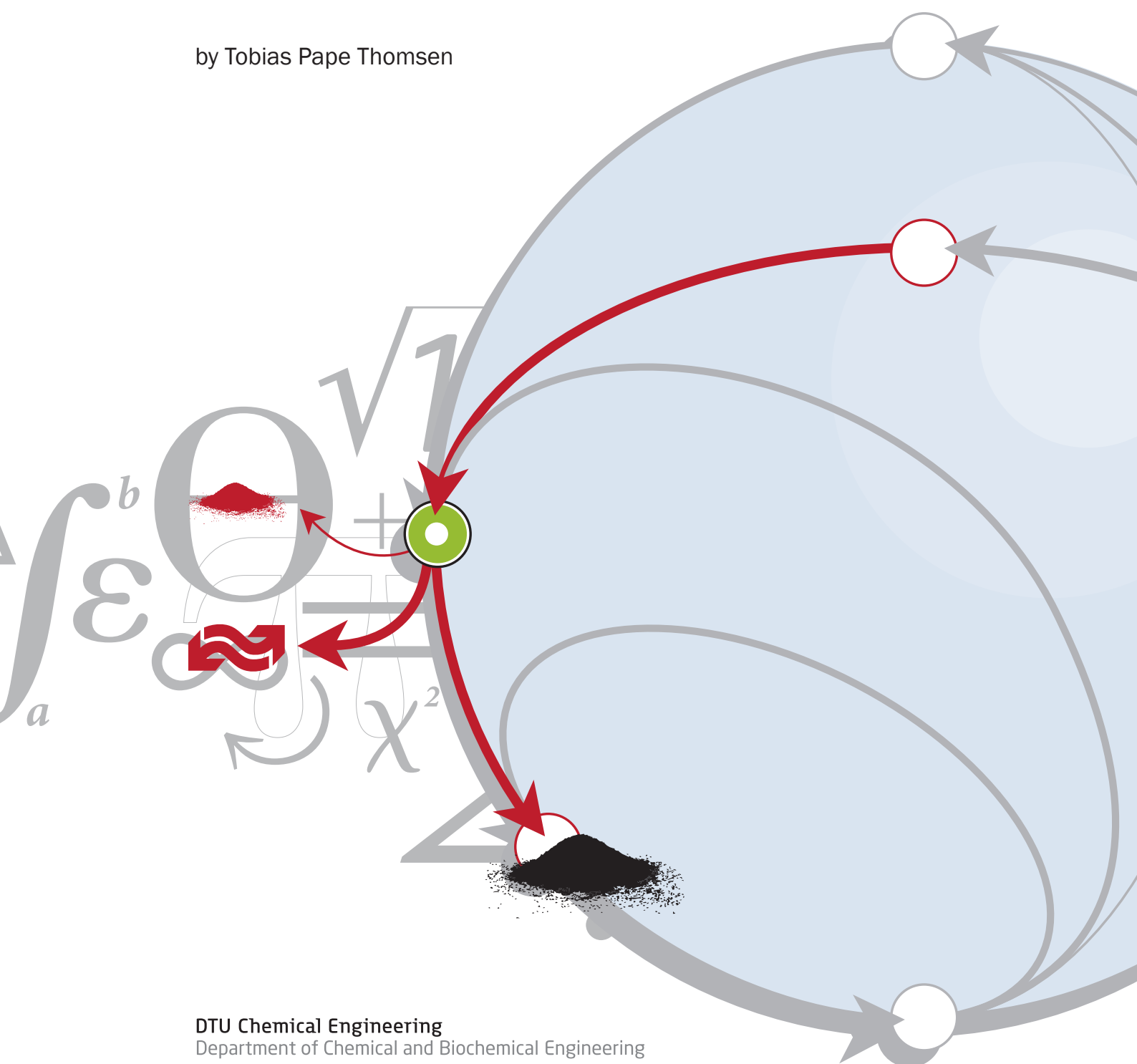


AquaGreen PCP phase 2, WP 5: Carbon Footprint Analysis of AquaGreen system:

DRYING AND PYROLYSIS OF SLUDGE - IN A CLIMATE PERSPECTIVE

by Tobias Pape Thomsen



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1 Summary

Current wastewater treatment systems are caught in a dilemma between recovery of non-renewable phosphorus as fertilizer on one hand and the environmental costs and uncertainties related to the current practice of applying modern wastewater sludge in agricultural systems on the other. To resolve these issues it has been proposed to integrate steam drying and thermal pyrolysis in the sludge conversion process to produce phosphorous rich char and a substantial amount of high quality district heating. The expected benefits of this new management option includes a decrease in transportation costs, reduced emissions of N_2O and CH_4 , thermal purifying the phosphorous rich char (removing organic xenobiotic compounds, pathogens, micro plastics and volatile heavy metals), realization of a larger fraction of the sludge energy potential and production of recalcitrant carbon in the char making this suitable for long term carbon sequestration and soil enhancement applications. On the other hand, the new thermal management option is expected to increase plant costs, increase consumption of power and utilities and lead to a loss of nitrogen fertilizer potential and organic matter.

In the present study, the potential pros and cons of integration of steam drying and thermal pyrolysis in sewage sludge management are investigated in a climate perspective. This is done by conducting a carbon footprint assessment in a full life cycle perspective of two reference systems without thermal sludge treatment and two scenario systems with thermal sludge treatment. The purpose of the study is to determine if integration of steam drying and thermal pyrolysis can improve the greenhouse gas balance of representative, Danish wastewater treatment. In addition, the study should point to the areas of the assessed systems where the impact on global warming potential from the systems is highest and therefore where the biggest optimization potential may be.

The study includes the following two references and two scenarios:

- Reference 1 (AD): A representative large Danish wastewater treatment plant with anaerobic sludge digestion, mechanical dewatering and distribution of residual sludge in nearby agricultural areas.
- Reference 2 (AER): A representative smaller wastewater treatment plant with aerobic sludge stabilization, mechanical dewatering and distribution of stabilized sludge in nearby agricultural areas.
- Scenario 1 (AD): A representative large Danish wastewater treatment plant with anaerobic sludge digestion, mechanical dewatering, steam drying and thermal sludge pyrolysis and distribution of pyrolysis char in nearby agricultural areas.
- Scenario 2 (NO): A representative smaller wastewater treatment plant without sludge stabilization, but with mechanical dewatering, steam drying and thermal pyrolysis and distribution of pyrolysis char in nearby agricultural areas.

It is found that steam drying and thermal pyrolysis of sewage sludge will have a very positive impact on the carbon footprint of systems with production, storage and agricultural application of dewatered sewage sludge. The thermal sludge treatment helps to avoid emissions of CH_4 , N_2O and CO_2 during especially storage and use-on-land processes, it increases energy production and the only substantial cost identified in this regard is related to the loss on nitrogen fertilizer potential.

In all investigated cases, it is found that there is a potential for 0.3-0.6% reduction in the average Danish persons carbon footprint from implementation of nationwide thermal sludge treatment. Additionally it was found that when modelling a system resembling Ejby Mølle waste water treatment plant in Odense, the results indicate a potential annual carbon footprint reduction of 7300 t $\text{CO}_2\text{-eq/year}$, corresponding to almost twice the reduction required by VandCenter Syd to reach a net zero emission profile.

Quality assessment of the method, data and results identified several sensitive aspects, but the overall conclusion from the analysis is that the approach and results are robust and representative, especially when used to assess the potential reductions in carbon footprint when moving from one of the reference systems to one of the modelled scenarios.

2 Introduction

The historical purpose of modern wastewater treatment (WWT) is the difficult task of controlling the potential damage caused by emitting wastewater from society into the ecosphere. Wastewater treatment plants (WWTPs) are therefore designed specifically to match the requirements and vulnerability of the recipient with optimal reduction of pathogens, nutrients and organic matter while also dealing with other harmful substances i.e. organic and inorganic pollutants [1]. However, in present society, the task of waste water treatment is growing even more complex. In addition to fighting eutrophication of local water recipients, modern waste water treatment companies are also engaged in mitigation of climate change, production of energy services as well as recovery of critical and valuable resources for the agricultural sector. A central by-product from waste water treatment in this regard is the residual solids from the water treatment known as wastewater sludge or sewage sludge.

Sewage sludge usually contain high concentrations of nitrogen, potassium, phosphorus and organic matter which has been removed from the treated waste water. These valuable constituents make the sludge - in many regards, a cheap fertilizer and soil enhancer [2]. However, sludge can also contain significant amounts of heavy metals, organic pollutants, micro plastics and pathogens depending on the specific design of the WWTP. Emerging new knowledge on this topic has led to new concerns related to the use of sludge on farm land and the potential harmful effects of this practice related to food production and ground water quality [3]. In addition, there is a growing concern about the potential negative effect on global warming from the current practice of sludge nutrient utilization which may involve a high risk of emissions of the very potent and harmful greenhouse gases nitrous oxide (N_2O) and methane (CH_4). In combination, these concerns have caught wastewater treatment systems in a dilemma between recovery of non-renewable phosphorus (+N, K and micro nutrients) as fertilizer on one hand and risk of substantial negative impact on climate, environment and human health on the other.

In Denmark, the official recommendation of the national trade organization for WWTPs and water producers is now to avoid the use of sludge in agricultural systems in areas with ground water reservoirs and in the long term to avoid the use of sludge in agricultural systems in general. The concern of the trade organization is related to the thousands of industrial chemicals, antibiotics, hormones etc. present in modern wastewater, and the many unknowns related to hazardous impacts of these compounds, their degradation products and potential cocktail effects. Instead, the Danish WWTP and water producers' trade organization (DANVA) propose to go by the precautionary principle and convert the sludge in thermal systems producing electricity, heat, concrete or cement as this would at least reduce the impact from WWTPs on energy use and related greenhouse gas emissions [4].

This approach would also resolve the issue related to potential production of N_2O and CH_4 from storage, transportation and farm soil distribution of sludge. These impacts have been included for several years in wastewater treatment related LCAs, but the data has been based on very conservative assumptions extrapolated from studies on degradation of organic food waste [5,6]. In recent studies, experiments on actual emissions from open sludge storage facilities have shown that the real impact from especially N_2O emissions from these sources may be much higher than previously anticipated [5,7].

However, the recommendation by DANVA is not very well aligned with the current practice, as the use of wastewater sludge on Danish farm soils increased to 77% of total sludge in 2012 which is the highest level recorded in official statistics [8]. Incineration of sludge and the related immobilization of phosphorus is also in sharp contrast to the ambitions of the Danish Ministry of Environment as there is an increased official focus on phosphorus scarcity and increased recovery from wastewater and wastewater sludge [9]. Phosphorus is a key constituent in all organic matter and P-availability is often a limiting factor in agricultural production systems. Phosphorous takes up two of 27 places on EU's list of critical raw materials and the strategic and political importance of the phosphorus resource, use- and recovery rates will increase further with increasing population [10,11]. Assessments of the present phosphorus resource and depletion rate vary significantly between studies and while one study predicts a peak in production of commercial phosphate in 2033 another study suggest availability of phosphorus on global scale to last for 48 to 235 years depending on the global increase in crop production [12,13]. Regardless of the rate of depletion, increased scarcity of commercial phosphorus will increase phosphate production costs – most likely by factor a 3 to 5 already in this century [14]. The phosphorus resource is a politically sticky topic with a highly unbalanced geopolitical dimension, since 85 % of the world's remaining P stocks are controlled by only 5 countries, with Morocco and China being the main players [15].

