Bioethanol from corn stover – Global warming footprint of alternative biotechnologies

Bioethanol from residual corn stover could contribute to lowering CO2 loads within the transport sector, if used as an amendment to gasoline. We modelled by life cycle assessment and Monte Carlo simulation seven different technological configurations for producing bioethanol from corn stover based on consistent mass flows and estimated ethanol production extracted from 141 datasets of reasonable quality. By parametrizing key processes and determining their statistical distribution based on actual data, we were able to estimate the Global Warming Potential (GWPs) for all the alternative technologies on a system level. Most of the individual cases showed a net saving in GWP when the savings obtained from recovering energy from anaerobic digestion of the liquid residues and incineration of the solid residues were included. The net savings could in some cases be as high as 900–1200 kg CO2-eq/t dry corn stover solids. If the residues were not subject to energy recovery, the production of bioethanol and use in gasoline would be a net load to global warming in more than 50% of the technological configurations. The “best-practice”, defined as the top 15% cumulative probability with respect to GWP, suggests that technologies based on steam explosion and ammonia-based pretreatment appear statistically the most promising and could contribute, with residue energy recovery, to GWP savings of 850–1050 kg CO2-eq/t dry corn stover solids and produce in the range 178–216 kg of bioethanol. This paper provides insights into the key parameters for bioethanol production from corn stover and suggests areas for further research.

Evaluation of a European textile sorting centre: Material flow analysis and life cycle inventory

Life cycle assessment (LCA) studies have shown that the optimal treatments of textile waste follow the waste hierarchy. Consequently, there is great potential for environmental improvements through ensuring that textiles are collected, reused, recycled and disposed of in the best possible way. Despite the fact that textile sorting centres play a central role in ensuring a high reuse rate, they have either been left out of previous LCAs or modelled based on low-quality data. In this study, a material flow analysis (MFA) of the textile flows in a sorting centre, and a life cycle inventory (LCI), was undertaken for the period 2015–2017, along with an assessment of the main economic factors. The MFA showed that the majority of the sorted textiles were indeed reusable, but their numbers decreased in the reference period, from 79.8% to 74.9%. The LCI and economic analysis showed increasing resource consumption in terms of electricity, gas (trucks) and packing per sorted tonne. Furthermore, the quality of textiles has generally decreased over the last decade, which is reflected in the share of reusable textiles of the highest quality, which undergo additional fine sorting. While in 2015, almost 33% of the reusable textiles were sorted out for fine sorting, in 2017, this figure was down to 29%. The number of recyclable textiles increased over the period, from 12.9% to 17.3%, and the amount of waste also increased, from 5.4 to 6.0%. The results presented herein are important for properly representing the sorting process in modelling textile waste management.
Quality Assessment and Circularity Potential of Recovery Systems for Household Plastic Waste

Plastic recycling is promoted in the transition toward a circular economy and a closed plastic loop, typically using mass-based recycling targets. Plastic from household waste (HHW) is contaminated and heterogeneous, and recycled plastic from HHW often has a limited application range, due to reduced quality. To correctly assess the ability to close plastic loops via recycling, both plastic quantities and qualities need to be evaluated. This study defines a circularity potential representing the ability of a recovery system to close material loops assuming steady-state market conditions. Based on an average plastic waste composition including impurities, 84 recovery scenarios representing a wide range of sorting schemes, source-separation efficiencies, and material recovery facility (MRF) configurations and performances were assessed. The qualities of the recovered fractions were assessed based on contamination and the circularity potential calculated for each scenario in a European context. Across all scenarios, 17% to 100% of the generated plastic mass could be recovered, with higher source-separation and MRF efficiencies leading to higher recovery. Including quality, however, at best 55% of the generated plastic was suitable for recycling due to contamination. Source-separation, a high number of target fractions, and efficient MRF recovery were found to be critical. The circularity potential illustrated that less than 42% of the plastic loop can be closed with current technology and raw material demands. Hence, Europe is still far from able to close the plastic loop. When transitioning toward a circular economy, the focus should be on limiting impurities and losses through product design, technology improvement, and more targeted plastic waste management.
Quantity and quality of clothing and household textiles in the Danish household waste

Despite the fact that studies have indicated that a large proportion of textiles is disposed in the waste, only few studies have looked at the content of textiles in waste, and even less have considered the quality of these textiles. However, it is crucial to know both quantity and quality, in order to assess the potential for improved reuse and recycling. Following a new method for assessing the quantity and quality of textile waste, this study assessed residual household waste from 17 areas and small combustible waste from six recycling stations throughout Denmark. The average contents of Clothing and Household textiles in residual household waste were 1.4±0.5% and 0.6±0.3%, respectively, whereas the content was 4.5±2.1% for Clothing and 2.6±1.2% for Household textiles in the small combustibles. On an annual basis each resident discards to 2.4±0.9kg of Clothing and 1.1±0.5kg/resident/year of Household textiles with the residual household waste. The quality assessments showed, that an average of 65±8.0% and 65±19.3% of the Clothing and Household textiles were reusable in the residual household waste, while in small combustibles it were an average of 69±5.8% and 66±9.6% of the Clothing and Household textiles. In addition, an average of 12±5.3% and 15±10.5% of the Clothing and Household textiles in residual waste, and an average of 14±3.9% and 16±8.7% of the Clothing and Household textiles in small combustibles, could be recycled. This emphasizes that there is good potential for improving textile waste management, as most of the identified Clothing and Household textiles were misplaced and little were actually waste.

