rotary kiln
Leaching from municipal solid waste incineration bottom ash treated in a rotary kiln was quantified using a combination of lab-scale leaching experiments and geochemical modelling. Thermal treatment in the rotary kiln had no significant effect on the leaching of Al, Ca, Mg, Si, Sr, Zn, sulfate and inorganic carbon. Leaching of these elements from the treated residues remained unchanged and was, in general, controlled by solubility of the same minerals as in the untreated residues. Leaching of Cd, Co, Ni, Ti, Be, Bi, and Sn from both untreated and treated residues was found to be close to or below their detection limits; no effects of the thermal treatment on leachability of these metals were observed. The leaching of Cl, dissolved organic carbon (DOC), Cu and Pb decreased by at least one order of magnitude after the thermal treatment. This could be explained by evaporation (Cl) and by a better burnout of organic matter which then limited metal–DOC complexation and mobility. At the same time, leaching of Mo and Cr appeared to increase by a factor of 4 and more than two orders of magnitude, respectively. The large changes in Cr leaching may be explained by decreases in Al reduction capacity after the thermal treatment. Overall, rotary kiln thermal treatment of bottom ashes can be recommended to reduce the leaching of Cu, Pb, Cl and DOC; however, increased leaching of Cr and Mo should be expected.
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Web of Science (2004): Indexed yes
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Web of Science (2003): Indexed yes
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Web of Science (2002): Indexed yes
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Leaching of metals from copper smelter flue dust (Mufulira, Zambian Copperbelt)
The leaching behaviour of electrostatic precipitator dust from the Mufulira Cu smelter (Copperbelt, Zambia) was studied using a 48-h pH-static leaching experiment (CEN/TS 14997). The release of metals (Cd, Co, Cu, Ni, Pb and Zn) and changes in mineralogical composition using X-ray diffraction and PHREEQC-2 modelling were investigated in the pH range of 3–7. The highest concentrations of metals were released at pH 3–4.5, which encompasses the natural pH of the dust suspension (∼4.3). About 40% of the total Cu was leached at pH3, yielding 107g/kg. Chalcanthite (CuSO4·5H2O), magnetite (Fe3O4) and delafossite (CuFeO2) represented the principal phases of the studied dust. In contact with water, chalcanthite was dissolved and hydrated Cu sulphates precipitated at pH4–7. Gypsum (CaSO4·2H2O) and secondary Fe or Al phases were observed in the leached residues. Serious environmental impact due to leaching may occur in dust-contaminated soil systems in the vicinity of the smelting plants.

General information
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Organisations: Residual Resource Engineering, Department of Environmental Engineering, Charles University, Czech Geological Survey
Authors: Vítková, M. (Ekstern), Ettler, V. (Ekstern), Hyks, J. (Intern), Astrup, T. (Intern), Kříbek, B. (Ekstern)
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Web of Science (2008): Indexed yes
Scopus rating (2007): SJR 1.075 SNIP 1.699
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Life cycle assessment of waste incineration in Denmark and Italy using two LCA models

In Europe, about 20% of municipal solid waste is incinerated. Large differences can be found between northern and southern Europe regarding energy recovery efficiencies, flue gas cleaning technologies and residue management. Life-cycle assessment (LCA) of waste incineration often provides contradictory results if these local conditions are not properly accounted for. The importance of regional differences and site-specific data, and choice of LCA model itself, was evaluated by assessment of two waste incinerators representing northern and southern Europe (Denmark and Italy) based on two different LCA models (SimaPro and EASEWASTE). The results showed that assumptions and modelling approaches regarding energy recovery/substitution and direct air emissions were most critical. Differences in model design and model databases mainly had consequences for the toxicity-related impact categories. The overall environmental performance of the Danish system was better than the Italian, mainly because of higher heat recovery at the Danish plant. Flue gas cleaning at the Italian plant was, however, preferable to the Danish, indicating that efficient flue gas cleaning may provide significant benefits. Differences in waste composition between the two countries mainly affected global warming and human toxicity via water. Overall, SimaPro and EASEWASTE provided consistent ranking of the individual scenarios. However, important differences in results from the two models were related to differences in the databases and modelling approaches, in particular the possibility for modelling of waste-specific emissions affected the toxicity-related impact categories. The results clearly showed that the use of site-specific data was essential for the results.
Materials And Carbon Flow In A Waste Refinery Process Using Enzymes

Recovery of resources from mixed Municipal Solid Waste (MSW) is a crucial aspect of waste management practices. In this paper the materials and carbon flows of an innovative waste refinery process using enzymes are presented. Through enzymatic treatment the process produces two main streams from the initial mixed MSW: a bioslurry (liquefied paper and organics) and a solid fraction (non-degradable materials). The discussion is based on the performance of the process in separating recyclables and recovery Cbiogenic as well as nutrients from the input MSW. The results of MFA and SFA
illustrate that the waste refinery has great potential for resource recovery: about 100% of the Cbiogenic and up to 90% of N and P can potentially be recovered in the bioslurry and returned to land after anaerobic digestion. Recovery of ferrous and non-ferrous material is estimated double compared to recovering the same material from bottom ash after incineration (current scenario). Hard plastic can also be separated and recovered. Potentially, only residual 20% of the initial MSW is to be incinerated after refining and separation of metals and plastic.

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- Authors: Tonini, D. (Intern), Woods, M. (Ekstern), Astrup, T. (Intern)
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**Optimal utilization of waste-to-energy in an LCA perspective**

Energy production from two types of municipal solid waste was evaluated using life cycle assessment (LCA): (1) mixed high calorific waste suitable for production of solid recovered fuels (SRF) and (2) source separated organic waste. For SRF, co-combustion was compared with mass burn incineration. For organic waste, anaerobic digestion (AD) was compared with mass burn incineration. In the case of mass burn incineration, incineration with and without energy recovery was modelled. Biogas produced from anaerobic digestion was evaluated for use both as transportation fuel and for heat and power production. All relevant consequences for energy and resource consumptions, emissions to air, water and soil, upstream processes and downstream processes were included in the LCA. Energy substitutions were considered with respect to two different energy systems: a present-day Danish system based on fossil fuels and a potential future system based on 100% renewable energy. It was found that mass burn incineration of SRF with energy recovery provided savings in all impact categories, but co-combustion was better with respect to Global Warming (GW). If all heat from incineration could be utilized, however, the two alternatives were comparable for SRF. For organic waste, mass burn incineration with energy recovery was preferable over anaerobic digestion in most impact categories. Waste composition and flue gas cleaning at co-combustion plants were critical for the environmental performance of SRF treatment, while the impacts related to utilization of the digestate were significant for the outcome of organic waste treatment. The conclusions
were robust in a present-day as well as in a future energy system. This indicated that mass burn incineration with efficient energy recovery is a very environmentally competitive solution overall.
Pyrolysis and Gasification

Pyrolysis and gasification include processes that thermally convert carbonaceous materials into products such as gas, char, coke, ash, and tar. Overall, pyrolysis generates products like gas, tar, and char, while gasification converts the carbon-containing materials (e.g. the outputs from pyrolysis) into a mainly gaseous output. The specific output composition and relative amounts of the outputs greatly depend on the input fuel and the overall process configuration. Although pyrolysis processes in many cases also occur in gasification (however prior to the gasification processes), the overall technology may often be described as gasification only. Pyrolysis, however, can also be employed without proceeding with gasification. Gasification is by no means a novel process; in the 19th century so-called 'town gas' was produced by the gasification of coal and for example used for illumination purposes. In Europe during World War II, wood-fueled gasifiers (or 'gas generators') were used to power cars during shortages of oil-based fuels. Sparked by oil price crises in 1970s and 1980s, further development in gasification technologies focused mainly on coal as a fuel to substitute for oil-based products. Today gasification is used within a range of applications, the most important of which are conversion of coal into syngas for use as chemical feedstock or energy production; but also gasification of biomass and waste is gaining significant interest as emerging technologies for sustainable energy. From a waste management perspective, pyrolysis and gasification are of relatively little importance as an overall management option. Today, gasification is primarily used on specific waste fractions as opposed to mixed household wastes. The main commercial activity so far has been in Japan, with only limited success in Europe and North America (Klein et al., 2004). However, pyrolysis and gasification of waste are generally expected to become more widely used in the future. A main reason for this is that public perceptions of waste incineration in some countries is a major obstacle for installing new incineration capacity, but also a better ability of gasification over incineration to preserve the chemical energy of the waste is important. This chapter provides an overview of pyrolysis and gasification processes related to waste, the technology involved, energy recovery options, and important environmental aspects.
Global Warming Potential Of A Waste Refinery Using Enzymatic Treatment

Decrease of fossil fuel dependence and resource saving has become increasingly important during the last years. In this perspective, higher recycling rates for valuable materials as well as energy recovery from waste streams could play a significant role substituting for virgin material production and fossil resources. This is especially important with respect to the residual waste (i.e. the remains after source-separation and separate collection) which is typically incinerated or landfill. In this paper the energy and Global Warming performance of a pilot-scale waste refinery for the enzymatic treatment of municipal solid waste (MSW) was presented. The refinery produced a liquid (liquefied organic materials and paper) and a solid fraction (non-degradable materials) from the initial waste. A number of scenarios for the utilization of the two outputs were analyzed. Co-combustion in existing power plants and utilization of the liquid fraction for biogas production turned out to be the best options with respect to energy and Global Warming performance.

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Authors: Tonini, D. (Intern), Astrup, T. (Intern)
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LCA Of The “Renescience” Concept: An Alternative To Incineration For The Treatment Of Residual Municipal Solid Waste

The “REnescience” system consists on a pretreatment of the waste based on heat and enzymes which liquefy the biogenic fraction of the waste (paper and organics). The outputs of the process are then liquid slurry and a remaining solid fraction from which metals, plastic and glass can eventually be separated for recycling. In this study the environmental assessment of a number of scenarios for the “REnescience” concept is presented. The scenarios assessed are co-combustion of solid and liquid fraction in coal-fired power plants (CC-CC), co-combustion of the liquid fraction and incineration of the solid fraction (CC-INC), anaerobic digestion of the liquid fraction to produce biogas and co-combustion of the solid fraction (BG-CC) and anaerobic digestion of the liquid fraction to produce biogas and incineration of the solid fraction (BG-INC). The reference technology for the comparison is the incinerator “Amagerforbrænding” (INC) located in Copenhagen (Denmark). Two different energy systems are considered for the assessment: coal as marginal energy and natural gas as marginal energy. The results of the LCA show that the co-combustion (CC-CC) and biogas scenarios (BG-CC) perform better than incineration (INC) with respect to Global Warming (GW), Acidification (AC) and Ecotoxicity in water, chronic (ETwc). The major savings are due to electricity recovery at the power plant. The waste refinery (pretreatment) contributes with a net load on GW equal to 20-30 mPE/tonne of ww. Savings from recycling are mainly connected to metals recovery (around -12 mPE/tonne of ww). The results for the toxicity categories show that the “REnescience” options are more environmentally friendly with respect to ETwc because of the higher recycling but contribute with environmental loads on HTs and HTw because of potential emissions of Hg and other metals to air (co-combustion) and to soil (use-on-land of the digestate). Keywords: environmental impact, waste, liquefaction, biogas.

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Life-cycle assessment of selected management options for air pollution control residues from waste incineration

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Web of Science (2010): Indexed yes
BFI (2009): BFI-level 1
Scopus rating (2009): SJR 1.571 SNIP 1.602
BFI (2008): BFI-level 2
Scopus rating (2008): SJR 1.463 SNIP 1.501
Web of Science (2008): Indexed yes
Scopus rating (2007): SJR 1.407 SNIP 1.491
Web of Science (2007): Indexed yes
Scopus rating (2006): SJR 1.515 SNIP 1.605
Web of Science (2006): Indexed yes
Thermal waste treatment: air emissions and residue quality

General information
State: Published
Organisations: Residual Resource Engineering, Department of Environmental Engineering
Authors: Astrup, T. (Intern)
Number of pages: 28
Publication date: 2010

Host publication information
Title of host publication: Proceedings of the 1st Sino-Danish Joint Conference on Sustainable Environmental Engineering, Shanghai, May 20-21, 2010
Place of publication: Shanghai
Publisher: Tongji University
Main Research Area: Technical/natural sciences
Conference: 1st Sino-Danish Joint Conference on Sustainable Environmental Engineering, Shanghai, China, 20/05/2010 - 20/05/2010
Source: orbit
Source-ID: 264723
Publication: Research › Conference abstract in proceedings – Annual report year: 2010

A Full-scale Study on the Partitioning of Trace Elements in Municipal Solid Waste Incineration-Effects of Firing Different Waste Types

General information
State: Published
Organisations: CHEC Research Centre, Department of Chemical and Biochemical Engineering, Department of Environmental Engineering, Residual Resource Engineering, Babcock & Wilcox Velund A/S, Fasan I/S
Authors: Pedersen, A. J. (Intern), Frandsen, F. (Intern), Riber, C. (Intern), Astrup, T. (Intern), Thomsen, S. N. (Ekstern), Lundtorp, K. (Ekstern), Mortensen, L. F. (Ekstern)
Pages: 3475-3489
Publication date: 2009
Main Research Area: Technical/natural sciences