To accommodate the dilemma between the risks associated with the current practice of direct sludge distribution and the loss of critical phosphorous resources if sludge is incinerated in e.g. cement production facilities, a large MUDP research project has recently been funded and initiated. The purpose of the project is to refine and develop current practice from Germany with chemically based phosphorous extraction from sewage sludge. The recovery potentials are high (80-90 %), but so is the current cost associated to this management strategy (160 kr/kg P) [16]. The high price of P recovery by refined chemical processes makes the P dilemma into a P trilemma as illustrated in

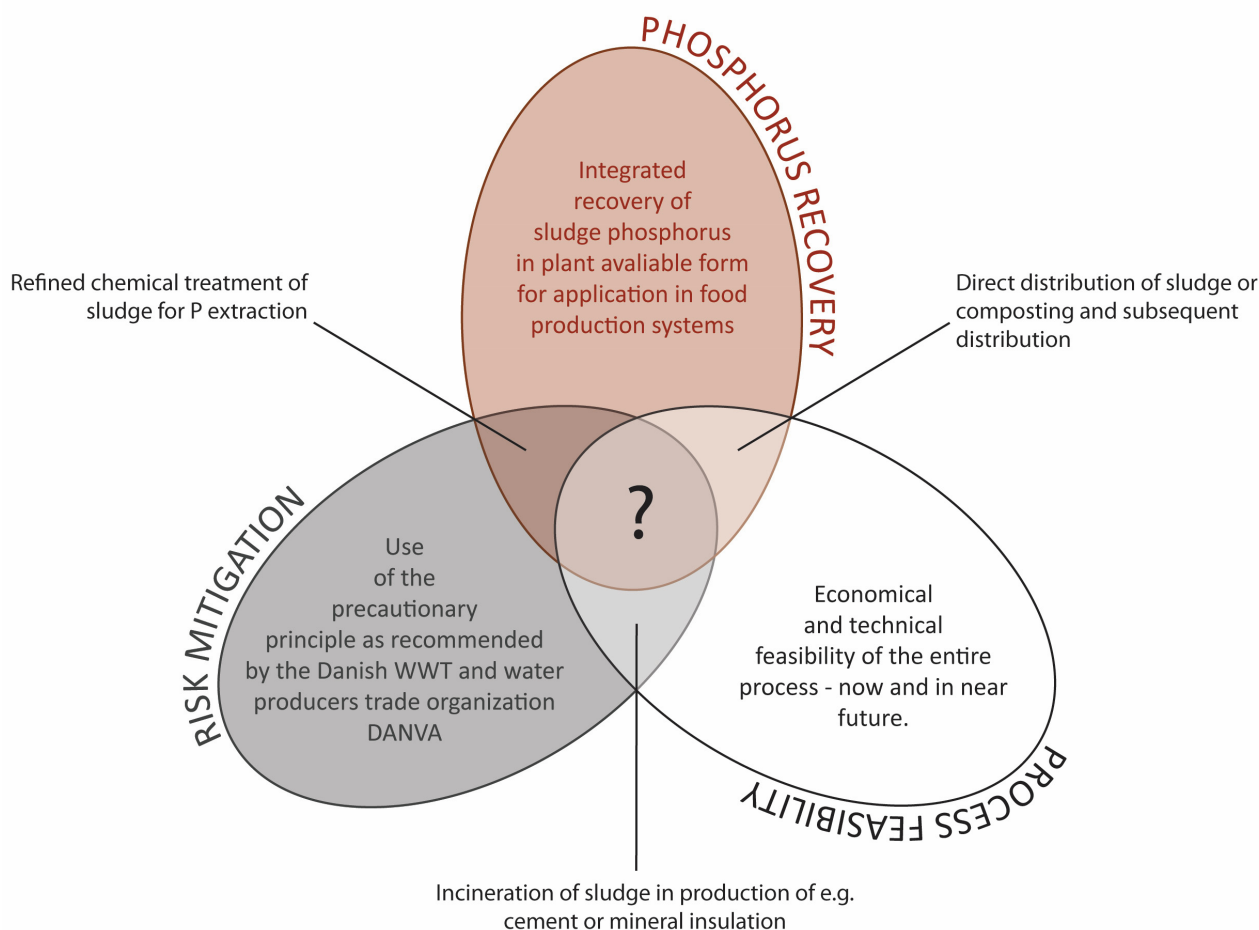


Figure 1: The sludge-P trilemma

A combination of drying and thermal gasification or pyrolysis has been proposed by actors in academia and industry as a way to mitigate the combined problems related to wastewater sludge and the scarcity of the phosphorus resource. Thermal pyrolysis and low temperature gasification are maturing technologies that may be used to convert a variety of low-value, hard-to-handle biomass fuels from different sectors of society to P-rich chars or ashes and a process gas of varying quality and quantity. The gas contains a substantial amount of the energy potential in the sludge, and is most readily used to fuel the process and/or provide heat to external sources and systems [17–21].

If the thermal process is kept at sufficiently low temperatures, sintering of the ashes and the related fouling and corrosion issues are largely avoided. In addition, a low temperature suppress the generation of toxic polycyclic aromatic hydrocarbons and is expected to keep phosphorus highly plant available and leave a significant fraction of recalcitrant char in the ash fraction making this suitable for long term carbon sequestration, P fertilization and potentially soil enhancement applications [18,22,23].

The background for the current study is the development of a new sludge management option consisting of combined steam drying and thermal sludge pyrolysis. The end goal of the development process is to provide a system to encompass all three legs of the sludge P-trilemma and provide a robust and cost-efficient solution that will recover energy and phosphorous from sludge as high quality district heating and P-rich, thermally purified pyrolysis char. A simplified illustration of such a system is provided in Figure 2.

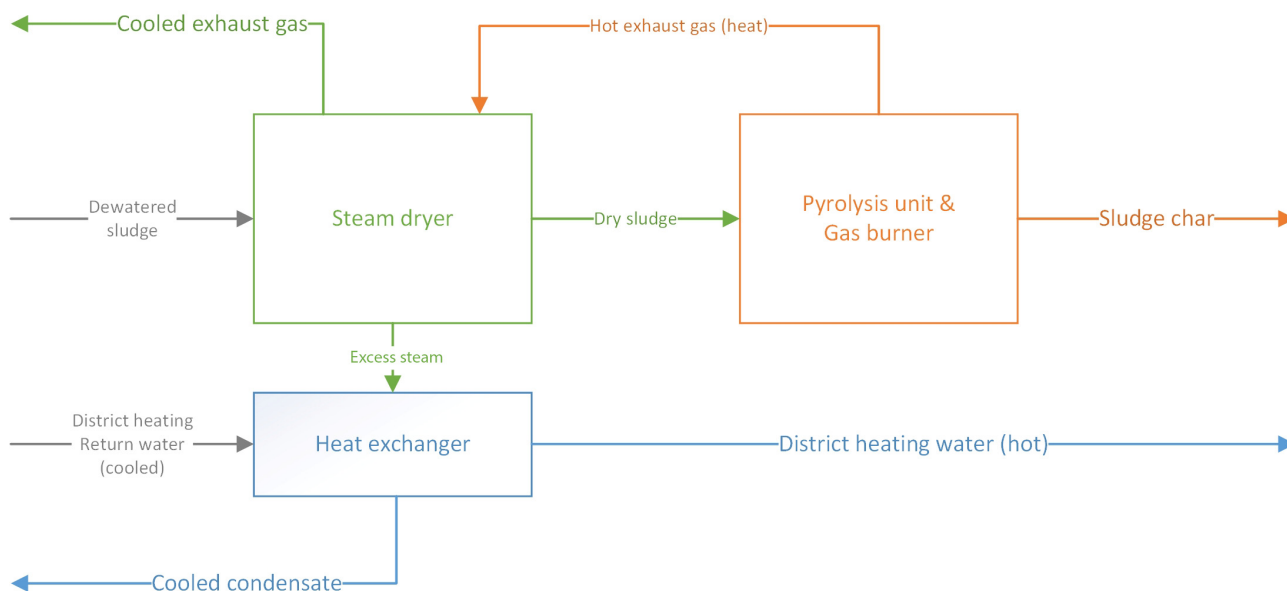


Figure 2: Simplified illustration of main mass and energy flows in a thermal sludge management system consisting of stem drying and thermal pyrolysis

In the current work, the proposed solution to the sludge-P trilemma is assessed from a climate perspective. This is important to avoid adding a substantially increased burden on the climate when aiming to solve the trilemma of risk and P-recovery issues related to modern sludge management. The focus of the assessment is therefore on the greenhouse gas balance of the proposed system and the potential difference in global warming potential from the system compared to current references – popularly referred to as a Carbon Footprint assessment. Issues of phosphorus recovery, toxicity impact and pollution issues are discussed in other work packages.

The carbon footprints of references and scenarios are investigated as a life cycle assessment of the sludge management part of a modern representative Danish wastewater treatment facility, taking into account direct emissions as well as emissions related to production of central plant equipment, the benefit of energy and fertilizer products and relevant end-of-life scenarios.

3 Materials and methods

This study is conducted in 4 stages; i) Specification of goal and scope of the study, ii) Procurement of data and Establishment of Life Cycle Index, iii) Implementation of Life Cycle Index data in LCA software and extraction of Life Cycle Impact Assessment results, and iv) Interpretation and validation of results.

3.1 Goal and Scope

The goal of this study is to provide a firsthand assessment of the potential impact of a new, thermal sewage sludge management strategy on the Carbon Footprint of sewage sludge management in Denmark. The new strategy involves integration of steam drying and thermal pyrolysis in a continuous on-site thermal sewage sludge treatment system and subsequent use of the solid residual char product as a soil-carbon enhancer and multi-component fertilizer. The study aims to quantify the following work hypothesis:

- Continuous on-site thermal treatment of sewage sludge will influence transport requirements in the system
- Continuous on-site thermal treatment of sewage sludge will influence greenhouse gas emissions from sludge storage and in-field decomposition
- Continuous on-site thermal treatment of sewage sludge will influence the net supply of district heating and power from the wastewater treatment plant to/from the national grids
- Continuous on-site thermal treatment of sewage sludge will influence total system infrastructure costs
- Continuous on-site thermal treatment of sewage sludge will influence on-site consumption of electricity and other utilities
- The effect of the thermal sludge management will vary with the sludge composition and the system design

To encompass the effect of sludge composition and maintain a simple assessment level in a representative Danish setting, it is decided to focus the work on the following four systems:

- Reference 1 (AD): A representative large Danish wastewater treatment plant with anaerobic sludge digestion, mechanical dewatering and distribution of residual sludge in nearby agricultural areas.
- Reference 2 (AER): A representative smaller wastewater treatment plant with aerobic sludge stabilization, mechanical dewatering and distribution of stabilized sludge in nearby agricultural areas.
- Scenario 1 (AD): A representative large Danish wastewater treatment plant with anaerobic sludge digestion, mechanical dewatering, steam drying and thermal sludge pyrolysis and distribution of pyrolysis char in nearby agricultural areas.
- Scenario 2 (NO): A representative smaller wastewater treatment plant with no dedicated sludge stabilization, but with mechanical dewatering, steam drying and thermal pyrolysis and distribution of pyrolysis char in nearby agricultural areas.

With this background, the goal of the study is to compare the Carbon Footprint of the above four mentioned scenarios for sewage sludge extraction, management and end-of-life in representative Danish wastewater treatment settings. The study encompasses a life cycle assessment of Global Warming Impact potential from the four systems. The LCA impact assessment results are generated from a series of models constructed in Easetech [24]¹ using the IPCC 2013 Life Cycle Impact Assessment method.

3.1.1 Functional unit, system boundaries, allocation and energy production/use

The study models are all based on the functional unit (FU) “management of 1 t of active sludge with a pre-determined global sludge composition”. The temporal boundaries of the assessed systems are from the reference state (today or near future) and 15-20 years onwards, with dynamic effects (global warming potential and soil C and N dynamics) evaluated in a 100 year perspective. The geographical boundaries are set by the reference WWTP and logistics system extending downstream from this facility required to clean 1 m³ of WW and handle all residuals. It is the aim that the

¹ Easetech is an LCA software developed by the Department of Environmental Engineering at the Technical University of Denmark (<http://www.easetech.dk>). The program applied in the present work is Easetech version 2.8.9 with the 2018-07 database

investigated systems should be representative for a broad range of waste water treatment plants in Denmark and comparable countries.

System processes that are similar or assumed similar between all four systems are not modelled. This approach reduces complexity of the model development and analysis as well as the total level of data-related uncertainty. The assessment only includes material and energy cost of infrastructure related to the steam drying system, the thermal pyrolysis system and the anaerobic digestion system as these are expected to represent the largest capital cost differences among the systems. Infrastructure material costs are assumed to be independent of plant size and single case values are assumed to be representative for assessment of the functional unit in general.

Avoided production of heat, electricity and NPK fertilizers are included in the model. The study is conducted as a consequential LCA, since the purpose of the study is to assess the consequences of a change in demand for a new sludge management service. For this reason, wherever possible only marginal suppliers are considered in the system. In LCA in general it is a recommended approach to replace the same source of energy as is used [25]. The background energy system can be expected to largely influence the carbon intensity of the electricity and heat used and produced in the different systems. As the purpose of the study is decision support related to decisions that have long-term implications, the relevant marginal supply is the long-term marginal supply, sometimes referred to as the ‘build-marginal’, i.e. the technology of the capacity to be installed next [26]. Build marginal technology for Danish production of electricity and heat has been thoroughly investigated in a series of studies conducted by DTU Management [27,28]. Based on these studies and the goal and scope of the present assessment, the setup in Table 1 is used in the model:

Table 1: Build marginal technology used in the primary system modelling for production and use of electricity and district heating

	Electricity % of demand	District heating % of demand
Off-shore wind	100	33*
Biomass	0	18

*Used in large scale district heating heat pumps with Coefficient of Performance 2.5. The remaining share of the district heating supply demand is provided from waste heat or low quality heat sources via the heat pumps.