A bioenergy integrated system with a process oriented LCA modelling approach

General information
A comparison of chemical MSW compositional data between China and Denmark

Chemical waste compositions are important for municipal solid waste management, as they determine the pollution potentials from different waste strategies. A representative dataset for chemical characteristics of individual waste fractions is frequently required to assess chemical waste composition, but it is usually reported in developed countries and not in developing countries. In this study, a dataset for Chinese waste was established through careful data screening and assessment, named as CN dataset. Meanwhile, a dataset for Danish waste (DK dataset) was also summarized based on previous studies. In order to quantitatively evaluate the reliabilities of CN and DK datasets, the chemical waste compositions in four Chinese cities were estimated by utilizing both of them, respectively. It is indicated that the usage of CN datasets led to significantly lower discrepancies from the actual values based on laboratory analysis in most cases. Within the datasets, the moisture contents of food waste, paper, textiles, and plastics, the carbon content of food waste, as well as the oxygen content of plastics would induce significant divergences, which should be paid special attention when gathering the information. In addition, the fractional waste compositions in China showed similar features with other developing countries but differ significantly with developed countries. Thus the above-mentioned conclusions could also be true in other developing countries.
Bioethanol from corn stover – a review and technical assessment of alternative biotechnologies

Reviewing the literature from the last decade regarding the biocconversion of corn stover into ethanol, 474 references were identified containing 561 datasets. We found 144 datasets which were sufficiently consistent and detailed to address the current state of the art of corn stover conversion to bioethanol, and we were able to categorise 93% of these datasets into eight different technological configurations for the production of bioethanol, based on the pretreatment approaches used. After pretreating, the corn stover is subject to hydrolysis and fermentation, but these two process steps were largely identical in all datasets, albeit a range of operating conditions was reported. The final distillation of the ethanol was very rarely included in the datasets. By parameterising the bioethanol production by 26 parameters, including corn stover compositions, solid loadings, operational conditions, conversion efficiencies and material consumption, we were able to quantify the material flows for each technological configuration and estimate the uncertainty of the flows. The eight technological configurations produced 11–22% ethanol from the dry solid content of the corn stover. Technologies using alkaline-, solvent or ammonia-based pretreatments produced the largest amount of ethanol (19–22%), while fungi-based pretreatment produced much less (11%). All technological configurations resulted in large flows of solid as well as liquid residues, typically containing 60 to 70% of the dry solid corn stover content. Based on the selected datasets, statistical description is provided for all parameters, including mode, median, average and deviation, within each technological configuration. Bivariate correlation analysis across and within all technological configurations indicates that some operational parameters usually considered crucial in laboratory studies, e.g. pretreatment severity, show from a statistical perspective very little correlation with the yields. The review reveals that a great deal of research has addressed the challenge of converting corn stover into bioethanol, but a significant part of these studies is of limited value in terms of scope and documentation when addressing overall material flows and key parameters in a technological context.

Combining circularity and LCA: Quality assessment and substitutability of recycled plastic from HHW

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Organisations: Residual Resource Engineering, Department of Environmental Engineering
Contributors: Eriksen, M. K., Damgaard, A., Boldrin, A., Astrup, T. F.
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Development and testing of a sorting and quality assessment method for textile waste

Due to the high resource consumption and environmental impacts of textile production, better handling of discarded materials has a great environmental improvement potential. A uniform definition of textile waste and a stringent sorting procedure is a precondition for thorough investigations of discarded textiles. A review of waste sorting studies showed that only a few included textiles, and mainly considered content and not quality. A lack of definition and quality assessment causes a high risk of mistakes when assessing the potential of textile waste prevention. This study establishes a method for sorting and quality assessment of textiles in household waste, validated through dialogue with professional textile sorting centres. It also suggests a minimum waste sample size. The quality assessment is based on analysis of product types, manufacturing methods, fibre composition and a product condition assessment based on 17 criteria. The developed method was applied in a case study and compared with other sorting methods. It showed that 61% of the clothing in residual waste and 83% in small combustibles and that 78% of the household textiles in residual waste and 85% in small combustibles were reusable or recyclable. The comparison with existing methods showed that sorted quantities varied significantly when different sorting methods were applied even when the sorting was done on the same sample. This study
suggests a new standard for defining and assessing categories and qualities of used textiles, adapted to real contemporary sorting technologies, and tested on waste samples.

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Source: FindIt
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Research output: Contribution to journal › Journal article – Annual report year: 2018 › Research › peer-review

**Eco-efficiency vurdering af alternativer for ressourceeffektiv plan for håndtering af regn- og drænvand**

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Organisations: Department of Environmental Engineering, Urban Water Systems, Residual Resource Engineering
Contributors: Faragó, M., Godskesen, B., Damgaard, A.
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**Life Cycle Assessment of grocery carrier bags**
The report provides a lifecycle assessment (LCA) of production, use and disposal of shopping bags available in Danish supermarkets in autumn 2017.

16 different environmental parameters have been compared, and the results are shown by how many times a given type of carrier bag should be used to be as environmentally good as a regular plastic carrier bag.

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Life Cycle Assessment of management options for beverage packaging waste

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Linking Data Choices and Context Specificity in Life Cycle Assessment of Waste Treatment Technologies: A Landfill Case Study

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 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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Contributors: Henriksen, T., Astrup, T. F., Damgaard, A.
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BFI (2018): BFI-level 2
Waste management in the Irkutsk region, Siberia, Russia: An environmental assessment of alternative development scenarios

The current waste management system, handling around 500,000 t of household, commercial, and institutional waste annually in the Irkutsk region, Siberia, is based on landfilling in an old landfill with no controls of leachate and gas. Life-cycle assessment modelling of the current system shows that it is a major load on the environment, while the simulation of seven alternative systems results in large savings in many impact categories. With respect to climate change, it is estimated that a saving of about 1200 kg CO2 equivalents is possible per year, per inhabitant, which is a significant reduction in greenhouse gas emissions. The best alternatives involve efficient energy recovery from waste and recycling by source separation for commercial and institutional waste, the major waste type in the Irkutsk region. Recycling of household waste seems less attractive, and it is therefore recommended only to consider this option after experience has been gained with the commercial and institutional waste. Sensitivity analysis shows that recovery of energy - in particular electricity, heat, and steam - from waste is crucial to the environmental performance of the waste management system. This relates to the efficiencies of energy recovery as well as what the recovered energy substitutes, that is, the ‘dirtier’ the off-set energy, the higher the environmental savings for the waste management system. Since recovered energy may be utilised by only a few energy grids or industrial users, it is recommended to perform additional local assessments of the integration of the waste energy into existing systems and facilities.