Publication information
Journal: Energy & Fuels
Volume: 23
Issue number: 7
ISSN (Print): 0887-0624
Ratings:
BFI (2018): BFI-level 2
Askedannelse i affaldsforbrændingsanlæg

General information
State: Published
Organisations: CHEC Research Centre, Department of Chemical and Biochemical Engineering, Residual Resource Engineering, Department of Environmental Engineering
Authors: Pedersen, A. J. (Intern), Astrup, T. (Intern), Frandsen, F. (Intern), Hyks, J. (Ekstern)
Pages: 19-21
Publication date: 2009
Main Research Area: Technical/natural sciences

Publication information
**Combustion Aerosols from municipal Waste Incineration – Effects of Feedstock Composition and Boiler Operation,**

**General information**
State: Published
Organisations: CHEC Research Centre, Department of Chemical and Biochemical Engineering, Department of Environmental Engineering, Residual Resource Engineering, Technical University of Denmark
Publication date: 2009

**Host publication information**
Title of host publication: IFRF 16th Members' Conference - Combustion and Sustainability: New Technologies, New Fuels, New Challenges, Boston, USA, 8-10 June
Main Research Area: Technical/natural sciences
Conference: IFRF 16th Members' Conference - Combustion and Sustainability: New Technologies, New Fuels, New Challenges, Boston, USA, 8-10 June, 01/01/2009
Source: orbit
Source-ID: 256283
Publication: Research - peer-review › Article in proceedings – Annual report year: 2009

**Combustion aerosols from municipal waste incineration – Influence of waste input composition and operational conditions**

**General information**
State: Published
Organisations: CHEC Research Centre, Department of Chemical and Biochemical Engineering, Department of Environmental Engineering, Residual Resource Engineering, Technical University of Denmark
Publication date: 2009

**Host publication information**
Title of host publication: Joint Meeting of the Scandinavian-Nordic and French Section of the Combustion Institute
Main Research Area: Technical/natural sciences
Conference: Joint Meeting of the Scandinavian-Nordic and French Section of the Combustion Institute, Snekkersten, Denmark, 01/01/2009
Source: orbit
Source-ID: 256282
Publication: Research - peer-review › Article in proceedings – Annual report year: 2009

**Energy use and recovery in waste management and implications for accounting of greenhouse gases and global warming contributions**

The energy system plays an essential role in accounting of greenhouse gas (GHG) emissions from waste management systems and waste technologies. This paper focuses on energy use and energy recovery in waste management and outlines how these aspects should be addressed consistently in a GHG perspective. Essential GHG emission data for the most common fuels, electricity and heat are provided. Average data on electricity provision show large variations from country to country due to different fuels being used and different efficiencies for electricity production in the individual countries (0.007—1.13 kg CO2-eq. kWh —1). Marginal data on electricity provision show even larger variations (0.004—3 kg CO2-eq. kWh —1). Somewhat less variation in GHG emissions is being found for heat production (0.01—0.69 kg CO2-eq. kWh —1). The paper further addresses allocation principles and the importance of applying either average or marginal energy data, and it discusses the consequences of introducing reduction targets on CO2 emissions. All discussed
aspects were found to significantly affect the outcome of GHG accounts suggesting transparent reporting to be critical. Recommendations for use of average/marginal energy data are provided.

**General information**
**State:** Published
**Organisations:** Residual Resource Engineering, Department of Environmental Engineering
**Authors:** Fruergaard, T. (Intern), Astrup, T. (Intern), Ekvall, T. (Ekstern)
**Pages:** 724-737
**Publication date:** 2009
**Main Research Area:** Technical/natural sciences

**Publication information**
**Journal:** Waste Management and Research
**Volume:** 27
**Issue number:** 8
**ISSN (Print):** 0734-242X
**Ratings:**
- BFI (2018): BFI-level 1
- BFI (2017): BFI-level 1
- Web of Science (2017): Indexed Yes
- BFI (2016): BFI-level 1
- Scopus rating (2016): CiteScore 1.76 SJR 0.655 SNIP 1.036
- BFI (2015): BFI-level 1
- Scopus rating (2015): SJR 0.617 SNIP 0.899 CiteScore 1.53
- Web of Science (2015): Indexed yes
- BFI (2014): BFI-level 1
- Scopus rating (2014): SJR 0.741 SNIP 1.085 CiteScore 1.28
- Web of Science (2014): Indexed yes
- BFI (2013): BFI-level 1
- Scopus rating (2013): SJR 0.588 SNIP 0.951 CiteScore 1.17
- ISI indexed (2013): ISI indexed yes
- Web of Science (2013): Indexed yes
- BFI (2012): BFI-level 1
- Scopus rating (2012): SJR 0.886 SNIP 1.046 CiteScore 1.4
- ISI indexed (2012): ISI indexed yes
- Web of Science (2012): Indexed yes
- BFI (2011): BFI-level 1
- Scopus rating (2011): SJR 1.027 SNIP 0.865 CiteScore 1.33
- ISI indexed (2011): ISI indexed yes
- Web of Science (2011): Indexed yes
- BFI (2010): BFI-level 1
- Scopus rating (2010): SJR 0.666 SNIP 0.975
- Web of Science (2010): Indexed yes
- BFI (2009): BFI-level 1
- Scopus rating (2009): SJR 0.877 SNIP 1.257
- Web of Science (2009): Indexed yes
- BFI (2008): BFI-level 1
- Scopus rating (2008): SJR 0.49 SNIP 0.933
- Web of Science (2008): Indexed yes
- Scopus rating (2007): SJR 0.352 SNIP 0.666
- Web of Science (2007): Indexed yes
- Scopus rating (2006): SJR 0.295 SNIP 0.755
- Web of Science (2006): Indexed yes
- Scopus rating (2005): SJR 0.449 SNIP 0.729
- Web of Science (2005): Indexed yes
- Scopus rating (2004): SJR 0.48 SNIP 0.787
**Estimating contents of biogenic and fossil carbon in municipal solid waste**

**General information**
State: Published
Organisations: Residual Resource Engineering, Department of Environmental Engineering
Authors: Astrup, T. (Intern)
Pages: 670
Publication date: 2009

**Host publication information**
Title of host publication: Sardinia 2009 : Twelfth International Waste Management and Landfill Symposium
Volume: Proceedings. CD-ROM
Place of publication: Cagliari, Italy
Publisher: CISA, Environmental Sanitary Engineering Centre
Main Research Area: Technical/natural sciences
Conference: Twelfth International Waste Management and Landfill Symposium, Sardinia, Italy, 01/01/2009
Source: orbit
Source-ID: 253397
Publication: Research › Journal article – Annual report year: 2009

**Evaluation of field-scale emissions from utilization of MSWI air-pollution-control residues stabilized with FeSO4**

**General information**
State: Published
Organisations: Residual Resource Engineering, Department of Environmental Engineering
Authors: Hyks, J. (Intern), Astrup, T. (Intern), Christensen, T. H. (Intern)
Publication date: 2009

**Host publication information**
Title of host publication: Wascon 2009: Sustainable Management of waste and recycled materials in construction. Lyon; June 3-5, 2009
Volume: CD-ROM
Main Research Area: Technical/natural sciences
Source: orbit
Source-ID: 257609
Publication: Research › Conference abstract in proceedings – Annual report year: 2009

**Incorporation and co-combustion of waste: accounting of greenhouse gases and global warming contributions**

Important greenhouse gas (GHG) emissions related to waste incineration and co-combustion of waste were identified and considered relative to critical aspects such as: the contents of biogenic and fossil carbon, N2O emissions, fuel and material consumptions at the plants, energy recovery, and solid residues generated. GHG contributions were categorized with respect to direct emissions from the combustion plant as well as indirect upstream contributions (e.g. provision of fuels and materials) and indirect downstream contributions (e.g. substitution of electricity and heat produced elsewhere).
GHG accounting was done per tonne of waste received at the plant. The content of fossil carbon in the input waste, for example as plastic, was found to be critical for the overall level of the GHG emissions, but also the energy conversion efficiencies were essential. The emission factors for electricity provision (also substituted electricity) affected the indirect downstream emissions with a factor of 3—9 depending on the type of electricity generation assumed. Provision of auxiliary fuels, materials and resources corresponded to up to 40% of the direct emission from the plants (which were 347—371 kg CO2-eq. tonne—1 of waste for incineration and 735—803 kg CO2-eq. tonne—1 of waste for co-combustion). Indirect downstream savings were within the range of —480 to —1373 kg CO2eq. tonne—1 of waste for incineration and within —181 to —2607 kg CO2-eq. tonne—1 of waste for co-combustion. N2O emissions and residue management did not appear to play significant roles.
Influence of operational conditions, waste input and ageing on contaminant leaching from waste incinerator bottom ash: A full-scale study

General information
State: Published
Organisations: Residual Resource Engineering, Department of Environmental Engineering
Authors: Hyks, J. (Intern), Astrup, T. (Intern)
Pages: 1178-1184
Publication date: 2009
Main Research Area: Technical/natural sciences

Publication information
Journal: Chemosphere
Volume: 76
Issue number: 9
ISSN (Print): 0045-6535
Ratings:
BFI (2018): BFI-level 2
BFI (2017): BFI-level 2
Web of Science (2017): Indexed yes
BFI (2016): BFI-level 2
Scopus rating (2016): CiteScore 4.39 SJR 1.417 SNIP 1.606
Web of Science (2016): Indexed yes
BFI (2015): BFI-level 2
Scopus rating (2015): SJR 1.51 SNIP 1.57 CiteScore 4.04
Web of Science (2015): Indexed yes
BFI (2014): BFI-level 2
Scopus rating (2014): SJR 1.593 SNIP 1.651 CiteScore 3.76
Web of Science (2014): Indexed yes
BFI (2013): BFI-level 2
Scopus rating (2013): SJR 1.724 SNIP 1.767 CiteScore 3.92
ISI indexed (2013): ISI indexed yes
Web of Science (2013): Indexed yes
BFI (2012): BFI-level 2
Scopus rating (2012): SJR 1.818 SNIP 1.623 CiteScore 3.5
Leaching from MSWI bottom ash: Evaluation of non-equilibrium in column percolation experiments

Impacts of non-equilibrium on results of percolation experiments on municipal solid waste incineration (MSWI) bottom ash were investigated. Three parallel column experiments were performed: two columns with undisturbed percolation and one column with two sets of 1-month-long flow interruptions applied at liquid-to-solid (L/S) ratios of L/S 2 L/kg and 12 L/kg, respectively. Concentrations of Na, K, Cl-, Ca, Si, SO42-, Al, Cu, Ni, Mo, Ba, Pb, Zn, and dissolved organic carbon (DOC) were monitored throughout the entire leaching period; geochemical modeling was used to identify non-equilibrium-induced changes in the solubility control. Despite both physical and chemical non-equilibrium, the Columns were found to provide adequate information for readily soluble compounds (i.e., Na, Cl-, and K) and solubility-controlled elements (i.e., Ca, SO42-, Ba, Si, Al, Zn, and Pb). The leaching of Cu and Ni was shown to depend strongly on DOC leaching, which was likely affected by physical non-equilibrium during flow interruptions. Consequently, the leaching of Cu and Ni in the undisturbed Columns was shown to be by about one order of magnitude lower compared with the interrupted column. The results indicate that the leaching of DOC-related metals in laboratory column experiments may be considerably underestimated compared with full-scale scenarios in which the impacts from non-equilibrium may be significantly lower. The leaching of Mo (or MoO42-) may be controlled solely by its availability in the mobile zone, which in turn appeared to be controlled by diffusion from the stagnant zone: no Mo controlling minerals were predicted by the geochemical modeling.

General information
State: Published
Long-term leaching from MSWI air-pollution-control residues: Leaching characterization and modeling

Long-term leaching of Ca, Fe, Mg, K, Na, S, Al, As, Ba, Cd, Co, Cr, Cu, Hg, Mn, Ni, Pb, Zn, Mo, Sb, Si, Sr, Ti, V, P, Cl, and dissolved organic carbon from two different municipal solid waste incineration (MSWI) air-pollution-control residues was monitored during 24 months of column percolation experiments; liquid-to-solid (L/S) ratios of 200-250 L/kg corresponding to more than 10,000 years in a conventional landfill were reached. Less than 2% of the initially present As, Cu, Pb, Zn, Cr, and Sb had leached during the course of the experiments. Concentrations of Cd, Fe, Mg, Hg, Mn, Ni, Co, Sn, Ti, and P were generally below 1 μg/L; overall less than 1% of their mass leached. Column leaching data were further used in a two-step geochemical modeling in PHREEQC in order to (i) identify solubility controlling minerals and (ii) evaluate their interactions in a water-percolated column system over L/S of 250 L/kg. Adequate predictions of pH, alkalinity, and the leaching of Ca, S, Al, Si, Ba, and Zn were obtained in a simultaneous calculation. Also, it was suggested that removal of Ca and S together with depletion of several minerals apparently caused dissolution of ettringite-like phases. In turn, significant increase in leaching of oxyanions (especially Sb and Cr) was observed at late stage of leaching experiments.