There are significant uncertainties related to the development of the future energy system and to the determination of the build marginal. An increased penetration of off-shore wind is quite certain based on recent reductions in the cost of electricity from off-shore wind farms and the current political focus hereon. However, the large scale implementation of heat pumps in district heating is still in a phase of early development. As this may be expected to have substantial influence on the LCA results, these aspects are included in the sensitivity analysis by comparing the near future models with models using a commonly applied marginal for present Denmark electricity and heat production – coal [5,29,30].

Avoided production of N, P and K fertilizer is modeled with average EU values instead of marginal fertilizer values as these were not available in the applied software. This inconsistency is expected to have limited effect on the overall impact assessment result as fertilizer production system differences and quality differences from the average to the marginal is likely to have a minor effect on the carbon balance whereas the effect on other impact categories e.g. terrestrial toxicity, may be much more prominent when shifting from average to marginal P fertilizer quality [2,15]. However, it is recommended to remedy this shortcoming in later studies.

3.2 System development

Currently, only one system for continuous steam drying and thermal pyrolysis of sewage sludge exist in Denmark. This system is placed at Ejby Mølle waste water treatment plant in Odense, which is owned and operated by the supply and utilities company VandCenter Syd.

To apply central data from the existing plant, the development and modelling of the four assessed systems takes origin in the setup at Ejby Mølle. The main reference is modelled as the site was before installation of the thermal

system. This is represented in the generalized system “Reference 1 (AD) - a larger representative wastewater treatment plant with anaerobic sludge digestion”.

From this system model, the other models are generated as what-if scenarios based on the following approach:

- Reference 2 (AER): what if there was no anaerobic digestion facility at the wastewater treatment plant
- Scenario 1 (AD): What if a steam drying and thermal pyrolysis system was installed with full capacity
- Scenario 2 (NO): What if there was no dedicated sludge stabilization and a steam drying and thermal pyrolysis system was installed with full capacity

Several other references and scenarios could be relevant to investigate as well, but with these two references and scenarios, a simple setup with broad applicability in Danish settings has been set. Overall differences and similarities between the sludge management pathways in the assessed systems are illustrated in Figure 3.

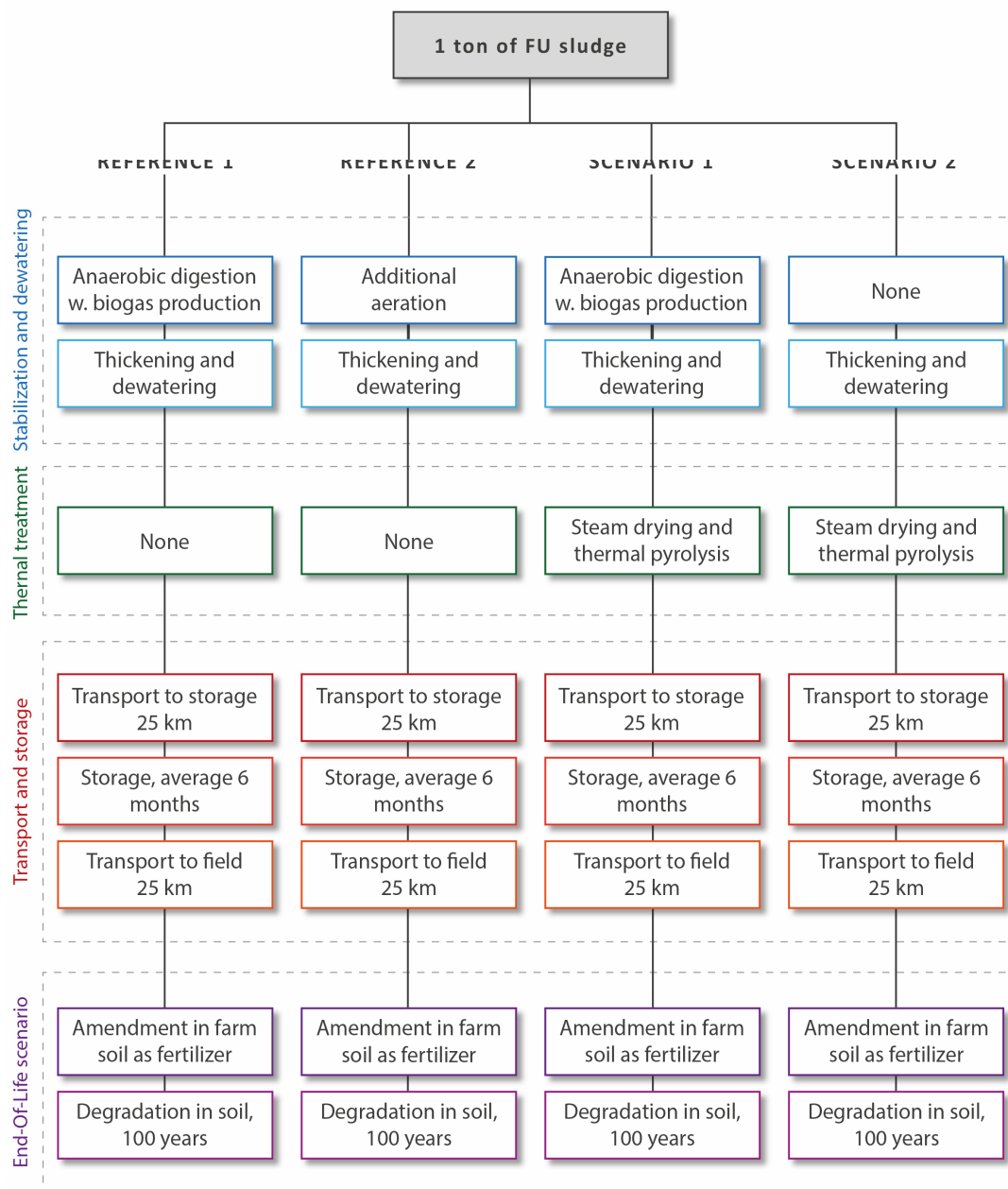


Figure 3: System model overview

To keep modeling and result interpretation simple and to the point, sludge stabilization is modelled as a separate stage in all systems. In real systems aerobic stabilization often takes place in the same reactors as nitrogen removal as aeration is an inevitable part of this process.

The primary relation between the modelling of Reference #1 and Ejby Mølle waste water treatment plant is found in a composition analysis of dewatered sludge from this facility. The analysis can be found in Appendix 1. From this analysis, the composition of the Functional Unit sludge is derived using the transfer functions described in section 3.3.2. The composition of the modelled sludge is influenced by the design of Ejby Mølle waste water treatment plant, as well as the geography and demography in the waste water collection area and finally by the season/time of collection. At Ejby Mølle, the plant treatment process includes mechanical cleaning, primary settling, biological P removal, nitrification and de-nitrification, secondary clarifiers, anaerobic digestion and dewatering. After dewatering, the sludge is composted at a local environmental facility [31]. The sludge is anaerobically digested under mesophilic conditions (i.e. 37 °C) for 20-25 days before dewatering in decanter centrifuges [31,32]. The sludge entering the digesters consist of approximately 40% primary sludge from the primary settling tanks and 60% that is a mixture of pre-thickened secondary sludge from the biological waste water treatment at Ejby Mølle, recuperative sludge from the digester as well as sludge from two other Vandcenter Syd treatment facilities and some industrial wastewater. During the primary settling, flocculation polymers and iron sulfate is added to facilitate precipitation [32]. To investigate the influence of the sludge composition on the overall results, three additional sludge composition models are evaluated in the section on model qualification (section 4.2).

For simplicity, all models use the same functional unit sludge composition. In reality there is a fundamental difference between systems with primary settlers and extraction of primary sludge and systems with secondary sludge only. In other recent sludge management LCAs in a Danish setting systems have been divided up into small and large plants [5]. However, such an approach only makes sense with a larger number of systems and a higher study complexity.

As shown in Figure 3, all systems are modelled with storage of sludge or char and subsequent amendment to farm soil. At Ejby Mølle, the sludge is composted. It has not been possible to obtain exact and up-to-date values on the share of sludge composting in Denmark. However, it has been found that as much as 77% of total sludge quantity is currently used on land while the share of identified composting in 2007 was approximately 16% of the total amount used on land [8,33]. Based on these numbers, and similar approaches in other studies, it is expected to be more broadly representative to model conventional storage and use on land than composting [34,35].

In addition to sludge composition, primary on-site data from Ejby Mølle has also been applied in the models with regard to the allocation between heat and power production from Ejby Mølle's biogas fueled gas engines [32] as well as the impact of steam drying and thermal pyrolysis on the sludge (see section 3.3.2).

3.3 LCA methodology

3.3.1 Impact assessment method and normalization

Since impact assessment only covers impact on climate change, it is decided to use IPCC2013 100 years Impact Assessment method with Carbon-Climate Feedback integrated with Easetech [24] version 2.8.9 with the 2018-07 database for the Life Cycle Impact Assessment.

Normalization of model results is performed to improve interpretation and decision making. Therefore, normalization is conducted using a scaling of the Impact Assessment results to match the normalized impact to an average Danish person's annual sewage sludge production based on dry matter content. The scaling factor 0.5 person equivalents per functional unit is used based on estimated values of total 140.000 t sludge dry matter per year in Denmark [8], 5.8 million Danes in Denmark [36], 1 person equivalent per Dane and 50 kg dry matter per FU (see section 3.3.2). Normalization of the potential impact on Global Warming is performed using an up-to-date reference of in-house greenhouse gas emissions in Denmark of 10 t CO₂-eq per Dane today as well as official forecast emission expectations of 7.4 t CO₂-eq per Dane in near future scenarios (2021) [37].

3.3.2 Development of LCIs

LCIs for the systems assessed in the study are comprehensive and only selected data are presented in the following. Additional data for the LCIs can be found in Appendix 1 through Appendix 7. Details on specific Easetech processes can be obtained upon request. Sludge and char composition analysis by Agrolab (appendix 1) have been supplemented by measurements conducted by KU PLEN. In such cases, samples have been analyzed by ICP-OES (Optima 5300 DV, Perkin Elmer, USA) using a procedure described by Hansen et al. (2009) [38] after digestion with HNO₃, H₂O₂ and HF.

3.3.2.1 Main material flow compositions and related transfer functions

The modelled composition of the Functional Unit sludge as well as sludge and char spread on land in the different system models are presented in Table 2. Compositions in the different stages between FU composition and soil application as well as after 100 years of degradation are included in Appendix 8.

Table 2: Sludge and char compositions. REF 1 and 2 = Reference systems 1 and 2. SCE 1 and 2 = Scenarios 1 and 2. UOL = Use on Land. AR = As received. AD = with Anaerobic Digestion. AER = with Aerobic stabilization. NO = System with no dedicated sludge stabilization.

		FU sludge	REF 1 (AD) sludge UOL	REF 2 (AER) sludge UOL	SCE 1 (AD) char UOL	SCE 2 (NO) char UOL
Water	wt% AR	95.0	95.0	74.3	0.0	0.0
Total Solids	wt% AR	5.0	5.0	25.7	100.0	100.0
Organic Carbon	wt% DRY	42.0	42.0	33.4	22.8	26.3
Nitrogen	wt% DRY	5.1	5.1	5.0	2.6	2.0
Phosphorous	wt% DRY	3.1	3.1	3.6	6.1	3.9
Potassium	wt% DRY	0.4	0.4	0.4	0.7	0.5
Magnesium	wt% DRY	0.7	0.7	0.6	1.1	0.7
Sulfur	wt% DRY	1.2	1.2	1.0	1.4	0.7
REST (org+inorg)	wt% DRY	47.0	47.0	56.0	65.2	66.0

It was assumed that the main difference between recovery of solids in the anaerobic digestion and the aerobic stabilization related to the carbon content of the sludge and the related heating value [5]. In this regard, a set of heating value measurements on sludge and char samples have been conducted to provide data for the energy balance. The heating value was determined as Higher Heating Value (HHV) in a Parr 6300 Bomb Calorimeter with an oxygen supply at 40 bar using small samples of 0.5-0.8 g. Heating value of pyrolysis chars was examined in the same way.

Transfer functions are used in Easetech modelling to move the masses of relevant substances, elements and compounds through different unit processes. All transfer functions applied in the models are provided in Appendix 4 to Appendix 7. In Table 3, an example is provided showing the transfer functions applied in the Reference 1 (AD) system encompassing anaerobic sludge digestion, sludge storage and use-on-land.

Table 3: Transfer functions from Reference 1 (AD). The functions following the main sludge mass are included in the table. AD = Anaerobic Digestion. All transfer functions from the model are provided in Appendix 4 to Appendix 7 where data references are also included.