Advanced life cycle assessment modelling of organic waste refineries

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

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Closing material loops: The case of plastic recycling from household waste

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Organisations: Residual Resource Engineering, Department of Environmental Engineering
Contributors: Eriksen, M. K., Damgaard, A., Boldrin, A., Astrup, T. F.
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Environmental assessment of presence of impurity materials and chemical pollutants in wood waste meant for recycling

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Environmental impacts and resource losses of incinerating misplaced household special wastes (WEEE, batteries, ink cartridges and cables)
The contribution of misplaced special waste (sWEEE, lamps, CRT, batteries, ink cartridges and cables) to environmental impacts from incineration of residual household waste was quantified through life cycle assessment (LCA)-modelling. Misplaced special waste was quantified to constitute less than 1% of the net impact for most environmental impact categories, except for the toxic impact categories (4–28% of toxic impacts) and the impact on abiotic resource depletion. It was found that the main contributor (96%) to the toxic impact categories was related to the presence of mercury (Hg) from lamps and batteries. However as shown by sensitivity analysis, lack of good data on the transfer of rare and hazardous
metals to the flue gas in the incineration process should receive further investigation before the environmental impacts from misplaced incinerated special waste can fully be concluded upon. Although the misplaced special waste is only 0.5% of residual household waste, it constitutes in the residual household waste the most significant fraction with respect to metal content when iron and aluminum are excluded. By extending the boundary of the LCA beyond the traditional "zero burden boundary", we were able to quantify the impact of abiotic resources not recovered from incineration residues. This appeared to be a significant impact category, and the special waste contributed about 96% of this category although it by weight makes up only 0.5% of the waste. Furthermore, enhancing the recovery of iron (Fe) and aluminum (Al) from the ashes would not affect the loss of abiotic resources significantly. Only by recovering elements as platinum (Pt), copper (Cu), gold (Au), and silver (Ag) would it be possible to reduce the loss of abiotic resources from the system. These elements are primarily found in misplaced special waste (sWEEE, lamps, CRT, batteries, ink cartridges, and cables).

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Environmental performance of household waste management in Europe - an example of 7 countries
An attributional life cycle assessment (LCA) of the management of 1 ton of household waste was conducted in accordance with ISO 14044:2006 and the ILCD Handbook for seven European countries, namely Germany, Denmark, France, UK, Italy, Poland and Greece, representing different household waste compositions, waste management practices, technologies, and energy systems. National data were collected from a range of sources regarding household waste composition, household sorting efficiency, collection, waste treatments, recycling, electricity and heat composition, and technological efficiencies. The objective was to quantify the environmental performance in the different countries, in order to analyze the sources of the main environmental impacts and national differences which affect the results. In most of the seven countries, household waste management provides environmental benefits when considering the benefits of recycling of materials and recovering and utilization of energy. Environmental benefits come from paper recycling and, to a lesser extent, the recycling of metals and glass. Waste-to-energy plants can lead to an environmental load (as in France) or a saving (Germany and Denmark), depending mainly on the composition of the energy being substituted. Sensitivity analysis and a data quality assessment identified a range of critical parameters, suggesting from where better data should be obtained. The study concluded that household waste management is environmentally the best in European countries with a minimum reliance on landfilling, also induced by the implementation of the Waste Hierarchy, though environmental performance does not correlate clearly with the rate of material recycling. From an environmental point of view, this calls for a change in the waste management paradigm, with less focus on where the waste is routed and more of a focus on the quality and utilization of recovered materials and energy.

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Organisations: Department of Environmental Engineering, Residual Resource Engineering, Atmospheric Environment, Water Technologies
Contributors: Andreasi Bassi, S., Christensen, T. H., Damgaard, A.
Pages: 545-557
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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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Contributors: Martinez Sanchez, V., Levis, J. W., Damgaard, A., DeCarolis, J. F., Barlaz, M. A., Astrup, T. F.
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Research output: Contribution to journal › Journal article – Annual report year: 2017 › Research › peer-review
Importance of waste composition for Life Cycle Assessment of waste management solutions
The composition of waste materials has fundamental influence on environmental emissions associated with waste treatment, recycling and disposal, and may play an important role also for the Life Cycle Assessment (LCA) of waste management solutions. However, very few assessments include effects of the waste composition and waste LCAs often rely on poorly justified data from secondary sources. This study systematically quantifies the influence and uncertainty on 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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Contributors: Bisinella, V., Götze, R., Conradsen, K., Damgaard, A., Christensen, T. H., Astrup, T. F.
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What type of shopping bag to use? Perspectives on the functionality and recycling of polymers

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Influence of data choices in Life Cycle Assessment of waste management systems

Life cycle assessment as development and decision support tool for wastewater resource recovery technology

Life cycle assessment (LCA) has been increasingly used in the field of wastewater treatment where the focus has been to identify environmental trade-offs of current technologies. In a novel approach, we use LCA to support early stage research and development of a biochemical system for wastewater resource recovery. The freshwater and nutrient content of wastewater are recognized as potential valuable resources that can be recovered for beneficial reuse. Both recovery and reuse are intended to address existing environmental concerns, for example, water scarcity and use of non-renewable phosphorus. However, the resource recovery may come at the cost of unintended environmental impacts. One promising recovery system, referred to as TRENS, consists of an enhanced biological phosphorus removal and recovery system (EBP2R) connected to a photobioreactor. Based on a simulation of a full-scale nutrient and water recovery system in its potential operating environment, we assess the potential environmental impacts of such a system using the EASETECH model. In the simulation, recovered water and nutrients are used in scenarios of agricultural irrigation-fertilization and aquifer recharge. In these scenarios, TRENS reduces global warming up to 15% and marine eutrophication impacts up to 9% compared to conventional treatment. This is due to the recovery and reuse of nutrient resources, primarily nitrogen. The key environmental concerns obtained through the LCA are linked to increased human toxicity impacts from the chosen end use of wastewater recovery products. The toxicity impacts are from both heavy metals release associated with land application of recovered nutrients and production of AlCl₃, which is required for advanced wastewater treatment prior to aquifer recharge. Perturbation analysis of the LCA pinpointed nutrient substitution and heavy metals content of algae biofertilizer as critical areas for further research if the performance of nutrient recovery systems such as TRENS is to be better characterized. Our study provides valuable feedback to the TRENS developers and identifies the importance of system expansion to include impacts outside the immediate nutrient recovery system itself. The study also show for the first time the successful evaluation of urban-to-agricultural water systems in EASETECH.
Life cycle assessment modelling considering impurities in recyclable materials

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Livscyklusscreening af affaldsforebyggelse: Emballageaffald og bygge- og anlægsaffald

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Quality assessment and estimation of substitution ratios for recycled plastic

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Quality of textile waste: a case study of residual household waste from Odense Municipality, Denmark

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Abstract_Noerup_ISWA2016.pdf
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Source-ID: 128112195
Research output: Contribution to conference › Conference abstract for conference – Annual report year: 2016 › Research › peer-review

Range of technology choices in life cycle assessment of environmental treatment technologies: An example of a solid waste landfill model
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 shows 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.