General information
State: Published
Organisations: Residual Resource Engineering, Department of Environmental Engineering
Authors: Hyks, J. (Intern), Astrup, T. (Intern), Christensen, T. H. (Intern)
Pages: 80-91
Publication date: 2009
Main Research Area: Technical/natural sciences

Publication information
Journal: Journal of Hazardous Materials
Volume: 162
Issue number: 1
ISSN (Print): 0304-3894
Ratings:
BFI (2018): BFI-level 1
BFI (2017): BFI-level 1
Web of Science (2017): Indexed yes
BFI (2016): BFI-level 1
Scopus rating (2016): CiteScore 6.31 SJR 1.727 SNIP 2.045
Web of Science (2016): Indexed yes
BFI (2015): BFI-level 1
Scopus rating (2015): SJR 1.651 SNIP 1.935 CiteScore 5.54
Web of Science (2015): Indexed yes
BFI (2014): BFI-level 1
Scopus rating (2014): SJR 1.814 SNIP 2.269 CiteScore 5.21
Web of Science (2014): Indexed yes
BFI (2013): BFI-level 1
Scopus rating (2013): SJR 1.822 SNIP 2.458 CiteScore 5.09
ISI indexed (2013): ISI indexed yes
Web of Science (2013): Indexed yes
BFI (2012): BFI-level 1
Scopus rating (2012): SJR 1.985 SNIP 2.467 CiteScore 4.73
ISI indexed (2012): ISI indexed yes
Web of Science (2012): Indexed yes
Recycling of plastic: accounting of greenhouse gases and global warming contributions

Major greenhouse gas (GHG) emissions related to plastic waste recycling were evaluated with respect to three management alternatives: recycling of clean, single-type plastic, recycling of mixed/contaminated plastic, and use of plastic waste as fuel in industrial processes. Source-separated plastic waste was received at a material recovery facility (MRF) and processed for granulation and subsequent downstream use. In the three alternatives, plastic was assumed to be substituting virgin plastic in new products, wood in low-strength products (outdoor furniture, fences, etc.), and coal or fuel oil in the case of energy utilization. GHG accounting was organized in terms of indirect upstream emissions (e.g. provision of energy, fuels, and materials), direct emissions at the MRF (e.g. fuel combustion), and indirect downstream emissions (e.g. avoided emissions from production of virgin plastic, wood, or coal/oil). Combined, upstream and direct emissions were estimated to be roughly between 5 and 600 kg CO2-eq. tonne^-1 of plastic waste depending on treatment at the MRF and CO2 emissions from electricity production. Potential downstream savings arising from substitution of virgin plastic, wood, and energy fuels were estimated to be around 60—1600 kg CO2-eq. tonne^-1 of plastic waste depending on substitution ratios and CO2 emissions from electricity production. Based on the reviewed data, it was concluded that substitution of virgin plastic should be preferred. If this is not viable due to a mixture of different plastic types and/or contamination, the plastic should be used for energy utilization. Recycling of plastic waste for substitution of other materials such as wood provided no savings with respect to global warming.

General information

State: Published
Organisations: Residual Resource Engineering, Department of Environmental Engineering
Authors: Astrup, T. (Intern), Fruergaard, T. (Intern), Christensen, T. H. (Intern)
Pages: 763-772
Scopus rating (2000): SJR 0.582 SNIP 0.879
Web of Science (2000): Indexed yes
Scopus rating (1999): SJR 0.579 SNIP 0.877
Original language: English
DoIs: 10.1177/0734242X09345868
Source: orbit
Source-ID: 253401
Publication: Research - peer-review › Journal article – Annual report year: 2009

Residues from waste incineration: Final report PSO-5784

General information
State: Published
Organisations: Residual Resource Engineering, Department of Environmental Engineering
Authors: Astrup, T. (Intern), Pedersen, A. (Ekstern), Hyks, J. (Intern), Frandsen, F. (EKstern)
Number of pages: 40
Publication date: 2009

Publication information
Place of publication: Kgs. Lyngby
Publisher: Department of Environmental Engineering, Technical University of Denmark (DTU)
Original language: English
Main Research Area: Technical/natural sciences
Electronic versions:
5784_Residues_from_waste_incineration.pdf
Source: orbit
Source-ID: 252237
Publication: Research › Report – Annual report year: 2009

Leaching from municipal solid waste incineration residues

General information
State: Published
Organisations: Residual Resource Engineering, Department of Environmental Engineering
Authors: Hyks, J. (Intern), Christensen, T. H. (Intern), Astrup, T. (Intern)
Number of pages: 29
Publication date: Sep 2008

Publication information
Place of publication: Kgs. Lyngby
Publisher: Technical University of Denmark, DTU Environment
Original language: English
Main Research Area: Technical/natural sciences
Electronic versions:
ENV2008_033_1_.pdf
Source: orbit
Source-ID: 213620
Publication: Research › Ph.D. thesis – Annual report year: 2008

A Full-Scale Study on the Partitioning of Trace Elements in Municipal Solid Waste Incineration – Effects of Firing Different Waste Types

General information
State: Published
Organisations: CHEC Research Centre, Department of Chemical and Biochemical Engineering, Department of Environmental Engineering, Residual Resource Engineering, Babcock & Wilcox Vølund A/S, Fasan I/S
Authors: Pedersen, A. J. (Intern), Frandsen, F. (Intern), Riber, C. (Intern), Astrup, T. (Intern), Thomsen, S. N. (Ekstern), Lundtorp, K. (Ekstern), Mortensen, L. F. (Ekstern)
Publication date: 2008

Host publication information
Title of host publication: Impact of Fuel Quality on Power Production and the Environment
**Consequences of energy demand for the environmental performance of waste incinerators**

**General information**
- State: Published
- Organisations: Residual Resource Engineering, Department of Environmental Engineering
- Authors: Fruergaard, T. (Intern), Astrup, T. (Intern)
- Publication date: 2008

**Host publication information**
- Volume: CD-ROM
- Place of publication: Cagliari, Italy
- Publisher: CISA, Environmental Sanitary Engineering Centre
- Main Research Area: Technical/natural sciences
- Source: orbit
- Source-ID: 235433
- Publication: Research › Article in proceedings – Annual report year: 2008

**Effect of drying on leaching testing of treated municipal solid waste incineration APC-residues**

Air-pollution-control (APC) residues from waste incinerators are hazardous waste according to European legislation and must be treated prior to landfilling. Batch and column leaching data determine which type of landfill can receive the treated APC-residues. CEN standards are prescribed for the batch and column leaching test; however, these standards do not specify whether or not the residue samples should be dried prior to the leaching testing. Laboratory tests were performed in parallel (dried/non-dried) on treated APC-residue samples and evaluated with respect to Cr, Cd, Cu, Pb and Zn leaching. The effect of drying of the wet APC-residue samples was particularly dramatic regarding the leaching of Cr. Drying resulted in 10—100 times more Cr leaching in both batch and columns test. Drying also affected the leaching of Cd, Cu and Pb. Initial Cd leaching was up to 100 times higher in column tests with dried APC-residue than in tests with wet residues. The effect of drying appeared to be a combination of decreasing the reduction capacity of the sample (Cr), decreasing pH (Cd, Cu) and in column tests also a wash-out of salts (probably affecting Cd and Pb). If the leaching tests are intended to mimic landfill conditions, the results of this paper suggest that the tests should be done on wet, non-dried residue samples, although this may be less practical than testing dried samples.

**General information**
- State: Published
- Organisations: Residual Resource Engineering, Department of Environmental Engineering
- Authors: Hu, Y. (Ekstern), Hyks, J. (Intern), Astrup, T. (Intern), Christensen, T. H. (Intern)
- Pages: 400-405
- Publication date: 2008
- Main Research Area: Technical/natural sciences

**Publication information**
- Journal: Waste Management and Research
- Volume: 26
- Issue number: 4
- ISSN (Print): 0734-242X
- Ratings:
  - BFI (2018): BFI-level 1
  - BFI (2017): BFI-level 1
  - Web of Science (2017): Indexed Yes
  - BFI (2016): BFI-level 1
  - Scopus rating (2016): CiteScore 1.76 SJR 0.655 SNIP 1.036
  - BFI (2015): BFI-level 1
  - Scopus rating (2015): SJR 0.617 SNIP 0.899 CiteScore 1.53
Full scale test incineration of special waste fractions: Residue quality and environmental aspects

General information
State: Published
Organisations: Residual Resource Engineering, Department of Environmental Engineering
Authors: Astrup, T. (Intern)
Low-temperature mechanical pyrolysis on MSW: LCIA-modeling and comparison with incineration

General information
State: Published
Organisations: Residual Resource Engineering, Department of Environmental Engineering
Authors: Balzan, A. (Intern), Astrup, T. (Intern)
Publication date: 2008

Host publication information
Title of host publication: Global waste management symposium, Promoting technology and scientific innovation, 7-10 September 2008, Copper Conference Center, Colorado, USA: Manuscripts
Volume: CD-ROM
Place of publication: New York, NY
Publisher: Penton Media Inc.
Main Research Area: Technical/natural sciences
Conference: Global waste management symposium, Promoting technology and scientific innovation, 7-10 September 2008, Copper Conference Center, Colorado, USA, 01/01/2008
Source: orbit
Source-ID: 235437
Publication: Research - peer-review › Article in proceedings – Annual report year: 2008

Management of APC residues from W-t-E plants. An overview of management options and treatment methods

General information
State: Published
Organisations: Residual Resource Engineering, Department of Environmental Engineering
Authors: Astrup, T. (Intern)
Publication date: 2008

Publication information
Place of publication: Copenhagen
Publisher: ISWA General Secretariat
Original language: English
Main Research Area: Technical/natural sciences
Source: orbit
Source-ID: 228137
Publication: Research › Report – Annual report year: 2008

Miljøvurdering af affaldsforbrænding og alternativer

General information
State: Published
Organisations: Residual Resource Engineering, Department of Environmental Engineering
Authors: Møller, J. (Intern), Frueergaard, T. (Intern), Riber, C. (Intern), Astrup, T. (Intern), Christensen, T. H. (Intern)
Publication date: 2008

Publication information
Publisher: DTU Miljø, Institut for Vand og Miljøteknologi, Danmarks Tekniske Universitet
Original language: Danish
Combustion aerosols from municipal waste incineration - Effect of fuel feedstock and plant operation

Combustion aerosols were measured in a 22MW (thermal energy) municipal waste incinerator. Different types of waste fractions were added to a base-load waste and the effect on aerosol formation was measured. The waste fractions applied were: PVC plastic, pressure-impregnated wood, shoes, salt (NaCl), batteries, and automotive shredder waste. Also, runs with different changes in the operational conditions of the incinerator were made. Mass-based particle size distributions were measured using a cascade impactor and the number-based size distributions were measured using a Scanning Mobility Particle Sizer. The plant is equipped with flue gas cleaning and the penetration through this was determined. The particle morphology was investigated by Transmission Electron Microscopy (TEM) and chemical analysis of the aerosol particles was made by Energy Dispersive X-ray Spectroscopy (EDS). The mass-based particle size distribution was bimodal with a fine mode peak around 0.4 mm and a coarse mode peak around 100 μm. The addition of NaCl, shredder waste, and impregnated wood increased the mass concentration of fine particles (aerodynamic diameter below 2.5 μm). In general, the mass concentration was stable and close to the reference PM2.5-value of 252 ± 21 mg/m³ (std. T, P). The total number concentration deviated during runs and between runs spanning from 43.10^6 to 87.10^6 #/cm³ (std. T, P). The aerosols formed were mixtures of dense and aggregated particles in all tests. The fine particles are mainly composed by alkali salts, zinc, and lead. The heavy metals Cu, Cd, Hg, and Pb are significantly enriched in the fine particles.
Influence of test conditions on solubility controlled leaching predictions from air-pollution-control residues

General information
State: Published
Organisations: Department of Environmental Engineering
Authors: Hyks, J. (Intern), Astrup, T. (Intern), Christensen, T. H. (Intern)
Pages: 457-466
Publication date: 2007
Main Research Area: Technical/natural sciences

Publication information
Journal: Waste Management and Research
Volume: 25
ISSN (Print): 0734-242X
Ratings:
BFI (2018): BFI-level 1
BFI (2017): BFI-level 1
Web of Science (2017): Indexed Yes
BFI (2016): BFI-level 1
Scopus rating (2016): CiteScore 1.76 SJR 0.655 SNIP 1.036
BFI (2015): BFI-level 1
Scopus rating (2015): SJR 0.617 SNIP 0.899 CiteScore 1.53
Web of Science (2015): Indexed yes
BFI (2014): BFI-level 1
Scopus rating (2014): SJR 0.741 SNIP 1.085 CiteScore 1.28
Web of Science (2014): Indexed yes
BFI (2013): BFI-level 1
Scopus rating (2013): SJR 0.588 SNIP 0.951 CiteScore 1.17
ISI indexed (2013): ISI indexed yes
Web of Science (2013): Indexed yes
BFI (2012): BFI-level 1
Scopus rating (2012): SJR 0.886 SNIP 1.046 CiteScore 1.4
ISI indexed (2012): ISI indexed yes
Web of Science (2012): Indexed yes
BFI (2011): BFI-level 1
Scopus rating (2011): SJR 1.027 SNIP 0.865 CiteScore 1.33
ISI indexed (2011): ISI indexed yes
Web of Science (2011): Indexed yes
BFI (2010): BFI-level 1
Scopus rating (2010): SJR 0.666 SNIP 0.975
Web of Science (2010): Indexed yes
BFI (2009): BFI-level 1
Scopus rating (2009): SJR 0.877 SNIP 1.257
Web of Science (2009): Indexed yes
BFI (2008): BFI-level 1
Scopus rating (2008): SJR 0.49 SNIP 0.933
Web of Science (2008): Indexed yes
Scopus rating (2007): SJR 0.352 SNIP 0.666
Web of Science (2007): Indexed yes
Scopus rating (2006): SJR 0.295 SNIP 0.755
Web of Science (2006): Indexed yes
Scopus rating (2005): SJR 0.449 SNIP 0.729
Web of Science (2005): Indexed yes
Scopus rating (2004): SJR 0.48 SNIP 0.787
Web of Science (2004): Indexed yes
Scopus rating (2003): SJR 0.626 SNIP 0.831
Web of Science (2003): Indexed yes
Scopus rating (2002): SJR 0.465 SNIP 0.707
Web of Science (2002): Indexed yes
Scopus rating (2001): SJR 0.691 SNIP 1.118
Web of Science (2001): Indexed yes
Scopus rating (2000): SJR 0.582 SNIP 0.879
Web of Science (2000): Indexed yes
Scopus rating (1999): SJR 0.579 SNIP 0.877
Original language: English
DOIs:
10.1177/0734242X07079050
Pretreatment and utilization of waste incineration bottom ashes: Danish experiences