All in % mass	AD: To residual sludge	Dewatering: To dewatered sludge	Storage: To remaining sludge	Soil degradation: In soil after 100 years
Water	98.3	13.5	99	0
Total Solids	68.1	93.6	95.0	69.9
Organic Carbon	56	92.36	88	5.6
Nitrogen	87.1	92.96	97	95.1
Phosphorous	100	93.62	100	100
Potassium	100	89.06	100	100
Magnesium	100	72.54	100	100
Sulfur	95	92	100	100
REST (org+inorg)	73	95	100	100

3.3.2.2 WWTP processes - Anaerobic digestion, aerobic sludge stabilization and dewatering

Most of the Waste Water Treatment Plant (WWTP) related processes are assumed to be comparable in all systems, and therefore omitted from the modelling. This is a simplification that includes the following assumptions:

- Emissions and utility consumption related to sludge thickening are the same in all cases and omitted
- Use of de-watering polymers is the same in all cases and omitted
- Global dewatering efficiency and effectivity, requiring 1.25E-04 kWh per kg total wet weight [7]
- Reject water from dewatering re-enters wastewater treatment and is modelled with Easetech external process "Domestic waste water treatment, 2003, EU-27, ELCD" by Susanna Andreasi Bassi, imported from ELCD database 3.2. To avoid shadowing of relevant results from redundant processes, it is only the difference in the impact from wastewater treatment of a given model compared to the Reference 1 model that is included when interpreting the main set of results.

Content of organic carbon in the FU sludge as well as the carbon conversion and related biogas production has been determined in an iterative process satisfying carbon content in digested sludge (from analysis data), carbon conversion rates between 40-50%, biogas potential of around 350 nm³ biogas per t total solids and 350 nm³ CH₄ produced per t volatile solids with a methane content in biogas of 65 vol% [5].

A 3 vol% total methane loss from the biogas plant, gas bell and gas engine is assumed [39]. This is expected to be a conservative value compared to recent studies on methane losses from biogas facilities [40]. Total CHP efficiency of the gas engines is modelled as 90% [5] with a share between heat and power production of 57/43 based on data from Ejby Mølle [32]. The heat consumption in the anaerobic digestion process is modelled as 1800 MJ/t total solids into the reactor while the electricity consumption is modelled as 50 kWh/t total solids [5]. It is assumed that aerobic stabilization takes place in the active sludge cycle or in a separate tank, and that the process only involves additional aeration. The power requirement of additional aeration in Reference 2 is comparable to the power consumption of the anaerobic digestion in Reference 1 and Scenario 1. Cost of biogas plant infrastructure is included based on the Easetech process "Capital goods Anaerobic digestion plant input 80000 t·year⁻¹" Developed by Line Brogaard at DU ENV.

3.3.2.3 Transport and storage

Total transport in all scenarios is 50 km including transport from waste water treatment plant to storage and from storage to field. All transport is modelled on basis of ton kilometer (mass limited) conducted in a truck using the Easetech process "Truck, 14t-20t, Euro5, highway". Mass loss in storage is disregarded in this regard and transport is modelled as one coherent process.

It has been a focal point in the study to try to include effect of sludge degradation during storage with regard to greenhouse gas emissions. Many related studies use a single reference on this matter dating back to 2005 and based on assumptions about degradation of organic food waste [5,6]. Recently, DTU Environment have conducted empirical investigations on this matter. So far, only one study has been published but more are expected to follow. In this study, results from the already published work by Julie D. Larsen et al are applied [7,41] but when additional results become available it is recommended to consider the potential implication of these on the modelled systems as well. The difference between formerly used storage degradation values and the up-to-date values are provided in Table 4.

Table 4: Degradation of sludge during storage

	Emission of C and N from sludge during storage	Previously used values from Kirkeby et al 2005 [6]	Values applied in this study from Larsen et al 2018 [7]
Methane	% of total organic carbon	2	6.1
Nitrous Oxide	% of total Nitrogen	0.5	0.8

Except for the linear effect of varying N and C content and the related differences in emission levels from sludge storage, no differences between anaerobically digested sludge and aerobically stabilized sludge are included in this regard. This is a simplification as the two processes will influence the characteristics of remaining C and N in different manners which would again influence volatility during storage.

No emissions from char storage is included in the modelling as no studies have been found that describes degradation of char/sludge char during a year under dry conditions. Based on carbon stability in pyrolysis char in general as well as the N₂O suppressive effect of pyrolysis char this assumption is expected to be reasonable [42–46].

3.3.2.4 Steam drying and thermal pyrolysis

The thermal system consisting of steam drying and thermal pyrolysis is modelled as a two-component input-output model where sludge and char composition analysis and total mass transfer evaluations determine the main set of data for the transfer functions. This is combined with a char yield estimation based on recovery of non-volatile elements in char from sludge pyrolysis. This assessment showed that approximately 57% sludge dry mass yield was recovered in the char fraction while the remaining 43% was volatilized into the pyrolysis gas product. The related energy balance based on heating value measurements on dry sludge and char determined a 53% energy yield in the gas product in the AD case with a related 36.5% energy potential in the char and 10.5% heat losses from the combined thermal system in the shape of low temperature condensate and exhaust gas. The analysis was combined with heat loss assessments from a thermodynamic model of the system developed in DNA modelling language² by associate professor Lasse Røngaard Clausen from DTU Mechanical Engineering.

In all scenarios with thermal treatment, it is assumed that the plant life is 15 years and it operates on average 8000 hours per year. Additional parameters for the LCI on the thermal system can be found in Appendix 2 and Appendix 3. An example of an energy and mass balances for the combined thermal system based on the applied transfer functions for Scenario 1 in Appendix 6 is provided in Figure 4.

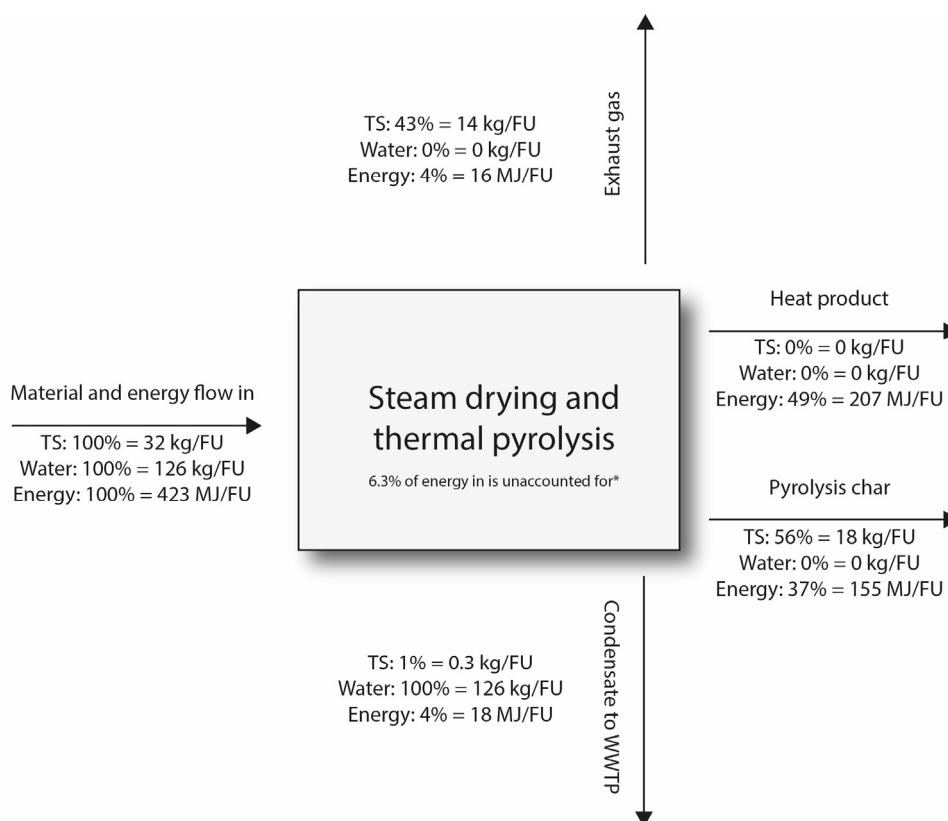


Figure 4: Energy and mass balances of the combined thermal system consisting of steam drying and thermal pyrolysis in Scenario 1.

* unaccounted energy leaves the system as sensible heat in the char fraction and as heat loss from hot system surfaces.

² [http://orbit.dtu.dk/en/publications/dna--a-thermal-energy-system-simulator\(b76040a4-5a29-4b04-a898-12711391c933\).html](http://orbit.dtu.dk/en/publications/dna--a-thermal-energy-system-simulator(b76040a4-5a29-4b04-a898-12711391c933).html)

It is assumed that CO₂ is the only greenhouse gas leaving the thermal system. Total direct energy consumption in manufacture of pyrolysis plant is assumed to be comparable to energy consumption in manufacture of Easetech waste incineration plant per FU: 0.00131 kWh electricity/kg total wet weight.

3.3.2.5 Soil application issues

Emissions to air when fertilizing farm soil with sludge and char is assumed to depend only on the composition of the material and have no dynamic effects on the soil composition. Based on a recent study by Yoshida et al [39] it is assumed that sewage sludge carbon and nitrogen is released to the atmosphere following the in Table 5.

Table 5: Fate of carbon and Nitrogen from sludge when applied to soil for 100 years [39,47]

	Carbon sequestration	C to Methane	C to CO ₂	N to N ₂ O
Dewatered mixed sludge, used in REF 2 (AER)	5.1 %	0.01 %	94.9 %	2.1 %*
Dewatered digested sludge, used in REF 1 (AD)	5.6 %	0.01 %	94.4 %	1.2 %

* In transfer functions described as 35% of the 6% total N released to air

** In transfer functions described as 24.5 % of the 4.9% total N released to air

No long term studies on biotic and abiotic conversion of sludge char carbon in soil have been found, but based on studies of other pyrolysis char types it is assumed that 10% of char carbon is released as CO₂ during the first 100 years after soil application [42,44]. No N₂O emissions are expected from char N degradation since biochar on many occasions have found to repress N₂O emissions from soil and fertilizer N conversion [46,48].

In all systems it is assumed that 45% of the N in the applied substrate (sludge or char) replace conventional N fertilizer since, in Denmark, the N has to be accounted for by the farmer with a degree of utilization of 45%. For P and K the avoided production of commercial fertilizer is assumed to be 1:1 in a 100 year perspective. This is in accordance with other comparable studies on the matter and makes sense from a farmers perspective and with regard to laws and regulations on the matter [5]. Due to limitations on data availability, only the benefit of avoided production of N, P and K fertilizer is included in the assessment even though there may be a sizable value attributed to S and Mg content as well.

3.3.3 Data quality, study qualification and risk of bias

Data for LCi development has been selected from high quality sources of three main types: i) Primary data from the case reference site at Ejby Mølle, the company AquaGreen and interviews with relevant stakeholders and researchers ii) Comparable and related LCA studies on Danish sludge management alternatives [5–7,39], and iii) Data from the official Easetech 2018-07 database. To embrace data quality issues, a range of the most sensitive parameters have been evaluated, and the potential impact from variation of these have been quantified (section 4.2).

The author have had a close collaboration on this and previous projects with the company AquaGreen who owns and operates the system for steam drying and thermal pyrolysis of sewage sludge. In addition, the author owns a share of a patent together with the company and two other DTU researchers on a related steam drying technology. With this background - and a profound scientific interest in the topic, there is a risk of methodological, unconscious bias in the study as well as in the interpretation of the results. Due to the awareness of these risks, an extraordinary emphasis has been put on transparency, fairness and scientific ethics in the work. However, it is recommended that the study is put under review by external reviewers if it is to be published, as is also recommended in the 14040 ISO standard.

It has not been possible to include a full (external) study review in the economic and temporal framework of the conducted study. To test the quality of the overall study results and conclusions it is attempted to compare the study results to other studies within the same topic (see section 4.2).

4 Results and discussion

Highlight results from the Life Cycle Impact Assessment analysis are presented in the following. Focus is on comparing the four systems and identifying relevant differences among the phases and processes in the individual systems. Additional details on the LCIA results are provided in Appendix 10.

4.1 Impact assessment results

In Figure 5, LCIA Carbon Footprint results from the four modeled sludge management systems are provided. Results are given in kg CO₂-eq per FU. The Stabilization phase in Reference 1 (AD) and Scenario 1 (AD) include the anaerobic digestion as well as the gas engine and avoided production of electricity and heat from biogas conversion. From these results it is evident that major impacts in the reference systems arise from sludge stabilization, sludge storage and in-field emissions while the major impact in the scenarios is from the thermal treatment (exhaust emissions from combustion of pyrolysis gas) as well as sludge stabilization in scenario 1 (AD). The fertilizer value of the sludge and char provide a sizable benefit to the accounting. In the reference systems, this benefit is twice as high as in the scenarios do to the value of the nitrogen fertilizer. Transportation, dewatering and WWT (waste water treatment) has limited impacts in all four systems with slightly higher transportation costs in the references and significantly higher WWT costs in the scenarios. As previously mentioned, only the difference in impact from WWT between Reference 1 (AD) and the other systems are included. This is done to limit the influence of this highly uncertain parameter as well as to avoid redundant processes shadowing the significance of the remaining impacts.