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State-of-the-Art Solid Waste Management Life-Cycle Modeling Workshop
There are many alternatives for the management of solid waste including recycling, biological treatment, thermal treatment and landfill disposal. In many cases, solid waste management systems include the use of several of these processes. Solid waste life-cycle assessment models are often used to evaluate the environmental consequences of various waste management strategies. The foundation of every life-cycle model is the development and use of process models to
estimate the emissions from solid waste unit processes. The objective of this workshop is to describe life-cycle modeling of the solid waste processes and systems. The workshop will begin with an introduction to solid waste life-cycle modeling and available models, which will be followed by sessions on life-cycle process modeling for individual processes (e.g., landfills, biological treatment, and thermal treatment). The first part of each session will be used to explain the state-of-the-art for a given solid waste process model and the remainder of the time will be devoted to input and discussion.

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### The Efficiency of Informality: Quantifying Greenhouse Gas Reductions from Informal Recycling in Bogotá, Colombia

The dual challenges of increasing urbanization and consumption are centered in cities in the Global South, where growing waste production threatens public and environmental health. Reuse and recycling are widely recognized to provide broad environmental benefits. Although most industrialized cities replaced their informal recycling sectors with municipally run recycling schemes and have had to build their recycling rates anew, most industrializing cities in the Global South remain centers of recycling and reuse through the work of informal workers. Bogotá, Colombia, is emblematic of many cities in the Global South seeking to modernize their city, in part by formalizing their recycling system. This article asks: What are the greenhouse gas (GHG) emission implications of this modernization? Using interviews and observation in combination with life cycle assessment, we compare GHG emissions resulting from the baseline case (1,200 tonnes per day [t/d] recycled through informal channels; 5,700 t/d landfilled) to three alternative scenarios that formalize the recycling sector: the prohibition of informal recycling; a reduction in informal recycling coupled with a scale-up of formalized recycling; and the replacement of informal recycling with formal recycling. We find that the baseline recycling scenario, dependent on the informal sector only, emits far fewer GHGs than do all formalization scenarios. Three processes drive the results, in order of magnitude: informal textile reuse (largest GHG savings); landfilling (largest emitter of GHGs); and metal recycling (GHG savings). A hybrid model could combine the incentives and efficiency of the informal system with the better working conditions of the municipal one.

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

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Analysis of material recovery facilities for use in life-cycle assessment
Insights derived from life-cycle assessment of solid waste management strategies depend critically on assumptions, data, and modeling at the unit process level. Based on new primary data, a process model was developed to estimate the cost and energy use associated with material recovery facilities (MRFs), which are responsible for sorting recyclables into saleable streams and as such represent a key piece of recycling infrastructure. The model includes four modules, each with a different process flow, for separation of single-stream, dual-stream, pre-sorted recyclables, and mixed-waste. Each MRF type has a distinct combination of equipment and default input waste composition. Model results for total amortized costs from each MRF type ranged from $19.8 to $24.9 per Mg (1 Mg = 1 metric ton) of waste input. Electricity use ranged from 4.7 to 7.8 kWh per Mg of waste input. In a single-stream MRF, equipment required for glass separation consumes 28% of total facility electricity consumption, while all other pieces of material recovery equipment consume less than 10% of total electricity. The dual-stream and mixed-waste MRFs have similar electricity consumption to a single-stream MRF. Glass separation contributes a much larger fraction of electricity consumption in a pre-sorted MRF, due to lower overall facility electricity consumption. Parametric analysis revealed that reducing separation efficiency for each piece of equipment by 25% altered total facility electricity consumption by less than 4% in each case. When model results were compared with actual data for an existing single-stream MRF, the model estimated the facility's electricity consumption within 2%. The results from this study can be integrated into LCAs of solid waste management with system boundaries that extend from the curb through final disposal. (C) 2014 Elsevier Ltd. All rights reserved.
Assessment of co-composting of sludge and woodchips in the perspective of environmental impacts (EASETECH)

To reveal potential impacts to environment and human health quantitatively, co-composting and utilization of sludge and woodchips were investigated using a life-cycle-based model, EASETECH. Three scenarios were assessed through experiments using different material ratios. Emission amounts during co-composting were determined by monitoring data and mass balance. With 100 t sludge treatment, co-composting showed impacts to acidification (29.9 PE) and terrestrial eutrophication (57.7 PE) mainly for ammonia emission. Compost utilization presented savings on freshwater eutrophication (-1.5 PE) because of phosphorus substitution. With the application of fewer woodchips, impacts to acidification and terrestrial eutrophication decreased because more ammonium was reserved rather than released. All impacts to human toxicity were not significant (8.2 ± 0.6 PE) because the compost was used for urban landscaping rather than farming. Trace gaseous compounds showed marginal impacts to global warming and toxicity categories. The results provide a new perspective and offer evidence for appropriate sludge treatment selection.

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.

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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.

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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.

Climate Benefits of Material Recycling: Inventory of Average Greenhouse Gas Emissions for Denmark, Norway and Sweden

The purpose of this project is to compare emissions of greenhouse gases from material recycling with those from virgin material production, both from a material supply perspective and from a recycling system perspective. The method for estimating emissions and climate benefits is based on a review, followed by a selection, of the most relevant publications on life cycle assessment (LCA) of materials for use in Denmark, Norway and Sweden. The proposed averages show that emissions from material recycling are lower in both perspectives, comparing either material supply or complete recycling systems. The results can be used by companies and industry associations in Denmark, Norway and Sweden to communicate the current climate benefits of material recycling in general. They may also contribute to discussions on a societal level, as long as their average and historic nature is recognised.
Life Cycle Assessment as Decision Support Tool for Development of a Resource Recovery Technology

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Life cycle assessment as decision support tool in early stage development of a new technology for wastewater resource recovery

Life cycle assessment (LCA) has been increasingly used in the field of wastewater treatment where the focus has been to identify environmental trade-offs of current technologies. In a novel approach, we use LCA to support early stage research and development of a biochemical system for wastewater resource recovery. The freshwater and nutrient content of wastewater are to a large extent recognized as potential valuable resources that can be recovered for beneficial reuse. Both recovery and reuse are intended to address existing environmental concerns, for example water scarcity and use of non-renewable phosphorus. However, the resource recovery may come at the cost of unintended environmental impacts.