Within recent years, researchers and authorities have had increasing focus on leaching properties from waste incineration bottom ashes. Researchers have investigated processes such as those related to carbonation, weathering, metal complexation, and leaching control. Most of these investigations, however, have had a strong emphasis on lab experiments with little focus on full scale bottom ash upgrading methods. The introduction of regulatory limit values restricting leaching from utilized bottom ashes, has created a need for a better understanding of how lab scale experiences can be utilized in full scale bottom ash upgrading facilities, and the possibilities for complying with the regulatory limit values. A range of Danish research and development projects have within 1997-2005 investigated important techniques for bottom ash upgrading. The primary focus has been placed on curing/aging, washing with and without additives, organic matter, sampling techniques, utilization options, and assessment tools. This paper provides an overview of these projects. The main results and experiences are discussed and evaluated with respect to bottom ash upgrading and utilization. Based on this discussion, development needs and potential management strategies are identified.

General information
State: Published
Organisations: Department of Environmental Engineering
Authors: Astrup, T. (Intern)
Pages: 1452-1457
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Main Research Area: Technical/natural sciences

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Scopus rating (2016): CiteScore 4 SJR 1.354 SNIP 2.044
Web of Science (2016): Indexed yes
BFI (2015): BFI-level 2
Scopus rating (2015): SJR 1.739 SNIP 2.256 CiteScore 4.33
Web of Science (2015): Indexed yes
BFI (2014): BFI-level 2
Scopus rating (2014): SJR 1.777 SNIP 2.482 CiteScore 3.43
Web of Science (2014): Indexed yes
BFI (2013): BFI-level 1
Scopus rating (2013): SJR 1.822 SNIP 2.435 CiteScore 3.39
ISI indexed (2013): ISI indexed yes
Web of Science (2013): Indexed yes
BFI (2012): BFI-level 1
Scopus rating (2012): SJR 1.611 SNIP 2.184 CiteScore 2.91
ISI indexed (2012): ISI indexed yes
Web of Science (2012): Indexed yes
BFI (2011): BFI-level 1
Scopus rating (2011): SJR 1.698 SNIP 2.085 CiteScore 2.99
ISI indexed (2011): ISI indexed yes
Web of Science (2011): Indexed yes
BFI (2010): BFI-level 1
Scopus rating (2010): SJR 1.555 SNIP 1.78
Web of Science (2010): Indexed yes
BFI (2009): BFI-level 1
Scopus rating (2009): SJR 1.502 SNIP 1.899
Web of Science (2009): Indexed yes
BFI (2008): BFI-level 2
Scopus rating (2008): SJR 1.378 SNIP 2.13
Web of Science (2008): Indexed yes
Scopus rating (2007): SJR 1.035 SNIP 1.767
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Scopus rating (2006): SJR 1.046 SNIP 1.749
Web of Science (2006): Indexed yes
Scopus rating (2005): SJR 1.059 SNIP 1.65
Scopus rating (2004): SJR 1.289 SNIP 1.939
Web of Science (2004): Indexed yes
Scopus rating (2003): SJR 0.847 SNIP 1.269
Web of Science (2003): Indexed yes
Scopus rating (2002): SJR 0.561 SNIP 0.874
Scopus rating (2001): SJR 0.456 SNIP 0.696
Web of Science (2001): Indexed yes
Scopus rating (2000): SJR 0.271 SNIP 0.451
Scopus rating (1999): SJR 0.262 SNIP 0.479
Second generation methodology for chemical characterization of solid waste fractions

General information
State: Published
Organisations: Department of Environmental Engineering
Authors: Riber, C. (Intern), Astrup, T. (Intern), Christensen, T. H. (Intern)
Publication date: 2007

Host publication information
Title of host publication: Sardinia 2007 : Eleventh International Waste Management and Landfill Symposium, 1-5 October, Sardinia, Italy. Proceedings
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Publisher: CISA, Environmental Sanitary Engineering Centre
Main Research Area: Technical/natural sciences
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State-of-the-art and outlook on management of waste-to-energy bottom ashes: Part 1: Treatment

General information
State: Published
Organisations: Department of Environmental Engineering
Authors: Polettini, A. (Ekstern), Astrup, T. (Intern), Cappai, G. (Ekstern), Lechner, P. (Ekstern), Muntoni, A. (Ekstern), Pomi, R. (Ekstern), van Gerven, T. (Ekstern), van Zomeren, A. (Ekstern)
Publication date: 2007

Host publication information
Title of host publication: Sardinia 2007 : Eleventh International Waste Management and Landfill Symposium, 1-5 October, Sardinia, Italy. Proceedings
Volume: CD-ROM
Place of publication: Cagliari, Italy
Publisher: CISA, Environmental Sanitary Engineering Centre
Main Research Area: Technical/natural sciences
Source-ID: 205445
Publication: Research › Article in proceedings – Annual report year: 2007

State-of-the-art and outlook on management of waste-to-energy bottom ashes: Part 2: Utilization

General information
State: Published
Organisations: Department of Environmental Engineering
Authors: Astrup, T. (Intern), Cappai, G. (Ekstern), Lechner, P. (Ekstern), Muntoni, A. (Ekstern), Polettini, A. (Ekstern), Pomi, R. (Ekstern), van Gerven, T. (Ekstern), van Zomeren, A. (Ekstern)
Publication date: 2007

Host publication information
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Publisher: CISA, Environmental Sanitary Engineering Centre
Main Research Area: Technical/natural sciences
The phoenix network on waste-to-energy residues

General information
State: Published
Organisations: Department of Environmental Engineering
Authors: van Gerven, T. (Ekstern), Astrup, T. (Intern), Cappai, G. (Ekstern), Lechner, P. (Ekstern), Muntoni, A. (Ekstern), Polettini, A. (Ekstern), Pomi, R. (Ekstern), van Zomeren, A. (Ekstern)
Publication date: 2007

Host publication information
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Place of publication: Cagliari, Italy
Publisher: CISA, Environmental Sanitary Engineering Centre
Main Research Area: Technical/natural sciences
Source: orbit
Source-ID: 205428
Publication: Research › Article in proceedings – Annual report year: 2007

Assessment of long-term leaching from waste incineration air-pollution-control residues

Assessment of long-term leaching from MSWI air-pollution-control (APC) residues is discussed with respect to use in environmental impact assessment, such as life-cycle assessment (LCA). A method was proposed for estimating leaching as a function of the liquid-to-solid (L/S) ratio in a long-term perspective (L/S 5000l/kg). Data for changes in residue pH as a function of L/S was used in combination with pH dependent leaching data to predict leachate concentrations of Al, Ca, Cd, Ba, Mg, Ni, Pb, S, Pb, V and Zn as a function of L/S. Mass balance calculations were used to determine the element fractions leached with respect to L/S. The estimated long-term leaching from a semi-dry residue and a fly ash was compared with short-term leaching determined by batch tests at L/S 10l/kg, both carbonated and non-carbonated versions of the residues were investigated. Generally, very high L/S ratios above 2000l/kg were required to leach 20–30% of the solid contents. However, Ca and S were depleted at L/S 200–900l/kg. The long-term leachate concentrations were found to either remain at the same level as the initial leaching determined by the L/S 10 batch test, or to significantly decrease compared with the initial leaching. Only Al and Zn were found to show higher leachate concentrations at L/S ratios above 3000–5000l/kg. Carbonation generally prolonged the time needed for depletion from the solid residues; however, Ca and S were depleted faster than in the case of non-carbonated residues. This study shows that uncritical use of batch leaching data for assessing the potential leaching is highly problematic, and evaluations of residue disposal should include scenario specific quantification of the long-term leaching.

General information
State: Published
Organisations: Department of Environmental Engineering
Authors: Astrup, T. (Intern), Mosbæk, H. (Intern), Christensen, T. H. (Intern)
Pages: 803-814
Publication date: 2006
Main Research Area: Technical/natural sciences

Publication information
Journal: Waste Management
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BFI (2017): BFI-level 2
Web of Science (2017): Indexed yes
BFI (2016): BFI-level 2
Scopus rating (2016): CiteScore 4 SJR 1.354 SNIP 2.044
Web of Science (2016): Indexed yes
Assessment of long-term pH developments in leachate from waste incineration residues

Environmental assessment of residue disposal needs to account for long-term changes in leaching conditions. Leaching of heavy metals from incineration residues are highly affected by the leachate pH; the overall environmental consequences of disposing of these residues are therefore greatly influenced by changes in pH over time. The paper presents an approach for assessing pH changes in leachate from municipal solid waste incineration (MSWI) air-pollution-control (APC) residues. Residue samples were subjected to a stepwise batch extraction method in order to obtain residue samples at a range of pH Values (similar to common pH-dependence tests), and then on these samples to determine leaching of alkalinity as well as remaining solid phase alkalinity. On a range of APC residues covering various pretreatment and
disposal options, this procedure was used to determine leachable and residual alkalinity as a function of pH. Mass balance calculations for typical disposal scenarios were used to provide data on pH as a function of the liquid-to-solid (L/S) ratio in the leaching system. Regardless of residue type and pretreatment, pH was found to stay above 7 for L/S ratios up to about 2000 L kg(-1) corresponding to about 100,000 years in typical landfill scenarios. It was found that pH changes were mainly governed by alkalinity decreases from leaching processes rather than neutralization reactions. The results suggest that leaching testing for assessment purposes should be carried out in the alkaline range, for example, at pH 9. The paper offers a thorough basis for further modelling of incineration residue leaching and for modelling the environmental consequences of landfilling and utilization of these residues.

General information
State: Published
Organisations: Department of Environmental Engineering
Authors: Astrup, T. (Intern), Jakobsen, R. (Intern), Christensen, T. H. (Intern), Hansen, J. (Ekstern), Hjelmar, O. (Ekstern)
Pages: 491-502
Publication date: 2006
Main Research Area: Technical/natural sciences

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Journal: Waste Management and Research
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Ratings:
BFI (2018): BFI-level 1
BFI (2017): BFI-level 1
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BFI (2016): BFI-level 1
Scopus rating (2016): CiteScore 1.76 SJR 0.655 SNIP 1.036
BFI (2015): BFI-level 1
Scopus rating (2015): SJR 0.617 SNIP 0.899 CiteScore 1.53
Web of Science (2015): Indexed yes
BFI (2014): BFI-level 1
Scopus rating (2014): SJR 0.741 SNIP 1.085 CiteScore 1.28
Web of Science (2014): Indexed yes
BFI (2013): BFI-level 1
Scopus rating (2013): SJR 0.588 SNIP 0.951 CiteScore 1.17
ISI indexed (2013): ISI indexed yes
Web of Science (2013): Indexed yes
BFI (2012): BFI-level 1
Scopus rating (2012): SJR 0.886 SNIP 1.046 CiteScore 1.4
ISI indexed (2012): ISI indexed yes
Web of Science (2012): Indexed yes
BFI (2011): BFI-level 1
Scopus rating (2011): SJR 1.027 SNIP 0.865 CiteScore 1.33
ISI indexed (2011): ISI indexed yes
Web of Science (2011): Indexed yes
BFI (2010): BFI-level 1
Scopus rating (2010): SJR 0.666 SNIP 0.975
Web of Science (2010): Indexed yes
BFI (2009): BFI-level 1
Scopus rating (2009): SJR 0.877 SNIP 1.257
Web of Science (2009): Indexed yes
BFI (2008): BFI-level 1
Scopus rating (2008): SJR 0.49 SNIP 0.933
Web of Science (2008): Indexed yes
Scopus rating (2007): SJR 0.352 SNIP 0.666
Web of Science (2007): Indexed yes
Scopus rating (2006): SJR 0.295 SNIP 0.755
Geochemical modeling of leaching from MSVI air-pollution-control residues

This paper provides an improved understanding of the leaching behavior of waste incineration air-pollution-control (APC) residues in a long-term perspective. Leaching was investigated by a series of batch experiments reflecting leaching conditions after initial washout of highly soluble salts from residues. Leaching experiments were performed at a range of pH-values using carbonated and noncarbonated versions of two APC residues. The leaching data were evaluated by geochemical speciation modeling and discussed with respect to possible solubility control. The leaching of major elements as well as trace elements was generally found to be strongly dependent on pH. As leaching characterization was performed in the absence of high salt levels, the presented results represent long-term leaching after initial washout from a disposal site, that is, liquid-to-solid ratios above 1-2 L/kg. The leaching of Al, Ba, Ca, Cr, Pb, S, Si, V, and Zn was found influenced by solubility control from Al₂O₃, Al(OH)₃, Ba(S,Cr)O₄ solid solutions, BaSO₄, Ca₆Al₂(SO₄)₃(OH)₁₂·₂₆H₂O, CaAl₂Si₄O₁₀·₁₂H₂O, Ca·(OH)₂, CaSiO₃, CaSO₄·H₂O, CaZn₂(OH)₆·₂H₂O, KAlSi₂O₆, PbCO₃, PbCrO₄, Pb₂O₃, Pb₂V₂O₇, Pb₃(VO₄)₂, ZnO, Zn₂SiO₄, and ZnSiO₃. The presented dataset and modeling results form a thorough contribution to the assessment of long-term leaching behavior of APC residues under a wide range of conditions.