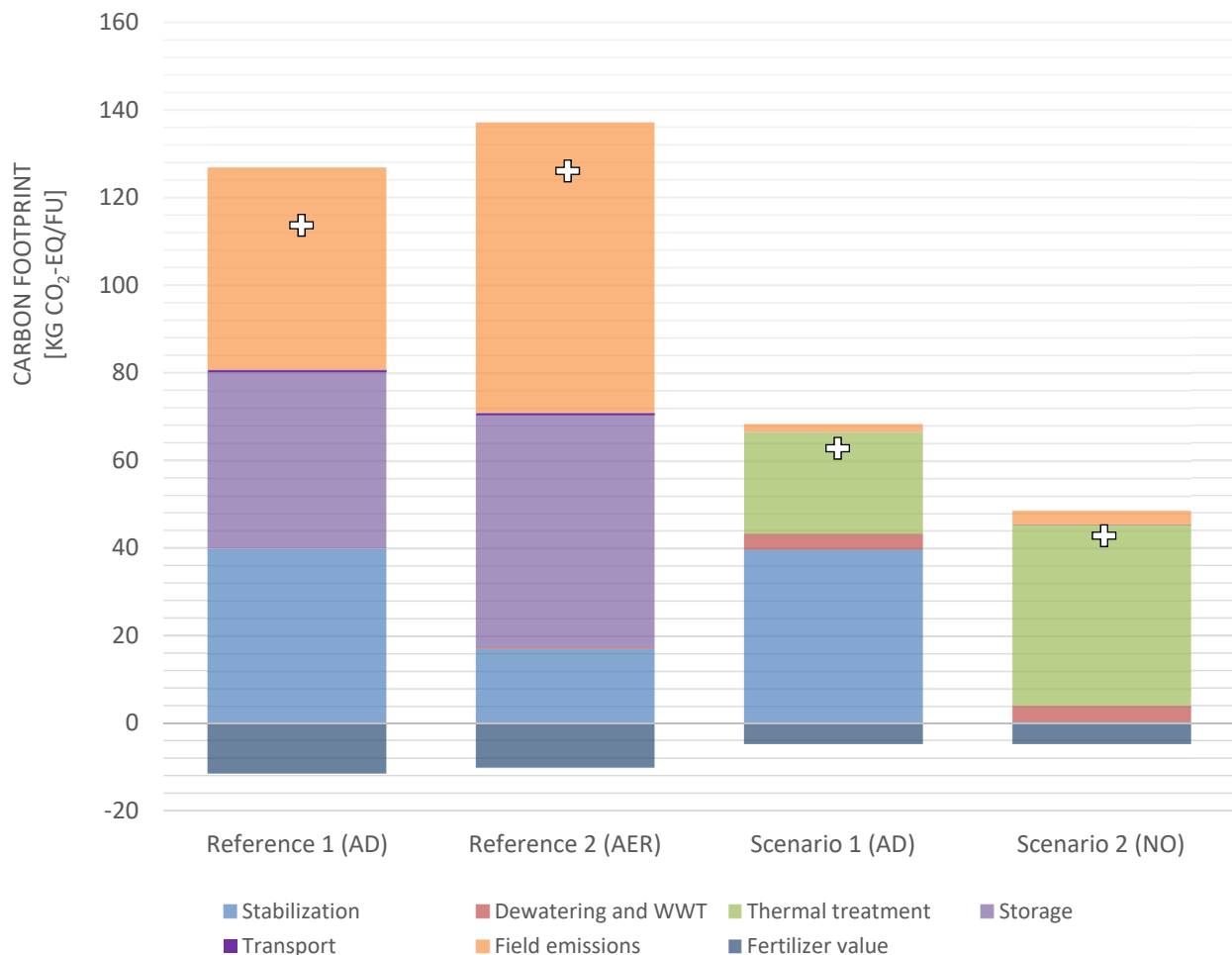


Figure 5: LCIA results divided into phases. Crosses mark sum impact. Energy marginal based on study of near future build marginal in Denmark i.e. Off-shore wind for electricity and wood & heat pumps (w. off shore wind) for district heating.

Based on the results in Figure 5, it is found that the carbon footprint from sludge management can be reduced with 52 - 83 kg CO₂-eq/FU. Ejby Mølle is represented in Reference 1 (AD), and the potential reduction in carbon footprint from immediate installation of thermal sludge treatment is thus 52 kg CO₂-eq/FU. 50 CO₂-eq/FU and an average flow of 400 FU through the sludge treatment system every day [32] all year, yields a reduction potential of 20 t CO₂-eq/day and 7300 t CO₂-eq/year. In the most recent responsibility report from VandCenter Syd it is stated that the company needs to save additional 4.257 ton CO₂-eq per year to reach a net zero emission profile [49]. The current study indicates that this is possible by installation of thermal treatment of at least 60% of the produced sewage sludge.

Recalculating the FU into person equivalent and comparing with the near future average PE carbon footprint (normalization reference) of 7.4 t CO₂-eq/average Danish citizen per year [37] indicates a potential reduction in the average Danes carbon footprint of 0.4-0.6% from implementation of a thermal sewage sludge management strategy.

As discussed in the goal and scope section, it is often found that background processes for production (and avoided production) of electricity and heat play a substantial role in the final LCIA results. Especially with regard to global warming potential and carbon footprint. To take this into account, the model has been tested with a substantially different set of energy marginal technologies. For electricity production, commonly applied marginal technology in consequential LCA in Denmark in recent years has been coal, whereas the marginal for nationwide district heating is less agreed upon [5,7,19]. In the results in Figure 6, coal is the applied energy marginal for electricity as well as heat. This is the standard marginal in the applied version of Easetech, and based on system modeling studies from DTU Management it is assumed reasonable to model this effect in the current Danish energy system [24,27,28].

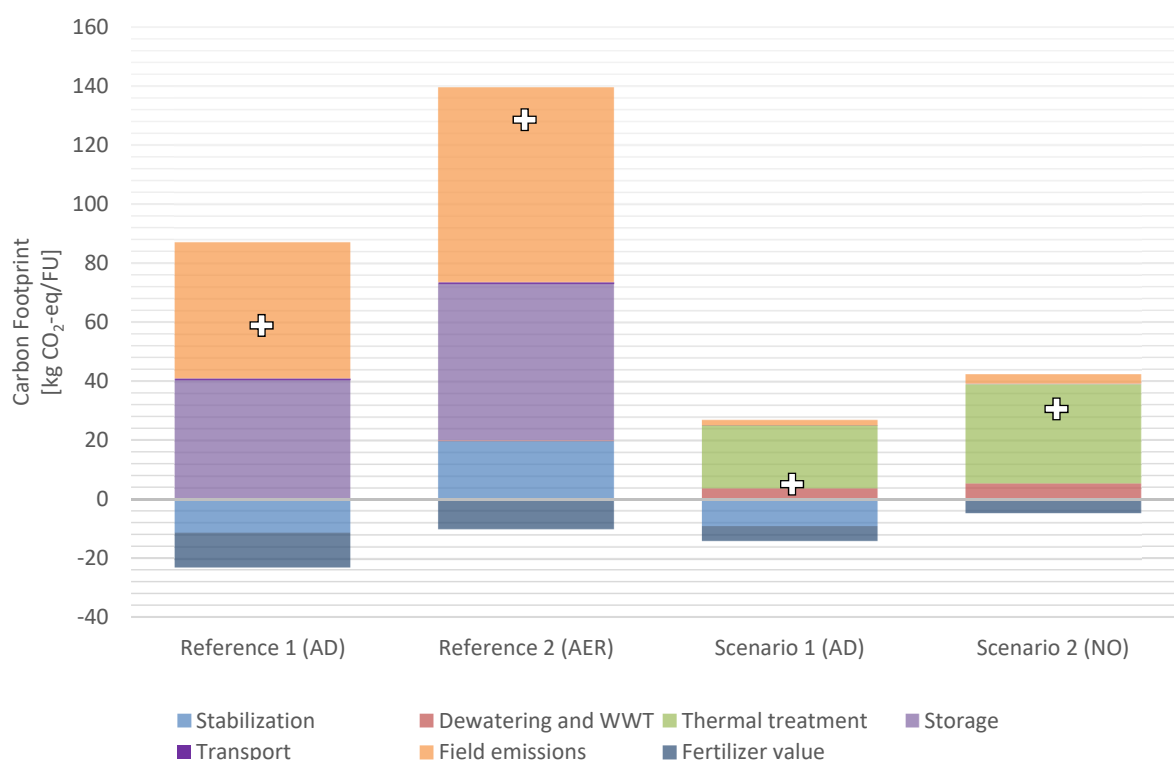


Figure 6: LCIA results divided into phases. Crosses mark sum impact. Energy marginal based on commonly applied coal marginal in Denmark in recent years.

In general, the differences among LCIA results from the four systems are more distinct with coal as energy marginal. The most substantial differences in the quantification is the much higher benefit of avoided electricity production from the two AD systems. One of the arguments for assessing the impact of the different energy marginal technologies is to investigate result robustness and representativeness. The primary set of marginal technologies were used in a near future setting whereas the coal marginal is a more current system. When we change the background energy system, we also change the average impact of a person within this system. It is therefore also relevant to include a modified normalization reference to compare the actual impact of the proposed systems. To do this, the

LCIA results are scaled with a factor of ½ to match a FU to a PE sludge production and matched to a GWP normalization reference representative for the coal marginal system in present state Denmark. In the current system an average Dane emit around 10 t CO₂-eq/year compared to an estimated 7.4 t CO₂-eq/year in the near-future system [37,50]. With these settings, it is found that there is a potential for 0.3-0.6% reduction in the average Danish persons carbon footprint from the investigated changes in sludge management. With the original set of marginal technology, this potential was found to be 0.4-0.6%.

It is expected to be most practically and economically feasible to change from Reference 1 (AD) to Scenario 1 (AD), maintaining the anaerobic digestion and from Reference 2 (AER) to Scenario 2 (NO) going from aerobic sludge stabilization to no dedicated sludge stabilization. However, there could be cases where a transition from an aerobic system to an anaerobic system with thermal sludge treatment is desired. With the fossil energy marginal technology this transition gives the highest total reduction in carbon footprint where the more straight forward change from REF 2 (AER) to SCE 2 (NO) gave the highest potential reduction with the renewable energy marginal technology.

The determined span in the potential reduction levels as well as the maximum potential is quite constant despite the significant changes in absolute impact. It makes sense that the relative differences are somewhat maintained as long as the normalization reference follows the development in the energy system and related energy marginal and the model reflects this in a consistent manner.

4.1.1 Carbon footprint of sludge stabilization phase

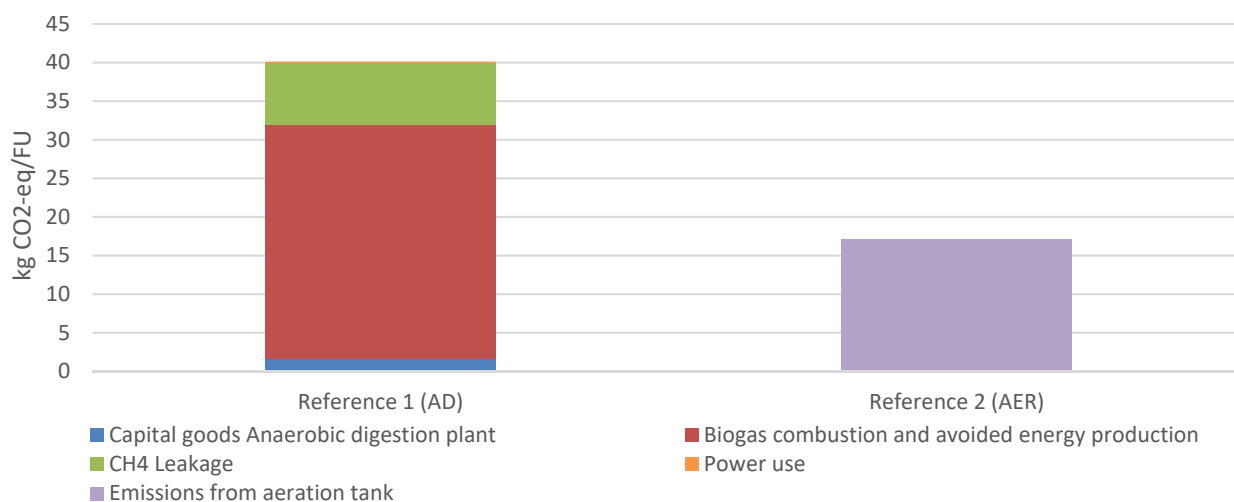


Figure 7: Process based LCIA impacts from stabilization phase. Electricity marginal = off shore wind power. District heating marginal = wood and heat pumps (using off-shore wind power)

Only Reference 1 (AD) and Reference 2 (AER) are included in Figure 7 since the impact from sludge stabilization in Scenario 1 (AD) is equal to that in Reference 1 (AER), and in Scenario 2 (NO) there is no dedicated sludge stabilization process.