One promising recovery system, referred to as TRENS, consists of an enhanced biological phosphorus removal and recovery system (EBP2R) connected to a photobioreactor. We present the environmental impact results of the first simulated full-scale TRENS system in its potential operating environment as a side-stream process to an existing Copenhagen wastewater treatment plant. The system recovers water and nutrients that can be used in scenarios of agricultural irrigation-fertilization and aquifer recharge. The environmental performance of the system has been evaluated through life cycle assessment using EASETECH software.

For the chosen scenarios, TRENS reduces global warming up to 15% and marine eutrophication impacts up to 9% compared to conventional treatment. This is due to the TRENS system’s lower aeration demands, and thus energy consumption, as well as recovery of nitrogen. The key environmental concerns obtained through the LCA are linked to increased human toxicity impacts from the chosen end use of TRENS products. The toxicity impacts are from both heavy metals release associated with land application of recovered wastewater nutrients and production of AlCl3, which is required for advanced treatment prior to aquifer recharge.

Perturbation analysis of the LCA model in EASETECH pinpointed nutrient substitution and heavy metals content of algae biofertilizer as critical areas for further research if TRENS performance is to be better characterized. These findings provided the first iteration in addressing the environmental performance of TRENS as it progresses from concept to commercial implementation. In conclusion, our study provided valuable feedback to the TRENS developers and identified the importance of system expansion to include impacts outside the immediate biological system of TRENS itself. Also the study showed for the first time the successful evaluation of urban-to-agricultural water systems in EASETECH.

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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 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 Models of Solid Waste Management: Defining the state-of-the-art for Collection, Material recovery, Combustion, biological Treatment, and Landfilling

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Livscyklusvurdering af behandling af deponeret shredderaffald

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Quantification of regional leachate variance from municipal solid waste landfills in China

The quantity of leachate is crucial when assessing pollution emanating from municipal landfills. In most cases, existing leachate quantification measures only take into account one source - precipitation, which resulted in serious underestimation in China due to its waste properties: high moisture contents. To overcome this problem, a new estimation method was established considering two sources: (1) precipitation infiltrated throughout waste layers, which was simulated with the HELP model, (2) water squeezed out of the waste itself, which was theoretically calculated using actual data of Chinese waste. The two sources depended on climate conditions and waste characteristics, respectively, which both varied in different regions. In this study, 31 Chinese cities were investigated and classified into three geographic regions according to landfill leachate generation performance: northwestern China (China-NW) with semi-arid and temperate climate and waste moisture content of about 46.0%, northern China (China-N) with semi-humid and temperate climate and waste moisture content of about 58.2%, and southern China (China-S) with humid and sub-tropical/tropical climate and waste moisture content of about 58.2%. In China-NW, accumulated leachate amounts were very low and mainly the result of waste degradation, implying on-site spraying/irrigation or recirculation may be an economic approach to treatment. In China-N, water squeezed out of waste by compaction totaled 22-45% of overall leachate amounts in the first 40 years, so decreasing the initial moisture content of waste arriving at landfills could reduce leachate generation. In China-S, the leachate generated by infiltrated precipitation after HDPE geomembranes in top cover started failing, contributed more than 60% of the overall amounts over 100 years of landfiling. Therefore, the quality and placing of HDPE geomembranes in the top cover should be controlled strictly for the purpose of mitigation leachate generation.

Quantifying uncertainty in sustainability assessments: from feedstock to end-of-life

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Quantifying uncertainty in sustainability assessments: from feedstock to end-of-life

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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.

Role of data quality in assessment of the sustainability of technologies

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.
An environmental assessment system for environmental technologies

A new model for the environmental assessment of environmental technologies, EASETECH, has been developed. The primary aim of EASETECH is to perform life-cycle assessment (LCA) of complex systems handling heterogeneous material flows. The objectives of this paper are to describe the EASETECH framework and the calculation structure. The main novelties compared to other LCA software are as follows. First, the focus is put on material flow modelling, as each flow is characterised as a mix of material fractions with different properties and flow compositions are computed as a basis for the LCA calculations. Second, the tool has been designed to allow for the easy set-up of scenarios by using a toolbox, the processes within which can handle heterogeneous material flows in different ways and have different emission calculations. Finally, tools for uncertainty analysis are provided, enabling the user to parameterise systems fully and propagate probability distributions through Monte Carlo analysis. © 2014 Elsevier Ltd.

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).

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Environmental impact assessment on the construction and operation of municipal solid waste sanitary landfills in developing countries: China case study
An inventory of material and energy consumption during the construction and operation (C&O) of a typical sanitary landfill site in China was calculated based on Chinese industrial standards for landfill management and design reports. The environmental impacts of landfill C&O were evaluated through life cycle assessment (LCA). The amounts of materials and energy used during this type of undertaking in China are comparable to those in developed countries, except that the consumption of concrete and asphalt is significantly higher in China. A comparison of the normalized impact potential between landfill C&O and the total landfilling technology implies that the contribution of C&O to overall landfill emissions is not negligible. The non-toxic impacts induced by C&O can be attributed mainly to the consumption of diesel used for daily operation, while the toxic impacts are primarily due to the use of mineral materials. To test the influences of different landfill C&O approaches on environmental impacts, six baseline alternatives were assessed through sensitivity analysis. If geomembranes and geonets were utilized to replace daily and intermediate soil covers and gravel drainage systems, respectively, the environmental burdens of C&O could be mitigated by between 2% and 27%. During the LCA of landfill C&O, the research scope or system boundary has to be declared when referring to material consumption values taken from the literature; for example, the misapplication of data could lead to an underestimation of diesel consumption by 60–80%.