General information

State: Published
Organisations: Residual Resource Engineering, Department of Environmental Engineering, Wageningen IMARES
Authors: Astrup, T. (Intern), Dijkstra, J. (Ekstern), Comans, R. (Ekstern), van der Sloot, H. (Ekstern), Christensen, T. H. (Intern)
Pages: 3551-3557
Publication date: 2006
Main Research Area: Technical/natural sciences

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Web of Science (2005): Indexed yes
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Web of Science (2001): Indexed yes
Web of Science (2000): Indexed yes
Original language: English
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Removal of readily soluble compounds prior to pH-static leaching experiments: effect of leaching predictions

General information
State: Published
Organisations: Department of Environmental Engineering
Authors: Hyks, J. (Intern), Astrup, T. (Intern), Christensen, T. H. (Intern)
Pages: 199-204
Publication date: 2006

Host publication information
Place of publication: Utrecht, NL
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Editors: Ilic, M., Goumans, J., Miletic, S., Heynen, J., Senden, G.
Main Research Area: Technical/natural sciences
Source: orbit
Source-ID: 193350
Publication: Research › Article in proceedings – Annual report year: 2006

Treatment and utilization of MSWI bottom ashes in Denmark

General information
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Organisations: Department of Environmental Engineering
Authors: Astrup, T. (Intern)
Pages: 37-47
Publication date: 2006

Host publication information
Place of publication: Utrecht, NL
Publisher: ISCOWA
Editors: Ilic, M., Goumans, J., Miletic, S., Heynen, J., Senden, G.
Main Research Area: Technical/natural sciences
Conference: WASCON 2006, 01/01/2006
Source: orbit
Source-ID: 190618
Publication: Research › Article in proceedings – Annual report year: 2006

Treatment and utilization of MSWI fly ashes: trends and outlook

General information
State: Published
Organisations: Department of Environmental Engineering
Authors: Astrup, T. (Intern)
Pages: 49-55
Publication date: 2006

Host publication information
Place of publication: Utrecht, NL
Publisher: ISCOWA
Editors: Ilic, M., Goumans, J., Miletic, S., Heynen, J., Senden, G.
Chromium release from waste incineration air-pollution-control residues

General information
State: Published
Organisations: Department of Environmental Engineering
Authors: Astrup, T. (Intern), Rosenblad, C. (Ekstern), Trapp, S. (Intern), Christensen, T. H. (Intern)
Pages: 3321-3329
Publication date: 2005
Main Research Area: Technical/natural sciences

Publication information
Journal: Environmental Science and Technology
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Ratings:
ISI indexed (2013): ISI indexed no
ISI indexed (2012): ISI indexed no
ISI indexed (2011): ISI indexed no
Web of Science (2005): Indexed yes
Web of Science (2004): Indexed yes
Web of Science (2001): Indexed yes
Web of Science (2000): Indexed yes
Original language: English
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Source: orbit
Source-ID: 181489
Publication: Research - peer-review › Journal article – Annual report year: 2005

Predicting Cr leaching from MSWI residues

General information
State: Published
Organisations: Department of Environmental Engineering
Authors: Astrup, T. (Intern), Hyks, J. (Ekstern), Christensen, T. H. (Intern)
Publication date: 2005

Host publication information
Title of host publication: Sardinia 2005 : Tenth International Waste Management and Landfill Symposium, 3-7 October, Sardinia, Italy
Volume: Proceedings. CD-ROM
Place of publication: Cagliari, Italy
Publisher: CISA, Environmental Sanitary Engineering Centre
Editors: Cossu, R., Stegmann, R.
Main Research Area: Technical/natural sciences
Conference: 10th International Waste Management and Landfill Symposium, Sardinia, Italy, 03/10/2005 - 03/10/2005
Source: orbit
Source-ID: 183533
Publication: Research › Article in proceedings – Annual report year: 2005

Waste incineration bottom ashes in Denmark: Status and development needs by 2003

General information
State: Published
Organisations: Department of Environmental Engineering
Authors: Astrup, T. (Intern), Christensen, T. H. (Intern)
Characterization of leaching from waste incineration air-pollution-control residues

General information
State: Published
Organisations: Department of Environmental Engineering, Residual Resource Engineering
Authors: Astrup, T. F. (Intern), Christensen, T. H. (Intern)
Number of pages: 50
Publication date: 2004

Genanvendelse af forbrændingsslagger

General information
State: Published
Organisations: Department of Environmental Engineering
Authors: Astrup, T. (Intern), Christensen, T. H. (Intern)
Pages: 50-52
Publication date: 2004
Main Research Area: Technical/natural sciences

Towards an improved understanding of the leaching behavior of MSWI residues - Report on the 2nd meeting of the IWWG pHOENIX working group on "Management of Municipal Solid Waste Incineration Residues"

General information
State: Published
Organisations: Department of Environmental Science and Engineering
Authors: Astrup, T. (Intern), Cappai, G. (Ekstern), Hjelmar, O. (Ekstern), Kihl, A. (Ekstern), Lechner, P. (Ekstern), Mostbauer, P. (Ekstern), Nyholm, M. (Ekstern), Polettini, A. (Ekstern), Pomi, R. (Ekstern), van der Sloot, H. (Ekstern), van Zomeren, A. (Ekstern)
Pages: 529-530
Publication date: 2004
Main Research Area: Technical/natural sciences
Assessment of long-term leaching of Pb, Cd and Cr from air-pollution-control residues

General information
State: Published
Organisations: Department of Environmental Engineering
Authors: Astrup, T. (Intern), Christensen, T. H. (Intern)
Pages: 263-270
Publication date: 2003

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Title of host publication: WASCON 2003: Fifth International Conference on the Environmental and Technical Implications of Construction with Alternative Materials
Place of publication: San Sebastian
Publisher: Inasmet
Editors: Ortiz de Urbina, G., Goumans, J. J. M.
Main Research Area: Technical/natural sciences
Conference: International Conference on the Environmental and Technical Implications of Construction with Alternative Materials, San Sebastian, June 4-6, 01/01/2003
Source: orbit
Source-ID: 135687
Publication: Research › Article in proceedings – Annual report year: 2003

Estimating long-term leaching of heavy metals from MSWI APC residues

General information
State: Published
Organisations: Department of Environmental Engineering
Authors: Astrup, T. (Intern), Christensen, T. H. (Intern)
Publication date: 2003

Host publication information
Title of host publication: Sardinia 2003: Ninth International Waste Management and Landfill Symposium, 6-10 October, Sardinia, Italy. Proceedings
Volume: CD-ROM
Place of publication: Cagliari, Italy
Publisher: CISA, Environmental Sanitary Engineering Centre
Editors: Christensen, T. H., Cossu, R., Stegmann, R.
Main Research Area: Technical/natural sciences
Conference: 9th International Waste Management and Landfill Symposium, Sardinia, Italy, 06/10/2003 - 06/10/2003
Source: orbit
Source-ID: 135688
Publication: Research › Article in proceedings – Annual report year: 2003

Factors affecting chromium leaching from waste incineration residues

General information
State: Published
Organisations: Department of Environmental Engineering
Authors: Chen, D. (Ekstern), Astrup, T. (Intern), Rosenblad, C. (Ekstern), Christensen, T. H. (Intern)
Publication date: 2003

Host publication information
Title of host publication: Sardinia 2003: Ninth International Waste Management and Landfill Symposium, 6-10 October, Sardinia, Italy. Proceedings
Volume: CD-ROM
Place of publication: Cagliari, Italy
Publisher: CISA, Environmental Sanitary Engineering Centre
Editors: Christensen, T. H., Cossu, R., Stegmann, R.
Main Research Area: Technical/natural sciences
Management of APC residues from WTE plants. An overview of important management options

**General information**
State: Published
Organisations: Department of Environmental Engineering
Authors: Ørnebjerg, H. (Ekstern), Birch, H. (Ekstern), Reimann, D. (Ekstern), Bader, C. (Ekstern), Astrup, T. (Intern), Crillesen, K. (Ekstern), Marklund, S. (Ekstern), Bánhidy, J. (Ekstern)
Publication date: 2003

**Publication information**
Place of publication: Copenhagen
Publisher: ISWA General Secretariat
Original language: English
Main Research Area: Technical/natural sciences
Source: orbit
Source-ID: 44038
Publication: Research › Report – Annual report year: 2003

Management of municipal solid waste incineration residues

**General information**
State: Published
Organisations: Department of Environmental Engineering
Authors: Sabbas, T. (Ekstern), Polettini, A. (Ekstern), Pomi, R. (Ekstern), Astrup, T. (Intern), Hjelmar, O. (Ekstern), Mostbauer, P. (Ekstern), Cappai, G. (Ekstern), Magel, G. (Ekstern), Salhofer, S. (Ekstern), Speiser, C. (Ekstern), Heuss-Assbichler, S. (Ekstern), Klein, R. (Ekstern), Lechner, P. (Ekstern)
Pages: 61-88
Publication date: 2003
Main Research Area: Technical/natural sciences

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Web of Science (2017): Indexed yes
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Scopus rating (2016): CiteScore 4 SJR 1.354 SNIP 2.044
Web of Science (2016): Indexed yes
BFI (2015): BFI-level 2
Scopus rating (2015): SJR 1.739 SNIP 2.256 CiteScore 4.33
Web of Science (2015): Indexed yes
BFI (2014): BFI-level 2
Scopus rating (2014): SJR 1.777 SNIP 2.482 CiteScore 3.43
Web of Science (2014): Indexed yes
BFI (2013): BFI-level 1
Scopus rating (2013): SJR 1.822 SNIP 2.435 CiteScore 3.39
ISI indexed (2013): ISI indexed yes
Web of Science (2013): Indexed yes
BFI (2012): BFI-level 1
Scopus rating (2012): SJR 1.611 SNIP 2.184 CiteScore 2.91
ISI indexed (2012): ISI indexed yes
Web of Science (2012): Indexed yes
Redox properties of Cr under alkaline conditions and their effect on Cr leaching control from waste incineration ashes

General information
State: Published
Organisations: Department of Environmental Engineering
Authors: Chen, D. (Ekstern), Astrup, T. (Intern), Christensen, T. H. (Intern)
Pages: 57-64
Publication date: 2003

Host publication information
Title of host publication: WASCON 2003 : Fifth International Conference on the Environmental and Technical Implications of Construction with Alternative Materials, June 4-6, 2003, San Sebastian
Place of publication: San Sebastian, Spain
Publisher: Inasmet
Editors: Ortiz de Urbina, G., Goumans, J. J. M.
Main Research Area: Technical/natural sciences
Conference: WASCON : International Conference on the Environmental and Technical Implications of Construction with Alternative Materials, San Sebastian, Spain, June 4-6, 01/01/2003
Source: orbit
Source-ID: 135700
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Slagge fra affaldsforbrænding. Status og udviklingsmuligheder 2003

General information
State: Published
Landfilling of waste incineration residues: Towards new approaches

Residues from waste incineration are bottom ashes and air-pollution-control (APC) residues including fly ashes. The leaching of heavy metals and salts from the ashes is substantial and a wide spectrum of leaching tests and corresponding criteria have been introduced to regulate the landfilling of the ashes. Leaching test, however, must be selected carefully to provide information relevant for the actual disposal scenario and for evaluating the benefits of pre-treating the residues prior to landfilling. This paper describes research at the Technical University of Denmark addressing some of these issues focusing on pH-development in landfilled residues, effects of leaching test conditions on Cr leaching and effects of pre-treatment with FeSO4.