CO₂ emissions from the aeration tank in Reference 2 (AER) and from the gas engine exhaust in Reference 1 (AD) dominate the total impact. With the renewable energy marginal technologies, the benefit from production of electricity and district heating is very limited (-0.23 kg CO₂-eq/FU for the district heating and -0.5 kg CO₂-eq/FU for the electricity) and direct emissions have a much higher impact. With coal marginal the benefit of the avoided production is much higher (-5 kg CO₂-eq/FU for the district heating and -46 kg CO₂-eq/FU for the electricity). It is obvious that the GWP related benefit of non-fossil energy production is higher when competing with fossil fuel based energy than it will be in a future energy system where competition is mainly renewables. This may be interpreted as an argument for fast implementation of thermal sludge treatment if the benefit in relation to the carbon footprint should be maximized.

Power consumption takes up a decimal part of the impact from the stabilization processes in the two reference systems. Subsequent analysis of other studies have revealed a quite large variation in the parameter values used even though this should be relatively simple to measure. It is found that the applied power consumption (50 kWh/t TS [5]) could be underestimated, but also that even a radical increase will have only a minor impact.

4.1.2 Carbon footprint of thermal sludge treatment phase

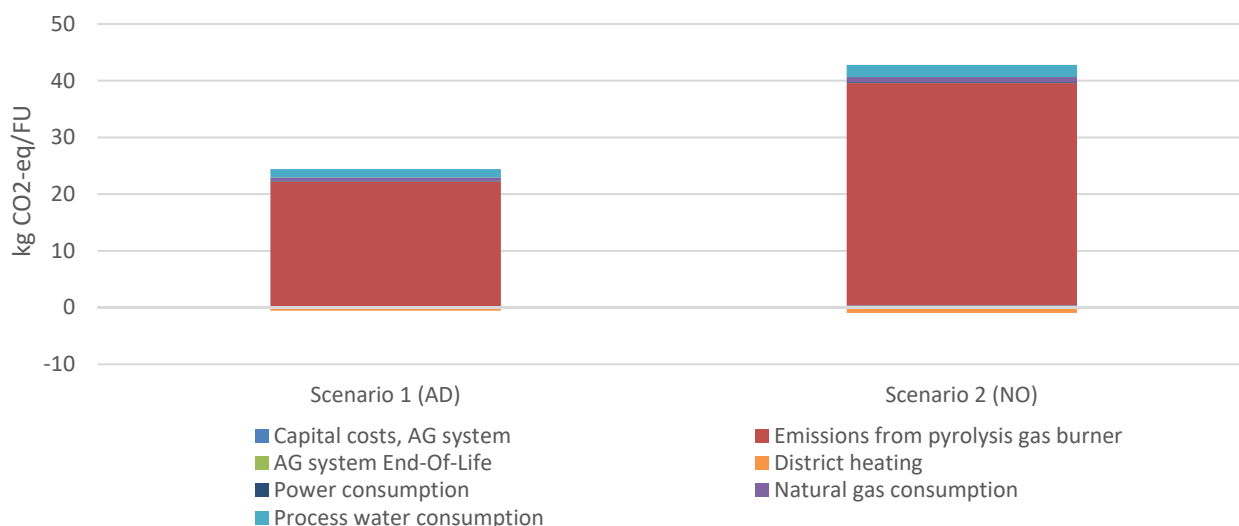


Figure 8: Process based LCIA impacts from thermal treatment phase. Electricity marginal = off shore wind power. District heating marginal = wood and heat pumps (using off-shore wind power)

Only the two scenarios have thermal sludge treatment and are therefore represented in Figure 8. Impact from the pyrolysis gas burner are directly related to the amount of sludge treated and the content of organic material. The emissions from the burner are dominated by CO₂ emissions and the impact is much higher than the accredited value of the avoided district heating production. In Scenario 1 the GWP benefit of the avoided district heating production sums up to -0.4 kg CO₂-eq/FU if the heat marginal technology is wood and heat pumps and as much -9.1 kg CO₂-eq/FU if the marginal is coal. In Scenario 2 the comparable benefits are -0.7 kg CO₂-eq/FU and -18.0 kg CO₂-eq/FU. In comparison to this, the impact of exhaust gas emissions are 2-2.5 times higher than the accounted benefit of avoided district heating production in the coal dominated district heating marginal and 55 times higher (!) in the near future district heating system. These findings suggest a keen focus on system development towards char carbon maximization and a related minimization of exhaust gas emissions. This could possibly be achieved by reducing pyrolysis temperature if other heat sources are available e.g. from gas engine exhaust in AD systems. However, the impact hereof on char carbon stability and fertilizer value should be investigated as well.

Capital costs (materials and production energy) of the thermal system are decimal, and even with a substantially shorter plant life time (e.g. 10 or even 5 years) or reduced operational time this changes very little. It has been investigated if other LCI and LCIA data related to material production would change the impact compared to the Easetech model results. EDIP LCIA used on processes from the Chalmers LCI process database³ gave very comparable results even when applying maximum costs values. Based on these results it seems that the investigated system is very resource efficient. However, due to substantial simplifications in the LCI development, it is recommended to test the assessment of the potential impact from plant manufacturing and material recycling using other databases e.g. Ecoinvent or Gabi Professional.

Water dominates utility consumption in the wood/heat pumps energy system while the electricity consumption has the biggest impact in the system with a coal marginal (+6.7 kg CO₂-eq/FU in Scenario 1 (AD) and + 9.9 kg CO₂-eq/FU in Scenario 2 (NO)).

³ <http://cpmdatabase.cpm.chalmers.se/IACalc/IACalcSelect.ASP?IAM=EDIP%20default&IAMVer=1997>

4.1.3 Carbon footprint of sludge storage phase

It is assumed that there are no greenhouse gas emissions from dry char storage, and therefore only the reference systems are included in Figure 9. The assumption is based on the expected stability of char C and N based on studies of biochar stability and biochar repression of nitrous oxide emissions [42,44,46,48]. To this date, no studies on greenhouse gas emissions from open, dry char storage have been found in published literature and a minor risk of an unaccounted impact from this source cannot be completely ruled out.

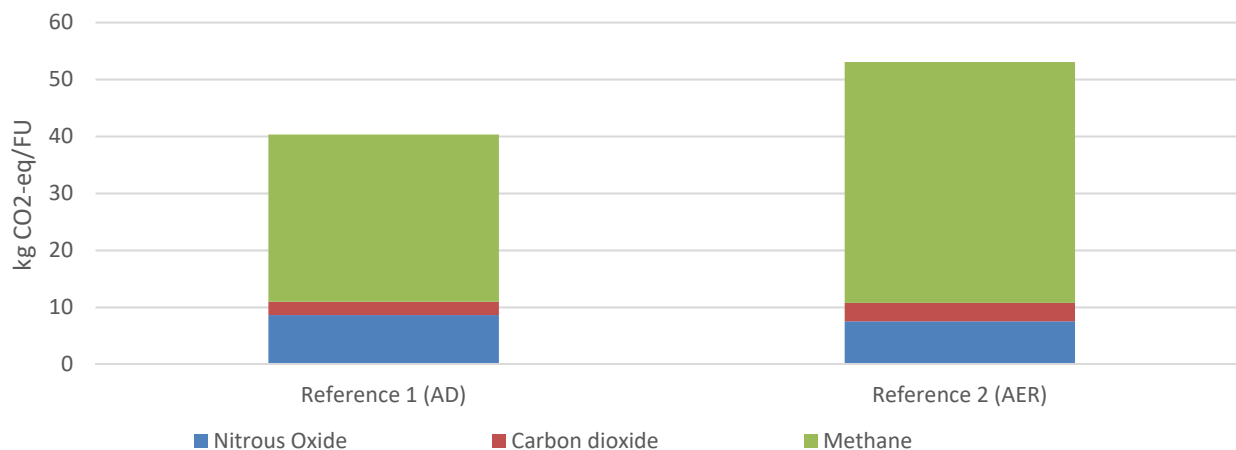


Figure 9: Substance based LCIA impacts from storage phase. Only main substance influences are included.

Carbon footprint of dewatered sludge storage is immense according to the results of the present study. Avoiding these emissions alone is considered reason enough to consider thermal sludge treatment. Especially methane emissions are severe in both reference systems. It should be noted that emissions from storage of digested sludge are modelled as linear functions of the transfer coefficient from the un-digested sludge. This is a simplification, and it is considered highly relevant to keep focus on this topic in the near future. More studies on this issue may be expected to be published from DTU Environment since they possess the tools as well as the interest to investigate this.

It is expected that an alternative method to avoid GHG emissions from sludge storage could be thermal drying of the sludge prior to storage. This has been normal practice in Denmark a few years back, but today no sludge drying ovens persist in the country. Based on interviews with technical personnel from Bjergmarken Renseanlæg near Roskilde, the main reasons for shutting down the dryer was related to very high operation and maintenance costs. Another mitigation strategy could include closed sludge storage e.g. following the development in manure management, but it is unknown how effective and price efficient this approach is.

4.1.4 Carbon footprint of use-on-land phase

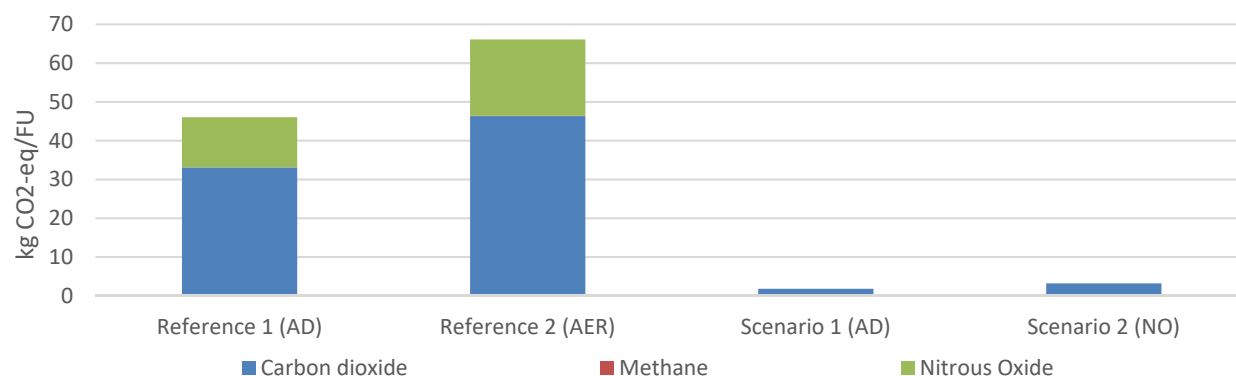


Figure 10: Substance based LCIA impacts from use-on-land phase. Only main substance influences are included.

Even though there is a substantial contribution from N₂O in the reference use-on-land processes, it is still conventional CO₂ emissions that dominate. It is no simple task to accumulate carbon in well-drained soil in constant rotation, and the accounted level of carbon emissions from the sludge are most likely very reasonable. However, the recalcitrant carbon of the sludge char may provide a substantial positive contribution to the soil carbon content and the release of greenhouse gases in this regard [43,44,51,52].

4.1.5 Carbon footprint of avoided fertilizer production

The accounted benefit of avoided fertilizer production in the different scenarios is presented in Figure 11.