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Evaluation of life cycle inventory data for recycling systems

This paper reviews databases on material recycling (primary as well as secondary production) used in life cycle assessments (LCA) of waste management systems. A total of 366 datasets, from 1980 to 2010 and covering 14 materials, were collected from databases and reports. Totals for CO2-equivalent emissions were compared to illustrate variations in the data. It was hypothesised that emissions from material production and the recycling industry had decreased over time due to increasing regulation, energy costs and process optimisation, but the reported datasets did not reveal such a general trend. Data representing the same processes varied considerably between databases, and proper background information was hard to obtain, which in turn made it difficult to explain the large differences observed. Those differences between the highest and lowest estimated CO2 emissions (equivalents) from the primary production of newsprint, HDPE and glass were 238%, 443% and 452%, respectively. For steel and aluminium the differences were 1761% and 235%, respectively. There is a severe lack of data for some recycled materials; for example, only one dataset existed for secondary cardboard. The study shows that the choice of dataset used to represent the environmental load of a material recycling process and credited emissions from the avoided production of virgin materials is crucial for the outcome of an LCA on waste management. Great care and a high degree of transparency are mandatory, but advice on which datasets to use could not be determined from the study. However, from the gathered data, recycling in general showed lower emission of CO2 per kg material than primary production, so the recycling of materials (considered in this study) is thus beneficial in most cases.
Municipal solid waste conversion to transportation fuels: a life-cycle estimation of global warming potential and energy consumption

This paper utilizes life cycle assessment (LCA) methodology to evaluate the conversion of U.S. municipal solid waste (MSW) to liquid transportation fuels via gasification and Fischer-Tropsch (FT). The model estimates the cumulative energy demand and global warming potential (GWP) associated with the conversion of 1 Mg (1 Mg = 1000 kg) of MSW delivered to the front gate of a refuse-derived fuel (RDF) facility into liquid transportation fuels. In addition, net energy production is reported to quantify system performance. The system is expanded to include substituted electricity and fuel. Under a set of default assumptions, the model estimates that 1 Mg of MSW entering the RDF facility yields 123 L of gasoline, 57 L of diesel, 79 kg of other FT products, and 193 kWh of gross electricity production. For each Mg of MSW, the conversion process consumes 4.4 GJ of primary energy while creating fuels and electricity with a cumulative energy content of 10.8 GJ. Across a range of waste compositions, the liquid fuels produced by gasification and FT processing resulted in a net GWP ranging from −267 to −144 kg CO2e per Mg MSW, including offsets for conventional electricity and fuel production. The energy requirement associated with syngas compression for FT processing was significant and resulted in high levels of process-related GWP. The model demonstrates that an increased biogenic MSW fraction, assumed to be carbon neutral, reduced the GWP. However, a greater GWP reduction could be obtained through reduced FT pressure requirements, increased gas reaction rates, or a less carbon intensive power mix.
Waste management in the Irkutsk Region, Siberia, Russia: Environmental assessment of current practice focusing on landfilling

The municipal waste management system of the region of Irkutsk is described and a life cycle assessment (LCA) performed to assess the environmental performance of the system. Annually about 500,000 tons of waste are managed. The waste originates from three sources: household waste (27%), commercial waste (23%) and office & institutional waste (44%). Other waste of unknown composition constitutes 6%. Only 3% of the waste is recycled; 97% of the municipal waste is disposed of at the old Alexandrovsky landfill. The environmental impact from the current system is dominated by the landfill, which has no gas or leachate collection system. The global warming contribution is due to the emission of methane of the order of 420,000 tons CO2-equivalents per year. Collection and transport of the waste are insignificant compared with impacts from the landfill. As the old landfill runs out of capacity in a few years, the LCA modelling showed that introduction of a new and modern landfill with gas and leachate collection could improve the performance of the waste management system significantly. Collection of landfill gas and utilization for 30 years for electricity production (gas turbine) would reduce the global warming completely and result in a net saving of 100,000 CO2-equivalents per year due to storage of biogenic carbon in the landfill beyond 100 years. Considering other first-order degradation rates for the landfilled organic matter did not overtly affect the results, while assumptions about the top cover oxidation of methane significantly affected the results. This shows the importance of controlling the gas escape from the landfill.
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.

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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.

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LCA af genbrug af mursten

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Modelling sensitivity and uncertainty in a LCA model for waste management systems - EASETECH

In the new model, EASETECH, developed for LCA modelling of waste management systems, a general approach for sensitivity and uncertainty assessment for waste management studies has been implemented. First general contribution analysis is done through a regular interpretation of inventory and impact assessment results. Based on findings from this step, the user can carry out sensitivity analysis on numerous key parameters through the use of parameters at most input places. For every parameter the users can then specify a list of values, termed a numberlist, to represent different values for each parameter, that is then propagated throughout the model. This means that all results are obtained in the form of numberlists. In the next step, uncertainty propagation is done through the use of single probability distributions in lieu of the parameters. Uncertainty contribution analysis can next be generated based on the results of steps 1 & 2. The 4th step of combined sensitivity analysis can currently not be carried graphically in the model, but can be performed by calculating in EASETECH for two scenarios' results for different combinations of values for two parameters and extrapolating the results to delimitate the space of predominance of each scenario.
A new modeling framework for environmental assessment of waste and energy systems

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.

Boundaries matter: Greenhouse gas emission reductions from alternative waste treatment strategies for California's municipal solid waste
How waste is managed – whether as a nuisance to be disposed of, or as a resource to be reused – directly affects local and global environmental quality. This analysis explores the GHG benefits of five treatment options for residual municipal solid waste (MSW) in California: Business As Usual (landfilling), Anaerobic Digestion, Incineration, 40% Reduction, and MaxEnergy (both incineration and anaerobic digestion). Because recycling efforts in California are already strong, this analysis focuses on non-recyclables and asks what else can be done with the material fractions that are currently reaching landfills. Using two different waste LCA models, EASEWASTE (a Danish model) and WARM (a U.S. model), we find that improved biogenic waste management through anaerobic digestion and waste reduction can lead to life-cycle GHG savings when compared to Business As Usual. The magnitude of the benefits depends strongly on a number of model assumptions: the type of electricity displaced by waste-derived energy, how biogenic carbon is counted as a contributor to atmospheric carbon stocks, and the landfill gas collection rate. Assuming that natural gas is displaced by waste-derived energy, that 64% of landfill gas is collected, and that our system boundary begins when waste is thrown away and ends with disposal or conversion to air emissions, reducing California's residual waste by 40% can lead to a savings of 6 Mt (million metric tonnes) of CO2-e per year, and digesting California's biogenic waste could save 0.6 Mt CO2-e per year. Source reduction is the most robust means to mitigate GHG emissions from waste, though either increasing landfill gas capture rates within the current management plan or digesting biogenic waste (and designing landfills to maximize carbon sequestration) provide two other important means for greenhouse gas mitigation from waste management.
LCA and economic evaluation of landfill leachate and gas technologies