Long-term development in APC ash landfills with respect to pH

General information
State: Published
Organisations: Department of Environmental Engineering
Authors: Astrup, T. (Intern), Hansen, J. (Ekstern), Hjelmar, O. (Ekstern), Christensen, T. H. (Intern)
Pages: 453-459
Publication date: 2001

Host publication information
Title of host publication: Sardinia 2001: The Sustainable Landfill
Volume: Vol. 1
Place of publication: Cagliari, Italy
Publisher: CISA, Environmental Sanitary Engineering Centre
Editors: Christensen, T. H., Cossu, R., Stegmann, R.
Main Research Area: Technical/natural sciences
Conference: 6th International Waste Management and Landfill Symposium, Sardinia, Italy, 01/10/2001 - 01/10/2001
Source: orbit
Source-ID: 135808
Publication: Research › Article in proceedings – Annual report year: 2001
Copper and zinc distribution coefficients for sandy aquifer materials

Distribution coefficients (K_d) were measured for copper (Cu) and zinc (Zn) in laboratory batch experiments for 17 sandy aquifer materials at environmentally relevant solute concentrations (Cu: 5±300 mg/l, Zn: 20±3100 mg/l). The K_d values ranged two to three orders of magnitude (Cu: 70±10,800 l/kg; Zn: 6±22,800 l/kg) and correlating them to the characteristics of the aquifer material (particle size distribution, organic C content, surface area, pH) revealed good correlation with pH in the range 5.3± 8.9 (Cu: r^2=0.72; Zn: r^2=0.94). Including any other of the measured aquifer characteristics improved the correlation only a few percent. The results indicate that the mobility of Cu and Zn in sandy aquifers, as reflected in the measured K_d values, is very restricted at pH values above 6, since the relative migration velocity is less than 1%. However, at lower pH values, Zn seems to become mobile in sandy aquifers. # 2000 Elsevier Science Ltd. All rights reserved

General information
State: Published
Organisations: Department of Environmental Science and Engineering
Authors: Christensen, T. H. (Intern), Astrup, T. (Intern), Boddum, J. K. (Ekstern), Hansen, B. Ø. (Ekstern), Redemann, S. (Ekstern)
Pages: 709-712
Publication date: 2000
Main Research Area: Technical/natural sciences

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Journal: Water Research
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Issue number: 3
ISSN (Print): 0043-1354
Ratings:
BFI (2018): BFI-level 2
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Web of Science (2017): Indexed yes
BFI (2016): BFI-level 2
Scopus rating (2016): CiteScore 7.49 SJR 2.629 SNIP 2.558
Web of Science (2016): Indexed yes
BFI (2015): BFI-level 2
Scopus rating (2015): SJR 2.689 SNIP 2.507 CiteScore 6.63
Web of Science (2015): Indexed yes
BFI (2014): BFI-level 2
Scopus rating (2014): SJR 2.957 SNIP 2.727 CiteScore 6.13
Web of Science (2014): Indexed yes
BFI (2013): BFI-level 2
Scopus rating (2013): SJR 2.956 SNIP 2.693 CiteScore 6.02
ISI indexed (2013): ISI indexed yes
Web of Science (2013): Indexed yes
BFI (2012): BFI-level 2
Scopus rating (2012): SJR 2.966 SNIP 2.456 CiteScore 5.15
ISI indexed (2012): ISI indexed yes
Web of Science (2012): Indexed yes
BFI (2011): BFI-level 2
Scopus rating (2011): SJR 2.867 SNIP 2.374 CiteScore 5.43
ISI indexed (2011): ISI indexed yes
Web of Science (2011): Indexed yes
BFI (2010): BFI-level 2
Scopus rating (2010): SJR 2.582 SNIP 2.196
Web of Science (2010): Indexed yes
BFI (2009): BFI-level 2
Scopus rating (2009): SJR 2.319 SNIP 2.225
Web of Science (2009): Indexed yes
BFI (2008): BFI-level 2
Immobilization of chromate from coal fly ash leachate using an attenuating barrier containing zero-valent iron

The purpose of this investigation was (i) to test the effectiveness of a barrier engineered to remove Cr(VI) from leachates of higher pH and salinity typical of coal burning ashes and (ii) to determine which geochemical processes control Cr immobilization. Laboratory column and batch desorption experiments show that a barrier composed of sand, Fe(0), and bentonite irreversibly immobilizes Cr. Concentrations fall from 25 mg Cr L⁻¹ in the leachate to below detection limits (0.0025 mg Cr L⁻¹) and solution pH increases by about two units. Solid-phase analytical techniques such as SEM, EDS, XPS, and TOFSIMS were used to characterize the barrier material prior to and after exposure to the Cr leachate. In the barrier material, Cr(III) was found associated with Fe(III)-oxides, as separate Cr oxides and as a Ca,Cr phase, probably Cachromite, CaCr₂O₄. The attenuating barrier can be an alternative to traditional liners and leachate collection systems at coal ash storage and disposal sites.

General information
State: Published
Organisations: Department of Environmental Science and Engineering
Authors: Astrup, T. (Intern), Stipp, S. L. S. (Ekstern), Christensen, T. H. (Intern)
Pages: 4163-4168
Publication date: 2000
Main Research Area: Technical/natural sciences

Publication information
Journal: Environmental Science and Technology
Volume: 34
ISSN (Print): 1382-3124
Ratings:
ISI indexed (2013): ISI indexed no
ISI indexed (2012): ISI indexed no
ISI indexed (2011): ISI indexed no
Web of Science (2005): Indexed yes
Web of Science (2004): Indexed yes
Web of Science (2001): Indexed yes
Web of Science (2000): Indexed yes
Engineered attenuation liners for landfills of coal combustion residues

General information
State: Published
Organisations: Department of Environmental Science and Engineering
Authors: Astrup, T. (Intern), Stipp, S. (Ekstern), Christensen, T. (Intern)
Publication date: 1999

Host publication information
Title of host publication: Sardinia 99 (eds.: Christensen, T.H., Cossu, R., Stegmann, R.)
Place of publication: Cagliari, Italy
Publisher: CISA, Environmental Sanitary Engineering Centre
Main Research Area: Technical/natural sciences

Lead distribution and mobility in a soil embankment used as a lead bullet stop at a shooting range

General information
State: Published
Organisations: Department of Environmental Science and Engineering
Authors: Astrup, T. (Intern), Boddum, J. (Intern), Christensen, T. (Intern)
Pages: 653 - 665
Publication date: 1999
Main Research Area: Technical/natural sciences

Publication information
Journal: Journal of Soil Contamination
Volume: 8
Original language: English
Source: orbit
Source-ID: 172712
Publication: Research - peer-review › Journal article – Annual report year: 1999

Intro duktion til affaldsteknologi. Kapitel 1.1

General information
State: Published
Organisations: Department of Environmental Science and Engineering
Authors: Christensen, T. H. (Intern), Astrup, T. (Intern)
Publication date: 1998

Host publication information
Title of host publication: Affaldsteknologi
Place of publication: København
Publisher: Nyt Teknisk Forlag
Editor: Christensen, T. H.
Main Research Area: Technical/natural sciences
Source: orbit
Source-ID: 171534
Publication: Education › Book chapter – Annual report year: 1998
Restprodukter fra energiproduktion. Kapitel 7.9

General information
State: Published
Organisations: Department of Environmental Science and Engineering
Authors: Astrup, T. (Intern)
Pages: 749-765
Publication date: 1998

Host publication information
Title of host publication: Affaldsteknologi
Place of publication: København
Publisher: Nyt Teknisk Forlag
Editor: Christensen, T. H.
Main Research Area: Technical/natural sciences
Source: orbit
Source-ID: 171531
Publication: Education › Book chapter – Annual report year: 1998

Distributionskoefficienter for tungmetaller i sandede grundvandsmagasiner

General information
State: Published
Organisations: Department of Environmental Science and Engineering
Authors: Christensen, T. (Intern), Redemann, S. (Ekstern), Boddum, J. (Intern), Astrup, T. (Intern), Hansen, B. (Ekstern), Holm, P. (Intern), Christensen, J. (Intern)
Publication date: 1997

Host publication information
Title of host publication: Distributionskoefficienter for tungmetaller i sandede grundvandsmagasiner
Place of publication: Lyngby
Publisher: Akademiet for de Tekniske Videnskaber, ATV
Main Research Area: Technical/natural sciences
Conference: Tungmetalforurenede grunde, ATV møde 30. september, Schæffergården, 01/01/1997
Source: orbit
Source-ID: 169728
Publication: Research › Article in proceedings – Annual report year: 1997

Projects:

Sustainability Assessment of Residual Biomass Resource Management
Department of Environmental Engineering
Period: 01/12/2017 → 30/11/2020
Number of participants: 3
Phd Student:
Albizzati, Paola Federica (Intern)
Supervisor:
Tonini, Davide (Intern)
Main Supervisor:
Astrup, Thomas Fruergaard (Intern)

Financing sources
Source: Internal funding (public)
Name of research programme: Institut stipendie (DTU)
Project: PhD

Circular Economy: Integrated sustainability assessment of resource recovery and cycling
Department of Environmental Engineering
Period: 01/12/2016 → 10/04/2020
Number of participants: 3
Phd Student:
Andresi Bassi, Susanna (Intern)
Supervisor:
Boldrin, Alessio (Intern)
Main Supervisor:
Astrup, Thomas Fruegaard (Intern)

Financing sources
Source: Internal funding (public)
Name of research programme: Anden EU-finansiering
Project: PhD

Circular Economy: Life cycle assessment of chemicals in material cycles
Department of Environmental Engineering
Period: 01/12/2016 → 30/11/2019
Number of participants: 3
Phd Student:
Xanthopoulou, Larisa (Intern)
Supervisor:
Baun, Anders (Intern)
Main Supervisor:
Astrup, Thomas Fruegaard (Intern)

Financing sources
Source: Internal funding (public)
Name of research programme: Institut stipendie (DTU)
Project: PhD

Life cycle assessment modelling of advanced (bio)energy technologies
Department of Environmental Engineering
Period: 01/12/2016 → 30/11/2019
Number of participants: 3
Phd Student:
Lodato, Concetta (Intern)
Supervisor:
Tonini, Davide (Intern)
Main Supervisor:
Astrup, Thomas Fruegaard (Intern)

Financing sources
Source: Internal funding (public)
Name of research programme: Institut stipendie (DTU)
Project: PhD

Characterization and recycling of waste fractions from recycling centers
Department of Environmental Engineering
Period: 15/10/2015 → 14/10/2018
Number of participants: 4
Phd Student:
Faraca, Giorgia (Intern)
Supervisor:
Boldrin, Alessio (Intern)
Damgaard, Anders (Intern)
Main Supervisor:
Astrup, Thomas Fruegaard (Intern)

Financing sources
Source: Internal funding (public)
Name of research programme: Offentlig finansiering
Project: PhD
Characterization of recyclable materials in household waste

Department of Environmental Engineering
Period: 01/09/2015 → 08/01/2019
Number of participants: 4
Phd Student:
Eriksen, Marie Kampmann (Intern)
Supervisor:
Boldrin, Alessio (Intern)
Damgaard, Anders (Intern)
Main Supervisor:
Astrup, Thomas Fruergaard (Intern)

Financing sources
Source: Internal funding (public)
Name of research programme: Offentlig finansiering
Project: PhD

Data quality in LCA of waste management: importance for result interpretation and result decision making

Department of Environmental Engineering
Period: 01/04/2015 → 31/07/2018
Number of participants: 3
Phd Student:
Henriksen, Trine (Intern)
Supervisor:
Astrup, Thomas Fruergaard (Intern)
Main Supervisor:
Damgaard, Anders (Intern)

Financing sources
Source: Internal funding (public)
Name of research programme: Samfinansierede - Virksomhed
Project: PhD

Risikovurdering og kildeidentificering af stoffer i digestat fra REnescience

Department of Environmental Engineering
Residual Resource Engineering
Environmental Chemistry
DONG Energy A/S
Period: 01/03/2014 → 31/12/2014
Number of participants: 3
Acronym: REnescience
Project participant:
Eriksen, Eva (Intern)
Pivnenko, Kostyantyn (Intern)
Project Coordinator:
Astrup, Thomas Fruergaard (Intern)

Characterization and Management of Nanowaste

Department of Environmental Engineering
Period: 15/01/2014 → 30/09/2017
Number of participants: 7
Phd Student:
Hegelund, Laura Roverskov (Intern)
Characterization of Biomass Combustion Ashes

Department of Environmental Engineering
Period: 01/09/2013 → 02/09/2017
Number of participants: 5
Phd Student:
Maresca, Alberto (Intern)
Main Supervisor:
Astrup, Thomas Fruergaard (Intern)
Examiner:
Kjeldsen, Peter (Intern)
Polettini, Alessandra (Ekstern)
Steenari, Britt-Marie (Ekstern)

Financing sources
Source: Internal funding (public)
Name of research programme: Samfinansieret - Andet

Relations
Publications:
Characterisation of wood combustion ashes
Project: PhD

Low Temperature Thermal Gasification of High-Alkali Bio Residues and Sludge

Department of Chemical and Biochemical Engineering
Period: 01/09/2013 → 26/04/2017
Number of participants: 8
Phd Student:
Thomsen, Tobias Pape (Intern)
Supervisor:
Hauggaard-Nielsen, Henrik (Intern)
Henriksen, Ulrik Birk (Intern)
Holm, Jens Kai (Intern)
Main Supervisor:
Ahrenfeldt, Jesper (Intern)
Examiner:
Astrup, Thomas Fruergaard (Intern)
Hindsgaul, Claus (Intern)
Skoglund, Nils (Ekstern)
**Future Scenario Analysis in Solid Waste Management**