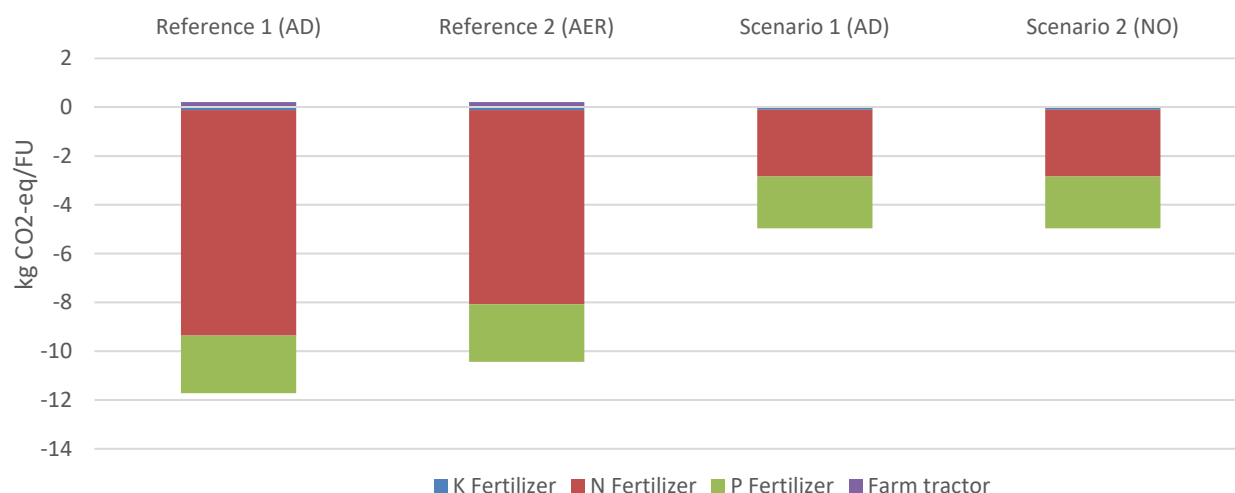


Figure 11: Process based LCIA impacts from fertilization phase

Impact from the avoided production of fertilizer indicate a huge benefit from nitrogen, a somewhat smaller benefit from phosphorous and a negligible benefit from potassium. Sludge and char may also contain relevant amounts of magnesium and sulfur as well as valuable micro nutrients. However, the impact from these on the carbon balance and carbon footprint is expected to be small. The loss of nitrogen and the related positive contribution from the avoided production of nitrogen fertilizer is a drawback of the systems encompassing thermal sludge treatment. However, the cost of nitrogen fertilizer in a near future energy system where power from renewable sources will be the main input may be substantially lower than in the present system that is based on natural gas [53].

4.2 Model quality assessment

To qualify the results from the study, it has been attempted to compare Reference system performance to other LCAs on sludge utilization in a Danish setting. The results are recalculated into normalized GWP impact as PE/t dry matter and collected in Table 6.

Table 6: Comparing carbon footprint results from the present work to related studies. Primarily coal marginal in all studies. All numbers given with the unit PE/t dry matter.

Carbon Footprint [PE/t dry matter]	This study 2018	Thomsen et al 2016 [19]	Larsen et al 2018 [7]	Yoshida et al 2018 [39]	Kirkeby et al 2013 [5]
Reference 1 (AD) comparable studies	0.13	0.15	n.a.	0.0	-0.1
Reference 2 (AER) comparable studies	0.26	n.a.	0.14	0.38	0.01
Difference AD -> AER	+0.13	n.a.	n.a.	+0.38	+0.11

From the comparison, it is evident that there are substantial differences among all the studies. These differences originate from many sources including methodological differences, influence of assumptions and simplifications, data variations and inconsistencies and to some extent, un-equivalent systems (system boundaries). However, from the viewpoint of the present work it is reassuring to note that the results from the current work, in all cases fall within the span of results from the external studies. However, the results from Reference 1(AD) exceed those from studies performed by other researchers, and therefore important to investigate further. The study that best compare to Reference 1 is Yoshida et al's DADS scenario. Recalculating comparable phases into the same unit (PE/t dry matter treated) provides the comparison in

Table 7: Comparing Reference 1 (AD) to the equivalent DADS scenario from Yoshida et al 2018 [39]

Carbon Footprint [PE/t dry matter]	Sludge treatment	Storage	Field application	Fertilizer value	Sum of included
This study, Reference 1	-0.023	0.081	0.092	-0.023	0.127
Yoshida et al 2018, DADS scenario [39]	-0.024	n.a.	0.035	-0.029	-0.018
Difference per ton dry matter Ref 1 -> DADS	-0.001	- 0.081	- 0.057	- 0.006	- 0.145

From the comparison it is clear that a small impact from all phases is determined in the study by Yoshida et al. However, the sludge treatment processes (anaerobic digestion, biogas utilization and dewatering) are very well aligned while there are substantial differences in the included impact from storage, field application and fertilizer value. It is found to be very reasonable to include emissions from storage since these were found to be substantial in recent works from DTU Environment [41]. It is surprising that the accounted benefit of fertilizer value in Yoshida et al is substantially higher than in the present work since N P and K content in the modelled sludge use-on-land is significantly higher in the present study and the assumed rates of Avoided production of commercial fertilizers are comparable. Therefore, it is expected that the carbon intensity of the avoided fertilizers in Yoshida et al (originating from Ecoinvent v. 2.2) is much higher than those used in the present work (Easetech native values). This matter is investigated in Kirkeby et al 2013 and it is found that there are substantial differences between accounted fertilizer impact in Ecoinvent and the Easetech database. As an example it is found that there is a factor of 3-4 between the two databases with regard to the impact from CO₂ and N₂O in the processes of P fertilizer production and as much as a factor of 14 with regard to CH₄ impacts. It is additionally determined that the main disagreement is related to the accounted electricity use in the two processes [5]. The result hereof is that there is a risk of underestimating the benefit of avoided fertilizer production in the present study. The last impact difference between Reference 1 (AD) and Yoshida's DADS scenario is in the field application. This is relevant since emission transfer coefficients for the present study originate from Yoshida et al 2018. However, by deeper analysis it is found that the main differences are not in the in-field emission rates but instead in i) the original sludge composition where the sludge from the present work contains 17% more carbon and 10% more nitrogen, and ii) significant differences in the transfer coefficients in the anaerobic digestion and the dewatering where much more C and N is removed from the original sludge in the DADS scenario. As the transfer functions in these two processes are calculated backwards from a dewatered and digested sludge sample in the present work, recalculating the model with the transfer functions of Yoshida et al would lead to severely unrepresentative C and N content in the original sludge. Based on this analysis, it is expected that the present approach with regard to the modelling of Reference 1 (AD) and 2 (AER) are solid and representative, but also that the value of avoided fertilizer production may be underestimated.

Unfortunately, it has not been possible to compare Scenario 1 and 2 to relevant studies by other research groups, as none have been identified. However, it is possible to compare the results to studies conducted with different methods and datasets. In Thomsen et al 2016, it was found that low temperature thermal gasification of pre-dried sludge from Bjergmarken Renseanlæg in Roskilde, Denmark would reduce the carbon footprint of the average person in the WWTP collection zone with around 0.65 % - 0.95 % [19]. In this system, sludge was pre-dried in a biogas heated oven at the waste water treatment plant and the dry sludge was gasified at Asnæsværket with high efficiency CHP. Main benefits were related to electricity production (coal marginal) and avoided emissions from the in-field application of the sludge. The system was modelled with Gabi v. 4.4 & EaseTech 2013 in different levels of detail and complexity and with different impact assessment methods (CML 2001 method, November 2009 update & ILCD recommended 2013 DTU update respectively). Despite substantial differences between these studies – and the present, there is a quite

good agreement about the potential for reducing the carbon footprint of the average Danish person by thermal sludge treatment.

4.2.1 Sensitivity assessment

An assessment of key issues in the model development related to sensitivity and uncertainty has been conducted. Highlight results of the most sensitive parameters are provided in the following:

4.2.1.1 Influence of LCIA method

Choice of LCIA method is known to influence results substantially. In the specific case the variation in results related to choice of LCIA method is expected to be limited since global warming potential is the only assessed impact category and characterization factors hereof are known to be very well documented. However, to verify this expectation an additional set of results are produced using the LCIA methods "ReCiPe, Europe" and "ILCD recommended 2013 w. LT".

From the assessment it is found that the IPCC LCIA account a larger impact on GWP from methane emissions than the two other methods. However, the difference has no huge impact on the relative difference between the carbon footprints of the different systems. From SCE 1 to REF 1 the impact increase 1.5/2.4 times depending on the energy marginal using IPCC and 1.5/2.3 using ReCiPe and ILCD. For SCE 2 to REF 2 the impact difference is 2.2/2.5 using IPCC and 2.1/2.4 using the other two methods.

4.2.1.2 Sensitivity and quality of emission factors related to sludge storage

From the model results it was evident that the emissions related to sludge storage has a huge potential impact on the carbon footprint of the reference systems. Therefore sensitivity assessment of these emission factors are investigated and the influence of the applied parameters is compared to the influence of a set of alternative emission factors from previous studies. Focus in this regard is on the allocation between CH₄ and CO₂ emissions as well as between N₂O and other N emissions.

From a sensitivity assessment it is found that the sensitivity in the two reference scenarios is 0.72-0.75 for the carbon allocation and 0.68-0.75 for the nitrogen allocation, varying with the reference system as well as the LCIA method (IPCC >> ReCiPe, Europe). This indicates very sensitive parameters that needs to be further assessed and qualified. It is therefore investigated if other emission factors from Danish sludge LCA studies could be more reasonable.

Several past and recent LCA studies on Danish sewage sludge treatment use storage emission factors from Kirkeby et al 2005 [5,6,54]. In this work, methane emission levels of 9.3 kg CH₄/ton TS are assumed from an assessed span of 3.4 – 19 kg CH₄/ton TS. Using Kirkeby's emission parameter in Reference 1 gives a 10% reduction in the overall carbon footprint while the full span gives a 4-18% reduction. This is severe and caution should be taken to verify the applied values. However, the experimental values applied for CH₄ emissions from a sludge stock pile is found to have much higher quality than the parameters estimated by Kirkeby, especially taking the huge span of possible parameter values in the estimation into account.

For nitrous oxide it is assumed in Kirkeby et al 2005 that 0.5% of total N is emitted as N₂O based on a 1997 reference on cattle manure [55]. This value has also been reused several times since e.g. [5,54]. However, another more recent study on N₂O emissions from different manure types found as much as 5-7% of original N released as N₂O. This huge span in N₂O emission from manure (factor > 10) makes the approach of applying manure based emission factors highly inappropriate, and it is found that the experimental values used in the present work have higher quality.

4.2.1.3 Carbon Footprint of Use-on-Land processes

Processes related to Use-on-land of sludge and char was also found to have a very large influence on the carbon footprint of especially the reference systems. It is therefore decided to investigate the emission factors from in-field sludge application and also the related benefit of avoided fertilizer production. This is done by producing a new set of carbon footprint results using commonly applied use-on-land processes from Easetech database and comparing these to the original results.

First, it is investigated how the carbon footprint of the reference systems change if the applied use-on-land modelling is replaced with standard easetech processes for the same impacts (GHG emissions from sludge degradation, machinery use and benefit of avoided fertilizer production). Easetech processes are divided into sludge type as well as soil type. Three different soil types (heavy clay, sandy loam and coarse sand) are tested for Reference 1 using processes for anaerobically digested, dewatered sewage sludge two different soil types (Sandy loam and coarse sand) are tested for Reference 2 using processes for dewatered, mixed sewage sludge. In Reference 1 the carbon footprint change with -11% to +2% depending on soil type and LCIA method. In Reference 2 the change is -25% to -11%. In both cases, the soil type drives the differences whereas LCIA method has a very limited impact. From deeper investigation it is found that the differences in CF impact is caused by two opposing effects: i) The native easetech processes accounts a larger impact from N (factor 1.2 to 5.0!) due to higher N₂O emission rates, and; ii) No impact from CO₂ emissions from sludge carbon conversion are included in the native easetech processes as sludge carbon is biologic carbon and easetech only accounts CO₂ impacts to CO₂ from fossil carbon. Due to the goal and scope of the present study it would be wrong to assume no impact from CO₂ originating from in-field degradation of sludge/char carbon. If these CO₂ emissions are accounted impacts and combined with the N-related impact from the native sludge UOL processes, the final CF impact of the UOL phase would increase 10-85% compared to the findings in the present work, and the final full-system carbon footprint would increase 4-21%. In other recent Danish sludge management LCAs, a generally higher impact from N-released as N₂O from the field based on references originating from Kirkeby et al 2005 [5,6,50]. This could support the emission schemes of the Easetech processes, but it is found that the parameters applied are average values from a set of very old estimations of in-field degradation of organic food waste and therefore the mutuality of the two sources may be completely random. Based on these results it is concluded that the emission scheme from sludge UOL applied in the two Reference systems may be conservative and underestimated – especially with regard to N-related impacts, but that the method is the most appropriate between the investigated options.

Easetech processes for use-on-land impacts only exist on sludge application and not on char, and there is no published experimental results on emissions from sludge char after application to farm soil. The sensitivity of the char carbon recalcitrance, C species emission allocation (CO₂ >> CH₄) and potential emissions of N₂O from residual N are found to be relatively low due to reduced concentrations and general consensus about carbon stability. However, it is recommended to be aware of upcoming studies on this matter, and if possible contribute to the initiation of such.