Landfills receiving a mix of waste, including organics, have developed dramatically over the last 3–4 decades; from open dumps to engineered facilities with extensive controls on leachate and gas. The conventional municipal landfill will in most climates produce a highly contaminated leachate and a significant amount of landfill gas. Leachate controls may include bottom liners and leachate collection systems as well as leachate treatment prior to discharge to surface water. Gas controls may include oxidizing top covers, gas collection systems with flares or gas utilization systems for production of electricity and heat. The importance of leachate and gas control measures in reducing the overall environmental impact from a conventional landfill was assessed by life-cycle-assessment (LCA). The direct cost for the measures were also estimated providing a basis for assessing which measures are the most cost-effective in reducing the impact from a conventional landfill. This was done by modeling landfills ranging from a simple open dump to highly engineered conventional landfills with energy recovery in form of heat or electricity. The modeling was done in the waste LCA model EASEWASTE. The results showed drastic improvements for most impact categories. Global warming went from an impact of 0.1 person equivalent (PE) for the dump to ~0.05 PE for the best design. Similar improvements were found for photochemical ozone formation (0.02 PE to 0.002 PE) and stratospheric ozone formation (0.04 PE to 0.001 PE). For the toxic and spoiled groundwater impact categories the trend is not as clear. The reason for this was that the load to the environment shifted as more technologies were used. For the dump landfill the main impacts were impacts for spoiled groundwater due to lack of leachate collection, 2.3 PE down to 0.4 PE when leachate is collected. However, at the same time, leachate collection causes a slight increase in eco-toxicity and human toxicity via water (0.007E to 0.013PE and 0.002 to 0.003 PE respectively). The reason for this is that even if the leachate is treated, slight amounts of contaminants are released through emissions of treated wastewater to surface waters. The largest environmental improvement with regard to the direct cost of the landfill was the capping and leachate treatment system. The capping, though very cheap to establish, gave a huge benefit in lowered impacts, the leachate collection system though expensive gave large benefits as well. The other gas measures were found to give further improvements, for a minor increase in cost.
Recycling of Glass
Glass is used for many purposes, but in the waste system glass is predominantly found in terms of beverage and food containers with a relatively short lifetime before ending up in the waste. Furthermore there is a large amount of flat glass used in building materials which also ends up in the waste system; this glass though has a long lifetime before ending up in the waste. Altogether these product types add up to 82% of the production of the European glass industry (IPCC, 2001). Recycling of glass in terms of cleaning and refilling of bottles as well as the use of broken glass in the production of new glass containers is well established in the glass industry. This chapter describes briefly how glass is produced and how waste glass is recycled in the industry. Quality requirements and use of recycled products are discussed, as are the resource and environmental issues of glass recycling.

Recycling of Metals
Metals like iron and aluminium are produced from mineral ore and used for a range of products, some of which have very short lifetimes and thus constitute a major fraction of municipal waste. Packaging in terms of cans, foils and containers are products with a short lifetime. Other products like appliances, vehicles and buildings, containing iron and aluminium metals, have long lifetimes before they end up in the waste stream. The recycling of production waste and postconsumer metals has a long history in the metal industry. Some metal smelters are today entirely based on scrap metals. This chapter describes briefly how iron and aluminium are produced and how scrap metal is recycled in the industry. Quality requirements and use of recycled products are discussed, as are the resource and environmental issues of metal recycling. Copper and other metals are also found in waste but in much smaller quantities than iron and aluminium; and the majority of these metals are found in waste electrical and electronic equipment (WEEE). A description of this can be found in Chapter 11.2.
Recycling of Paper and Cardboard

Paper and cardboard are produced from pulp derived from plant fibers, primarily wood. Paper and cardboard is used for many different products, such as for packaging material, newsprint and advertisements. Most of these products have very short lifetimes and thus constitute a major fraction of most waste. Recycling of paper and cardboard production waste and postconsumer waste has a long history in the pulp and paper industry. The recycled material now makes up more than half of the raw material used in European pulp and paper industry (ERPC, 2004). This chapter describes briefly how paper and cardboard are produced and how waste paper is recycled in the industry. Quality requirements and use of recycled products are discussed, as are the resource and environmental issues of paper recycling.

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Implementation of life cycle assessment models in solid waste management

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Life-cycle-assessment of the historical development of air pollution control and energy recovery in waste incineration

Incineration of municipal solid waste is a debated waste management technology. In some countries it is the main waste management option whereas in other countries it has been disregarded. The main discussion point on waste incineration is the release of air emissions from the combustion of the waste, but also the energy recovery efficiency has a large importance.

The historical development of air pollution control in waste incineration was studied through life-cycle-assessment modelling of eight different air pollution control technologies. The results showed a drastic reduction in the release of air emissions and consequently a significant reduction in the potential environmental impacts of waste incineration. Improvements of a factor 0.85–174 were obtained in the different impact potentials as technology developed from no
The importance of efficient energy recovery was studied through seven different combinations of heat and electricity recovery, which were modelled to substitute energy produced from either coal or natural gas. The best air pollution control technology was used at the incinerator. It was found that when substituting coal based energy production total net savings were obtained in both the standard and toxic impact categories. However, if the substituted energy production was based on natural gas, only the most efficient recovery options yielded net savings with respect to the standard impacts. With regards to the toxic impact categories, emissions from the waste incineration process were always larger than those from the avoided energy production based on natural gas. The results shows that the potential environmental impacts from air emissions have decreased drastically during the last 35 years and that these impacts can be partly or fully offset by recovering energy which otherwise should have been produced from fossil fuels like coal or natural gas.