Department of Environmental Engineering  
Period: 01/07/2013 → 05/12/2017  
Number of participants: 6  
Phd Student:  
Bisinella, Valentina (Intern)  
Supervisor:  
Christensen, Thomas Højlund (Intern)  
Main Supervisor:  
Astrup, Thomas Fruergaard (Intern)  
Examiner:  
Boldrin, Alessio (Intern)  
Brandão, Miguel M. R. (Ekstern)  
Guyonnet, Dominique (Ekstern)

**Financing sources**  
Source: Internal funding (public)  
Name of research programme: Institut stipendie (DTU) Samf.

**Relations**  
Publications:  
Future scenario development within life cycle assessment of waste management systems  
Project: PhD

**Resource quality indicators: Concept and methodology development**

Department of Environmental Engineering  
Period: 01/12/2012 → 31/05/2014  
Number of participants: 2  
Phd Student:  
Rørbech, Jakob Thaysen (Intern)  
Main Supervisor:  
Astrup, Thomas Fruergaard (Intern)

**Financing sources**  
Source: Internal funding (public)  
Name of research programme: Institut stipendie (DTU) Samf.

**Relations**  
Publications:  
Composition of waste materials and recyclables  
Project: PhD

**Composition of waste materials and recyclables**

Department of Environmental Engineering  
Period: 01/10/2012 → 21/04/2016  
Number of participants: 7  
Phd Student:  
Götze, Ramona (Intern)  
Supervisor:  
Boldrin, Alessio (Intern)  
Scheutz, Charlotte (Intern)  
Main Supervisor:  
Astrup, Thomas Fruergaard (Intern)
Assessment of resource quality in waste management
Department of Environmental Engineering
Period: 01/09/2012 → 15/10/2013
Number of participants: 4
Phd Student: Vyzinkarova, Dana (Intern)
Supervisor: Hellweg, Stefanie (Ekstern)
Rechberger, Helmut (Ekstern)
Main Supervisor: Astrup, Thomas Fruergaard (Intern)

Financing sources
Source: Internal funding (public)
Name of research programme: Institut stipendie (DTU) Samf.
Project: PhD

Composition of municipal solid waste in Denmark
Department of Environmental Engineering
Period: 01/09/2012 → 01/09/2016
Number of participants: 6
Phd Student: Edjabou, Maklawe Essonanawe (Intern)
Supervisor: Scheutz, Charlotte (Intern)
Main Supervisor: Astrup, Thomas Fruergaard (Intern)
Examiner: Kjeldsen, Peter (Intern)
Fischer, Christian (Ekstern)
Salhofer, Stefan (Ekstern)

Financing sources
Source: Internal funding (public)
Name of research programme: Institut stipendie (DTU) Samf.
Project: PhD

Quantification and critical analysis of resource flows in Denmark
Department of Environmental Engineering
Period: 01/09/2012 → 29/09/2016
Number of participants: 6
Phd Student: Klinglmair, Manfred (Intern)
Supervisor: Astrup, Thomas Fruergaard (Intern)
Main Supervisor: Scheutz, Charlotte (Intern)
Examiner:
Ibrom, Andreas (Intern)
Binder, Claudia R. (Ekstern)
Kirkeby, Janus Søgaard (Intern)

Financing sources
Source: Internal funding (public)
Name of research programme: Institut stipendie (DTU) Samf.

Relations
Publications:
Anthropogenic phosphorus flows in Denmark
Project: PhD

Waste material recycling: Assessment of contaminants limiting recycling
Department of Environmental Engineering
Period: 15/08/2012 → 01/09/2016
Number of participants: 6
Phd Student:
Pivnenko, Kostyantyn (Intern)
Supervisor:
Eriksson, Eva (Intern)
Main Supervisor:
Astrup, Thomas Fruergaard (Intern)
Examiner:
Hansen, Steffen Foss (Intern)
Dornack, Christina (Ekstern)
Riber, Christian (Intern)

Financing sources
Source: Internal funding (public)
Name of research programme: 1/3 DTU-stip, 2/3 FUR/andet
Project: PhD

Integrated environmental and economical assessment of waste management systems
Department of Environmental Engineering
Period: 15/12/2011 → 22/03/2016
Number of participants: 5
Phd Student:
Martinez Sanchez, Veronica (Intern)
Main Supervisor:
Astrup, Thomas Fruergaard (Intern)
Examiner:
Rygaard, Martin (Intern)
Eriksson, Ola Norman (Ekstern)
Herczeg, Márton (Ekstern)

Financing sources
Source: Internal funding (public)
Name of research programme: Institut stipendie (DTU)
Project: PhD

Life cycle impact assessment of long-term emissions from landfills
Department of Management Engineering
Period: 15/12/2011 → 22/06/2015
Number of participants: 7
Phd Student:
Bakas, Ioannis (Intern)
Supervisor:
Astrup, Thomas Fruergaard (Intern)
Rosenbaum, Ralph K. (Intern)
Main Supervisor:
Hauschild, Michael Zwicky (Intern)
Examiner:
Olsen, Stig Irving (Intern)
Finnveden, Göran (Ekstern)
Henderson, Andrew D. (Ekstern)

Financing sources
Source: Internal funding (public)
Name of research programme: Institut stipendie (DTU) Samf.
Project: PhD

Resource Recovery from Waste Incineration Bottom Ashes

Department of Environmental Engineering
Period: 01/09/2011 → 19/12/2014
Number of participants: 6
Phd Student:
Allegrini, Elisa (Intern)
Supervisor:
Boldrin, Alessio (Intern)
Main Supervisor:
Astrup, Thomas Fruergaard (Intern)
Examiner:
Kjeldsen, Peter (Intern)
Grosso, Mario (Ekstern)
Hjelmar, Ole (Ekstern)

Financing sources
Source: Internal funding (public)
Name of research programme: Eksternt finansieret virksomhed
Project: PhD

AFATEK
Det er samarbejdsaftalens formål at udarbejde en miljøvurdering af nye teknikker til sortering af slagger hos AFATEK.

Forskningen ligger inden for følgende fagområde: Livscyklusvurdering af sortering af slagger fra affaldsforbrændingsanlæggen under AFATEK baseret på nye sorteringsteknikker: 1 project management 2 recovery of metals 3 recovery of minerals 4 product development and applications 5 environment and economy

Department of Environmental Engineering
Period: 17/05/2011 → 31/12/2014
Number of participants: 1
Acronym: AFATEK
Project ID: 30875
Project Manager, organisational:
Astrup, Thomas Fruergaard (Intern)

Financing sources
Source: Sam.arb.aftaler, Private danske - Andre virksomheder
Name of research programme: Ukendt
Amount: 1,570,000.00 Danish Kroner
Project

Life cycle assessment of energy technologies and energy systems

Department of Environmental Engineering
Period: 01/09/2010 → 04/06/2014
Number of participants: 5
Phd Student:
Turconi, Roberto (Intern)
Main Supervisor:  
Astrup, Thomas Fruergaard (Intern)
Examiner:  
Scheutz, Charlotte (Intern)
Olsen, Stig Irving (Intern)
Powers, Susan E. (Ekstern)

Financing sources
Source: Internal funding (public)
Name of research programme: Institut stipendie (DTU) Samf.
Project: PhD

Resource and environmental assessment of recycling of construction and demolition waste (C&D waste)
Department of Environmental Engineering
Period: 01/09/2010 → 01/04/2015
Number of participants: 6
PhD Student:  
Butera, Stefania (Intern)
Supervisor:  
Christensen, Thomas Højlund (Intern)
Main Supervisor:  
Astrup, Thomas Fruergaard (Intern)
Examiner:  
Kjeldsen, Peter (Intern)
Birgisdottir, Harpa (Intern)
Polettini, Alessandra (Ekstern)

Financing sources
Source: Internal funding (public)
Name of research programme: Institut stipendie (DTU) Samf.
Project: PhD

Innovation network for environmental Technology (Innovationsnetværk på miljøteknologi)
Innovationsnetværket for Miljøteknologi skal være det oplagte forum for netværkets medlemmer og cleantech-branchen, når den tager initiativ til at igangsætte teknologi- og udviklingsprojekter der kræver supplerende, tværgående kompetencer og nye samarbejdsparter, uanset om medlemmernes forretningsområde og kernekompetencer primært er på luft-, vand-, jord- eller affaldsområdet.

Department of Environmental Engineering
Period: 01/07/2010 → 01/07/2014
Number of participants: 7
Acronym: 1113
Project ID: 30856
Project participant:  
Baun, Anders (Intern)
Albrechtsen, Hans-Jørgen (Intern)
Henze, Mogens (Intern)
Bjerg, Poul Løgstrup (Intern)
Astrup, Thomas Fruergaard (Intern)
Ambjerg-Nielsen, Karsten (Intern)
Project Manager, organisational:  
Andersen, Henrik Rasmus (Intern)

Financing sources
Source: Forskningsrådene - Andre
Name of research programme: Ukendt
Amount: 180,000.00 Danish Kroner
Project
CO2 opgørelse i affaldssektoren
Affaldssektoren har behov for at opgøre CO2 regnskaber for anlæg, processer, systemer, firmaer osv. Der er behov for at:
Udvikle et fælles transparent system for opgørelse af CO2 regnskaber og synliggørelse af sektorens CO2 bidrag. Udvikle fælles data for hvorledes gevinster, der rettelig falder i andre sektorer, kan opgøres og vises i sammenhæng med affaldssektorens egne CO2 bidrag.

Department of Environmental Engineering
Period: 01/06/2010 → 30/11/2010
Number of participants: 2
Acronym: CO2 opgørelse
Project ID: 30772
Project participant:
Astrup, Thomas Fruergaard (Intern)
Project Manager, organisational:
Christensen, Thomas Højlund (Intern)

Financing sources
Source: Samarb.arb. aftaler, Private danske - Andre virksomheder
Name of research programme: Ukendt
Amount: 225,000.00 Danish Kroner
Project

Life cycle assessment of emerging waste-to-energy technologies
Department of Environmental Engineering
Period: 01/05/2009 → 27/03/2013
Number of participants: 5
PhD Student:
Tonini, Davide (Intern)
Main Supervisor:
Astrup, Thomas Fruergaard (Intern)
Examiner:
Scheutz, Charlotte (Intern)
Hellweg - SLET, Stefanie (Ekstern)
Jensen, Lars Stoumann (Ekstern)

Financing sources
Source: Internal funding (public)
Name of research programme: Institut stipendie (DTU) Samf.
Project: PhD

Biogenic Carbon in Danish Combustible Waste
The ratio between biogenic (biomass) and fossil carbon in fuels affects the "sustainability" of the fuel and the energy technology using this fuel. Today waste contribute with a significant share of Danish renewable energy, however the current data for contents of biogenic and fossil carbon in Danish combustible waste are highly uncertain. To provide accurate accounts of national CO2 emissions, assess whether reduction targets can be met or new renewable energy projects need to be initiated, and overall to further develop the waste-to-energy sector, better carbon data has to be provided. This project combine actual full-scale measurements of carbon in off-gases with modeling approaches to provide documented sampling/measurement procedures and recommendations for implementation of upcoming CEN standards in DK, robust data on biogenic carbon in Danish combustible waste, and suggestions for future use of modeling/estimation approaches. The project is done in collaboration with Force Technology, NERI, and 5 Danish Waste-to-Energy plants (affald danmark)

Department of Environmental Engineering
Period: 01/04/2009 → 30/10/2011
Number of participants: 2
Acronym: 889
Project ID: 30697
Project participant:
Astrup, Thomas Fruergaard (Intern)
Project Manager, organisational:
Astrup, Thomas Fruergaard (Intern)
LCA-screening of 8 European waste management scenarios

Eight waste management scenarios representing various generic European approaches are screened by using EASEWASTE in collaboration with the Sustainable Landfill Foundation. The scenarios involve source separation of recyclables, MBT, incineration, composting, anaerobic digestion, RDF and landfilling.

Department of Environmental Engineering
Period: 15/11/2008 → 28/02/2009
Number of participants: 5
Acronym: 935
Project participant:
Astrup, Thomas Fruegaard (Intern)
Christensen, Thomas Højlund (Intern)
Boldrin, Alessio (Intern)
Manfredi, Simone (Intern)
Project Manager, organisational:
Møller, Jacob (Intern)

Implementation of Easewaste at VESTFORBRÆNDING as part of the environmental management system

VESTFORBRÆNDING, which is the largest waste management company in Denmark, has committed itself to base all environmental management on a life-cycle approach and has adopted the DTU model EASEWASTE as the supporting tool. DTU Environment contributes by setting up the waste management technologies specifically for VESTFORBRÆNDING and develops approaches for assessing operational problems by an LCA approach.

Department of Environmental Engineering
Period: 01/04/2008 → 30/06/2010
Number of participants: 3
Acronym: Implementeringsprojektet
Project ID: 30613
Project participant:
Astrup, Thomas Fruegaard (Intern)
Christensen, Thomas Højlund (Intern)
Project Manager, organisational:
Møller, Jacob (Intern)

A flexible and integrated energy system based on gasification of liquefied biomass and waste

The project develops a technology suitable for flexible and integrated production of power, heat and liquid fuels based on biomass and municipal waste. The process involves liquefaction of the organic materials using heat and enzymes, and gasification at high pressure. Outputs can be either heat and electricity or various liquid or gaseous fuels. The technology is evaluated in a life-cycle assessment perspective, including direct and indirect consequences for the waste management system as well as the energy system.