Models for waste life cycle assessment: Review of technical assumptions

A number of waste life cycle assessment (LCA) models have been gradually developed since the early 1990s, in a number of countries, usually independently from each other. Large discrepancies in results have been observed among different waste LCA models, although it has also been shown that results from different LCA studies can be consistent. This paper is an attempt to identify, review and analyse methodologies and technical assumptions used in various parts of selected waste LCA models. Several criteria were identified, which could have significant impacts on the results, such as the functional unit, system boundaries, waste composition and energy modelling. The modelling assumptions of waste management processes, ranging from collection, transportation, intermediate facilities, recycling, thermal treatment, biological treatment, and landfilling, are obviously critical when comparing waste LCA models. This review infers that some of the differences in waste LCA models are inherent to the time they were developed. It is expected that models developed later, benefit from past modelling assumptions and knowledge and issues. Models developed in different countries furthermore rely on geographic specificities that have an impact on the results of waste LCA models. The review concludes that more effort should be employed to harmonise and validate non-geographic assumptions to strengthen waste LCA modelling.
Life-cycle assessment of the municipal solid waste management system in Hangzhou, China (EASEWASTE)

With the purpose of assessing the environmental impacts and benefits of the current municipal solid waste management system and two modified systems, EASEWASTE, a life-cycle-based model, was used to evaluate the waste system of Hangzhou city in China. An integrated model was established, including waste generation, collection, transportation, treatment, disposal and accompanying external processes. The results showed that CH4 released from landfilling was the primary pollutant contributing to global warming, and HCl and NH3 from incineration contributed most to acidification. Material recycling and incineration with energy recovery were important because of the induced savings in material production based on virgin materials and in energy production based on coal combustion. A modified system in which waste is transported to the nearest incinerators would be relatively better than the current system, mainly due to the decrease of pollution from landfilled waste and the increase in energy production from waste avoiding energy production by traditional power plants. A ban on free plastic bags for shopping was shown to reduce most environmental impacts due to saved oil resources and other materials used in producing the plastic bags. Sensitivity analysis confirmed the robustness of the results. LCA methodology and a model like EASEWASTE are very suitable for evaluating the overall environmental consequences, and can be used for decision support and strategic planning in developing countries such as China where pollution control has become increasingly important with the rapid increase of waste generation as well as the increasing public awareness of environmental protection.

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Recycling of metals: accounting of greenhouse gases and global warming contributions

Greenhouse gas (GHG) emissions related to recycling of metals in post-consumer waste are assessed from a waste management perspective; here the material recovery facility (MRF), for the sorting of the recovered metal. The GHG accounting includes indirect upstream emissions, direct activities at the MRF as well as indirect downstream activities in terms of reprocessing of the metal scrap and savings in terms of avoided production of virgin metal. The global warming factor (GWF) shows that upstream activities and the MRF causes negligible GHG emissions (12.8 to 52.6 kg CO₂-equivalents tonne⁻¹ of recovered metal) compared to the reprocessing of the metal itself (360—1260 kg CO₂-equivalents tonne⁻¹ of recovered aluminium and 400—1020 kg CO₂-equivalents tonne⁻¹ of recovered steel). The reprocessing is however counterbalanced by large savings of avoided virgin production of steel and aluminium. The net downstream savings were found to be 5040—19 340 kg CO₂-equivalents tonne⁻¹ of treated aluminium and 560—2360 kg CO₂-equivalents tonne⁻¹ of treated steel. Due to the huge differences in reported data it is hard to compare general data on the recovery of metal scrap as they are very dependent on the technology and data choices. Furthermore, the energy used in both the recovery process as well as the avoided primary production is crucial. The range of avoided impact shows that recovery of metals will always be beneficial over primary production, due to the high energy savings, and that the GHG emissions associated with the sorting of metals are negligible.

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Recycling of paper: Accounting of greenhouse gases and global warming contributions

Greenhouse gas (GHG) emissions have been established for recycling of paper waste with focus on a material recovery facility (MRF). The MRF upgrades the paper and cardboard waste before it is delivered to other industries where new paper or board products are produced. The accounting showed that the GHG contributions from the upstream activities and operational activities, with global warming factors (GWFs) of respectively 1 to 29 and 3 to 9 kg CO₂-eq. tonne⁻¹ of paper waste, were small in comparison with the downstream activities. The GHG contributions from the downstream reprocessing of the paper waste ranged from approximately 490 to 1460 kg CO₂-eq. tonne⁻¹ of paper waste. The system may be expanded to include crediting of avoided virgin paper production which would result in GHG contributions from —1270 to 390 kg CO₂-eq. tonne⁻¹ of paper waste. It may also be assumed that the wood not used for virgin paper production instead is used for production of energy that in turn is assumed to substitute for fossil fuel energy. This would result in GHG contributions from —1850 to —4400 kg CO₂-eq. tonne⁻¹ of paper waste. These system expansions reveal very large GHG savings, suggesting that the indirect upstream and operational GHG contributions are negligible in comparison with the indirect downstream emissions. However, the data for reprocessing of paper waste and the data for virgin paper production are highly variable. These differences are mainly related to different energy sources for the mills, both in regards to energy form (heat or electricity) and fuel (biomass or fossil fuels).

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Life cycle assessment of waste paper management: The importance of technology data and system boundaries in assessing recycling and incineration

The significance of technical data, as well as the significance of system boundary choices, when modelling the environmental impact from recycling and incineration of waste paper has been studied by a life cycle assessment focusing oil global warming potentials. The consequence of choosing a specific set of data for the reprocessing technology, the virgin paper manufacturing technology and the incineration technology, as well as the importance of the recycling rate was studied. Furthermore, the system was expanded to include forestry and to include fossil fuel energy substitution from saved biomass, in order to study the importance of the system boundary choices. For recycling, the choice of virgin paper manufacturing data is most important, but the results show that also the impacts from the reprocessing technologies fluctuate greatly. For the overall results the choice of the technology data is of importance when comparing recycling including virgin paper Substitution with incineration including energy Substitution. Combining an environmentally high or low performing recycling technology with an environmentally high or low performing incineration technology can give quite different results. The modelling showed that recycling of paper, from a life cycle point of view, is environmentally equal or better than incineration with energy recovery only when the recycling technology is at a high environmental performance level. However, the modelling also showed that expanding the system to include Substitution of fossil fuel energy by production of energy from the saved biomass associated with recycling will give a completely different result. In this case recycling is always more beneficial than incineration, thus increased recycling is desirable. Expanding the system to include forestry was shown to have a minor effect on the results. As assessments are often performed with a set choice of data and a set recycling rate, it is questionable how useful the results from this kind of LCA are for a policy maker. The high significance of the system boundary choices stresses the importance of scientific discussion on how to best address system analysis of recycling, for paper and other recyclable materials.
Experience with the use of LCA-modelling (EASEWASTE) in waste management

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Life-cycle assessment of waste incinerators - the significance of increasing air pollution control on the environmental impact

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