Department of Environmental Engineering
Period: 07/03/2007 → 07/03/2011
Number of participants: 1
Coherent Energy and Environmental System Analysis

The project integrates existing energy and environmental analysis tools by combining life cycle assessment and energy system and market analysis methodologies. The project thereby aim to meet three of the major challenges of future sustainable energy systems: 1) how to integrate the transport sector, 2) how to develop future power systems suitable for the integration of distributed renewable energy sources, and 3) how to develop public regulation in an international market environment.

Department of Environmental Engineering
Period: 01/01/2007 → 30/09/2011
Number of participants: 1
Acronym: CEESA
Project ID: 30554
Project Manager, organisational:
Astrup, Thomas Fruegaard (Intern)

Financing sources
Source: Forskningsrådene - Andre
Name of research programme: Ukendt
Amount: 1,200,000.00 Danish Kroner

Life-cycle assessment of biorefineries and biofuel production based on biomass resources

The project involves evaluation of environmental consequences of producing biofuels from biorefineries. This is done using a life-cycle assessment approach with specific focus on potentials for process optimizations, but also includes evaluations of the utilization of residual biomass resources for biofuel production. The project is a sub-project of a larger project (BioREF) hosted at the departments Bioenergy research group.

Department of Environmental Engineering
Period: 01/01/2007 → 31/12/2011
Number of participants: 2
Acronym: Bio.REF2
Project ID: 30520
Project participant:
Boldrin, Alessio (Intern)
Project Manager, organisational:
Astrup, Thomas Fruegaard (Intern)

Financing sources
Source: Forskningsrådene - Andre
Name of research programme: Ukendt
Amount: 1,952,866.00 Danish Kroner

Kortlægning af kilder til miljøskadelige stoffer i affaldet.

Der udføres en opgørelse af potentielle miljømæssige besparelser ved udsortering af 3 udvalgte affaldstyper/fraktioner tilført Århus Forbrændingsanlæg. De miljø- og energimæssige konsekvenser af udsorteringen modelleres i EASEWASTE baseret på konkrete målinger ved forbrændingstests.

Department of Environmental Engineering
Period: 01/08/2006 → 31/01/2007
Number of participants: 3
Acronym: Århus F2
Project ID: 30446
Improved energy efficiency and bottom ash quality for waste incinerators

The project involves test in pilot-scale of bottom ash sintering in a rotary kiln designed for waste incinerators. Ash qualities are evaluated with respect to leaching behavior as a function of rotary kiln design and operation parameters. In addition to this, the project evaluates potential improvements in furnace design with an aim to improve overall energy recovery efficiency while at the same time improving bottom ash qualities by sintering.

Department of Environmental Engineering
Period: 01/04/2006 → 30/06/2009
Number of participants: 2
Acronym: PSO-Kemiteknik
Project ID: 30496
Project participant:
Hyks, Jiri (Intern)

Financing sources
Source: Forskningsprojekter - Miljø- og Energiministeriet
Name of research programme: Ukendt
Amount: 492,000.00 Danish Kroner
Project

Environmentally sustainable utilization of waste resources for energy production

Environmentally sustainable utilization of waste resources for energy production

Department of Environmental Engineering
Period: 01/01/2006 → 31/12/2008
Number of participants: 2
Acronym: ENSUWE
Project ID: 30449
Project participant:
Fruergaard, Thilde (Intern)

Financing sources
Source: Unknown
Name of research programme: Ukendt
Amount: 2,500,000.00 Danish Kroner
Project

PSO-ELSAM. Undersøgelse af restprodukter (slagger og flyveaske/røggasaffald) fra affaldsforbrænding.

Investigation of the correlation between waste input to MSW incinerators and residue quality. Specific waste fractions are co-incinerated at a full scale incinerator, and all emission routes are monitored.

Department of Environmental Engineering
Period: 09/12/2005 → 01/05/2009
Number of participants: 2
Acronym: PSO-Elsam
Project ID: 30428
Project participant:
Riber, Christian (Intern)
Project Manager, organisational:
Astrup, Thomas Fruergaard (Intern)

**Financing sources**
Source: Unknown
Name of research programme: Ukendt
Amount: 4,482,000.00 Danish Kroner

**Modellering af miljøbelastning fra Århus Forbrændingsanlæg pr. 2005/2006. Århus F1.**
En model opstilles for Århus Forbrændingsanlæg i EASEWASTE, og en vurdering af de miljø- og energimæssige forhold omkring anlægget foretages.

Department of Environmental Engineering
Period: 01/12/2005 → 30/11/2006
Number of participants: 3
Acronym: Århus F1
Project ID: 30445
Project participant:
Astrup, Thomas Fruergaard (Intern)
Riber, Christian (Intern)

**Financing sources**
Source: Unknown
Name of research programme: Ukendt
Amount: 710,000.00 Danish Kroner

**Systematic leaching data for waste incineration bottom ashes**
Formål er på systematisk vis at frembringe et skalerbart datasæt for udvaskningen af udvalgte slagger

Department of Environmental Engineering
Number of participants: 2
Acronym: BA Leaching
Project ID: 30416
Project participant:
Hyks, Jiri (Intern)

**Financing sources**
Source: Samarb.aftaler - Amter og kommuner
Name of research programme: Samarb.aftaler - Amter og kommuner
Amount: 168,000.00 Danish Kroner

**TB2 Anvendelse af RGA i beton : indledende undersøgelser**

Section for Construction Materials

Department of Civil Engineering

Department of Environmental Engineering
Period: 01/08/2005 → 31/03/2006
Number of participants: 4
Project ID: 25699
Project participant:
Kjeldsen, Ane Mette (Intern)
Christensen, Thomas Højlund (Intern)
Astrup, Thomas Fruegaard (Intern)
Project Manager, organisational:
Geiker, Mette Rica (Intern)

Financing sources
Source: Sam.arb.aftaler, Private danske - Andre virksomheder
Name of research programme: Sam.arb.aftaler, Private danske - Andre virksomheder
Amount: 600,000.00 Danish Kroner
Project

Kvantificering af miljøeffekter fra RGA.
Projektet forventes at beskæftige sig med stabiliseret, deponeret RGA og en til to genanvendelsesteknologier. De faktiske teknologier udvælges af styringsgruppen, idet relevans og tilgængelighed af relevante prøveemner er afgørende. Selve værktøjet, dvs. en sammenhængende procedure for sammenstilling af data, laboratorie-testning samt modellering er projektets hovedformål, men værdien heraf øges ved at basere sig på relevante RGA-teknologier.

Department of Environmental Engineering

Energy Research Centre of the Netherlands
Period: 01/10/2004 → 30/09/2007
Number of participants: 3
Acronym: 432
Project ID: 30333
Project participant:
Astrup, Thomas Fruegaard (Intern)
Sloot, Hans van der (Ekstern)

Project Manager, organisational:
Christensen, Thomas Højlund (Intern)

Financing sources
Source: Sam.arb.aftaler - Amter og kommuner
Name of research programme: Sam.arb.aftaler - Amter og kommuner
Amount: 1,965,000.00 Danish Kroner
Project

Prediction of Leaching from Waste Incineration Residues

Department of Environmental Engineering
Period: 01/10/2004 → 01/09/2008
Number of participants: 6
PhD Student:
Hyks, Jiri (Intern)
Supervisor:
Astrup, Thomas Fruegaard (Intern)
Main Supervisor:
Christensen, Thomas Højlund (Intern)
Examiner:
Jakobsen, Rasmus (Intern)
Jensen, Dorthe Lærke (Intern)
Johnson, Carola Annette (Ekstern)

Financing sources
Source: Internal funding (public)
Name of research programme: Eksternt finansieret virksomhed
Project: PhD

Udarbejdelse af statusnotat vedrørende forbrændingsslager.
Projektet skal skabe en udtømmende, men kort oversigt over væsentlige projekter vedr. slager fra affaldsforbrænding, beskrive det nuværende vidensniveau mht. håndtering af forbrændingsslager, og fremhæve centrale udviklingsområder fremover. Afrapportering består af en sammenskrivning af disse forhold i et engelsksproget statusnotat.

Department of Environmental Engineering
Period: 30/08/2004 → 31/12/2004
Number of participants: 1
Acronym: 538
Project ID: 30348
Project Manager, organisational:
Astrup, Thomas Fruergaard (Intern)

Financing sources
Source: Sam.arb.aftaler - Amter og kommuner
Name of research programme: Sam.arb.aftaler - Amter og kommuner
Amount: 68,750.00 Danish Kroner

Project

DTUs bidrag til koordinering og uddøring.
Formål er at: - sikre DTU en gennemgående rolle i koordinerings process af samarbejdets projekter(Affald Danmark, RGA-samarbejde(ELSAM, AF, VF) - udføre, efter konkret aftale, mindre uddønings-og sammenskrivningsopgaver

Department of Environmental Engineering
Period: 01/04/2004 → 31/03/2007
Number of participants: 3
Acronym: 429
Project ID: 30335
Project participant:
Astrup, Thomas Fruergaard (Intern)
Röttger, Ulla (Ekstern)
Project Manager, organisational:
Christensen, Thomas Højlund (Intern)

Financing sources
Source: Sam.arb.aftaler, Private danske - Andre virksomheder
Name of research programme: Ukendt
Amount: 300,000.00 Danish Kroner

Project

Fugttekniske undersøgelser på dansk hørmåtte

Section for Building Materials and Geotechnics

Department of Civil Engineering

Dansk Landbrugsrådgivning
Period: 01/09/2003 → 01/02/2004
Number of participants: 3
Project ID: 25509
Project participant:
Astrup, Thomas Fruergaard (Intern)
Jacobsen, Ulla Gjøl (Intern)
Project Manager, organisational:
Hansen, Kurt Kielsgaard (Intern)

Financing sources
Source: Sam.arb.aftaler, Private danske - Andre virksomheder
Name of research programme: Sam.arb.aftaler, Private danske - Andre virksomheder
Amount: 85,000.00 Danish Kroner

Project

Status om forbrændingsslagger

Status om forbrændingsslagger

Department of Environmental Engineering
Period: 01/02/2003 → 01/07/2003
Number of participants: 1
Acronym: 346
Project ID: 30274
Kemisk stabilisering af røggasrensningsprodukter

Department of Environmental Engineering
Period: 01/01/2000 → 14/05/2004
Number of participants: 6
PhD Student:
Astrup, Thomas Fruergaard (Intern)
Supervisor:
Hjelmar, Ole (Ekstern)
Main Supervisor:
Christensen, Thomas Højlund (Intern)
Examiner:
Kjeldsen, Peter (Intern)
Johnson, Carola Annette (Ekstern)
Stipp, Susan Louise Svane (Ekstern)

Financing sources
Source: Internal funding (public)
Name of research programme: Forskningsrådsfinansiering
Project: PhD

Leaching of heavy metals from soils

Quality criteria for soils with respect to heavy metals have traditionally focused on the environmental issues related to the land use (ingestion of soil, skin contact, etc.) and very little attention has been given to protection of the groundwater. The complex form of heavy metals in polluted soils makes prediction of leachability difficult and leaching experiments or leaching test are usually the only way to assess the amount of metal to leach from the soil. Model scenarios are being developed to evaluate heavy metal leaching in the context of groundwater protection and allow for simplified methods to account for groundwater quality criteria, depth and location of polluted soil, reduction in infiltration and leachable amounts determined in leaching test. Experimental studies have been performed at actual sites and leaching experiments are conducted in the laboratory.

Department of Environmental Science and Engineering
National Institute of Aquatic Resources
VKI Water Quality Institute
Period: 01/01/1996 → 31/12/1998
Number of participants: 9
Project participant:
Kjeldsen, Peter (Intern)
Astrup, Thomas Fruergaard (Intern)
Boddum, Jens Kjærsgaard (Intern)
Astrup, Thomas Fruergaard (Intern)
Jensen, Dorthe Lærke (Intern)
Foverskov, Anja (Intern)
Holm, P. (Ekstern)
Hjelmar, O. (Ekstern)
Project Manager, organisational:
Christensen, Thomas Højlund (Intern)

Financing sources
Source: Unknown
Name of research programme: Ukendt
Leaching of heavy metals from soils.
Quality criteria for soils with respect to heavy metals have traditionally focused on the environmental issues related to the land use (ingestion of soil, skin contact, etc.) and very little attention has been given to protection of the groundwater. The complex form of heavy metals in polluted soils makes prediction of leachability difficult and leaching experiments or leaching tests are usually the only way to assess the amount of metal to leach from the soil. Model scenarios are being developed to evaluate heavy metal leaching in the context of groundwater protection and allow for simplified methods to account for groundwater quality criteria, depth and location of polluted soil, reduction in infiltration and leachable amounts determined in leaching test. Experimental studies have been performed at actual sites and leaching experiments are conducted in the laboratory.

Department of Environmental Engineering
Period: 01/01/1996 → 31/12/1998
Number of participants: 5
Acronym: 10
Project participant:
Foverskov, Anja (Intern)
Jensen, Dorthe Lærke (Intern)
Kjeldsen, Peter (Intern)
Astrup, Thomas Fruegaard (Intern)
Project Manager, organisational:
Christensen, Thomas Højlund (Intern)