4.2.1.4 Sludge composition

Sludge composition varies substantially with geography, demography, treatment plant design, seasonal variations etc. It is therefore decided to test the sensitivity of the overall model predictions on carbon footprint of the references compared to the scenarios when changing the sludge composition. Three additional compositions are tested. Two of the sludges originate from the applied Easetech database (“Sewage sludge” and “Mixed Sludge_Yoshi”) while the last one originates from a previously conducted study on thermal sludge treatment based on empirical data [18,19]. The sludge compositions are tested using the IPCC LCIA method as well as the ReCiPe method, and two sets of energy marginal technologies; set 1) wind and wood “WnW”, and set 2) mainly “coal”. The absolute results show carbon footprints with large variations as indicated in Table 8.

Table 8: Differences in carbon footprint results from the original models using sludge composition analysis data from VandCenter Syd (VCS) and compared to model results using three other sludge compositions

Carbon Footprint [kg Co ₂ -eq/FU]	Average difference	Max difference	VCS is highest impact
Easetech “Mixed sludge_Yoshi”	15-18% lower than VCS	45 % higher than VCS in SCE 1 “coal”	12 of 16 results
CPSE sludge, Bjergmarken [18,19]	48 % higher than VCS	140 % higher than VCS in SCE 1 “coal”	2 of 16 results
Easetech “sewage sludge”	96 % higher than VCS	320 % higher than VCS in REF 1 “coal”	0 of 16 results

In general, the results using the “Mixed sludge_Yoshi” composition provided lower carbon footprint results than results using the sludge from VandCenter Syd/Ejby Mølle. On the other hand, both the CPSE sludge from Bjergmarken and the generic Easetech sludge provided much higher carbon footprint results. It can be concluded that the sludge

composition has a tremendous effect on the carbon footprint results and that variation among the four tested compositions is very high.

To use these findings to challenge/validate the overall pattern in the model results, the carbon footprint of reference and the related scenario are paired and compared. These results are provided in Figure 12 and Figure 13 using two different sets of energy marginal technologies.

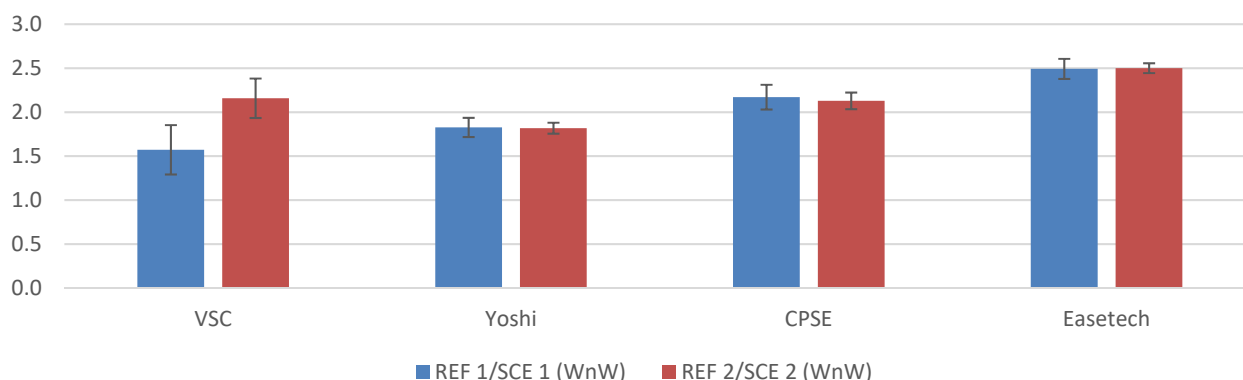


Figure 12: Relative carbon footprint result between reference and related scenario derived using four different sludge types and energy marginal technologies wind power and wood. VCS = VandCenter Syd sludge from Ejby Mølle. CPSE sludge from Bjergmarken [18,19]. Error bars indicate variation due to LCIA method.

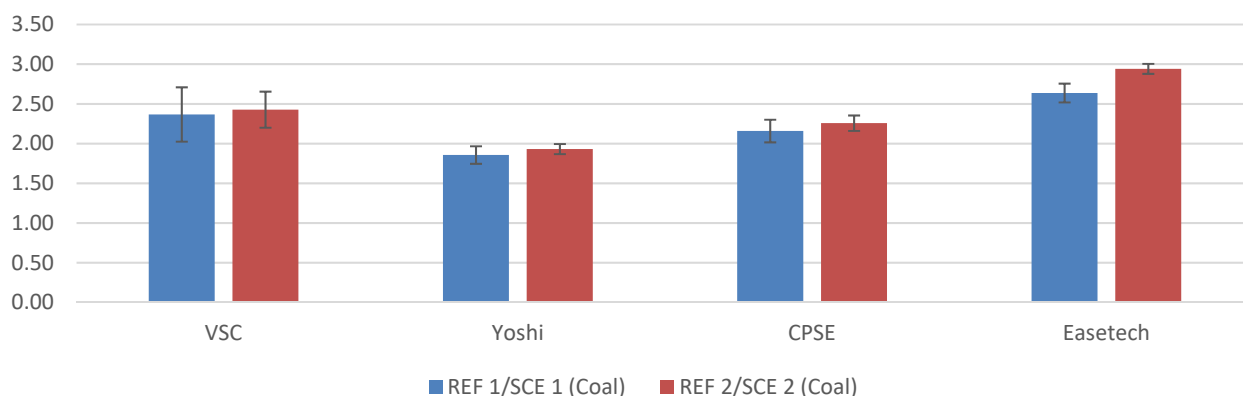


Figure 13: Relative carbon footprint result between reference and related scenario derived using four different sludge types and energy marginal technologies based predominately on coal. VCS = VandCenter Syd sludge from Ejby Mølle. CPSE sludge from Bjergmarken [18,19]. Error bars indicate variation due to LCIA method.

It is interesting that the scenarios perform better than the references in all cases. Minimum difference is found between reference 1 and scenario 1 using the VCS sludge composition and the wind and wood energy marginal. In the minimum case, the reference has a carbon footprint approximately 50% higher than the related scenario. However, the minimum difference between reference 2 and scenario 2 is found using Mixed Sludge_Yoshi from easetech and the same energy marginal. Here the difference is around 75%. There is a really strong pattern in the results indicating a correlation between relative impacts of the two reference/scenario sets in almost all cases. Largest inconsistency is between the reference/scenario sets using the VCS sludge and the wind and wood energy marginal.

From the results it is argued that it is unlikely that the influence of the applied sludge composition has led to overestimation of the carbon footprint results or the benefits of the thermal sludge management process. However, to confirm this the model should be tested with consistent datasets where sludge composition, transfer coefficients and the related energy and material transfers in the systems match.

5 Conclusions and recommendations

Thermal sludge treatment in systems encompassing steam drying and thermal pyrolysis has a very positive impact on the carbon footprint of modern sludge management in systems with utilization of the sludge fertilizer potential by direct use in agricultural systems. The thermal sludge treatment helps to avoid emissions of CH₄, N₂O and CO₂ during especially storage and use-on-land processes.

In all investigated cases, it is found that there is a potential for 0.3-0.6% reduction in the average Danish persons carbon footprint from implementation of nationwide thermal sludge treatment! It is obvious that the carbon footprint related benefit of non-fossil energy production is higher when competing with fossil fuel based energy than it will be in a future energy system where competition is mainly renewables. And since the investigated systems produce more energy than they consume, this is given as an argument for fast implementation of thermal sludge treatment if the benefit in relation to the carbon footprint should be maximized.

However, even in near future systems with renewable energy marginal technology there is a huge potential for improving the carbon footprint of sludge management by thermal treatment. Approximated studies on a system resembling Ejby Mølle in Odense indicate a potential annual carbon footprint reduction of 7300 t CO₂-eq/year. This is almost twice the reduction required by VandCenter Syd to reach a net zero emission profile. This result was found to be very solid and the reduction is the same with fossil and with renewable energy marginal technologies for background production - and avoided production, of electricity and district heating.

And if a treatment system with aerobic sludge stabilization is transformed into a system with steam drying and thermal pyrolysis and no dedicated sludge stabilization, the reduction potential would be almost 60%-100% higher than in the case with Ejby Mølle that includes anaerobic digestion before as well as after the implementation of thermal sludge treatment. It is expected to be most practically and economically feasible to change from Reference 1 (AD) to Scenario 1 (AD), maintaining the anaerobic digestion and from Reference 2 (AER) to Scenario 2 (NO) going from aerobic sludge stabilization to no dedicated sludge stabilization. However, there could be cases where a transition from an aerobic system to an anaerobic system with thermal sludge treatment is desired. With the fossil energy marginal technology this transition gives the highest total reduction in carbon footprint where the more straight forward change from REF 2 (AER) to SCE 2 (NO) gave the highest potential reduction with the renewable energy marginal technology.

Major impacts in the reference systems was found to arise from sludge stabilization, sludge storage and in-field emissions while the major impact in the scenarios is from the thermal treatment (exhaust emissions from combustion of pyrolysis gas) as well as sludge stabilization in scenario 1 (AD). The fertilizer value of the sludge and char provide a sizable benefit to the accounting. In the reference systems, this benefit is twice as high as in the scenarios do to the value of the nitrogen fertilizer. The loss of nitrogen and the related positive contribution from the avoided production of nitrogen fertilizer is a drawback of the systems encompassing thermal sludge treatment. However, the cost of nitrogen fertilizer in a near future energy system where power from renewable sources will be the main input may be substantially lower than in the present system that is based on natural gas. Transportation and power consumption takes up only small parts of the impact in all assessed systems. In the systems with thermal sludge treatment there could be a benefit in minimizing water consumption or replacing water with cooled condensate if non-water constituents allow for this. Capital costs (materials and production energy) of the thermal system was expected to contribute significantly to the total carbon footprint of the thermal treatment scenarios, but was found to be almost negligible and thereby indicating a very resource efficient process design.

In systems with thermal treatment, the impact of burner emissions largely outweighs the benefit of avoided district heating production. This is the case even in systems with a fossil energy marginal. The implications hereof is that it will always be in the interest of the carbon footprint to maximize carbon content in the char. Pyrolysis gas combustion should be kept at a minimum, high enough only to drive the process. In systems with excess heat (e.g. in AD system with a gas engine), it can make sense to replace some heat from pyrolysis in the drying to be able to reduce pyrolysis temperature and thus minimize emissions and maximize carbon sequestration. However, studies on different sludge char products in farm soil application should be conducted to determine the correlation between char carbon stability and process temperature profile.

The results of the present work are influenced by uncertainties related to data inconsistency, sensitive parameters and assumptions, but the relative results among the assessed systems are regarded as sound and a good starting point for further investigations in the area of steam drying and thermal pyrolysis within wastewater treatment systems. The model results are found especially useful when comparing the references and scenarios and assessing the relative impact of implementing thermal sludge treatment in existing systems resembling the model reference systems.

Despite the clear and solid results there are many areas of the study – or related studies, that could further strengthen the conclusions and improving the system understanding. Here are some recommendations in that regard:

- To this date, no studies on greenhouse gas emissions from open, dry char storage have been found in published literature and a minor risk of an unaccounted impact from this source cannot be completely ruled out. Such studies should be relatively simple to conduct and would rule out significant uncertainties.
- Investigate costs of AG plant manufacturing and infrastructure costs in general using alternative databases e.g. Ecoinvent or Gabi Professional. Investigate also in this regard the benefits associated to plant end-of-life processes.
- Model system with marginal fertilizer production costs- and quality. Include the value of more fertilizer compounds (S, Mg and micro nutrients)
- Keep an eye out for new studies on emissions from sludge management – especially with regard to emissions from storage and use-on-land.
- Facilitate char >< sludge storage emission measurements
- From the results it is argued that it is unlikely that the influence of the applied sludge composition has led to overestimation of the carbon footprint results or the benefits of the thermal sludge management process. However, to confirm this the model should be tested with consistent datasets where sludge composition, transfer coefficients and the related energy and material transfers in the systems match.
- With regard to many of the identified key aspects/hotspots of the carbon footprint, the method and data applied in the present work is considered to be more solid and representative than several other Danish LCA studies on sewage sludge management. There seem to be a benefit in a strict focus on carbon balances, greenhouse gas emissions and Global Warming Potential. However, it is strongly recommended to follow up on the present work with LCA investigations on other important impact indicators (e.g. eutrophication, eco toxicity and human toxicity) to avoid burden shifting within the assessed systems.

Finally, if the results from the study are to be used in public, it is recommended that the study is subjected to an external review and quality control check.

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Fysisk-kemisk Parameter

	Enhed	Værdi i OS	Værdi i TS	Kvantifi- ceringsgr.	Grænse- værdi	Metode
Tørstof	%	24,8		0,1		DS 204 (M029)
Tørstof	mg/kg	248000	1000000	1000		DS 204 (M029)
Vandindhold	%	75,2		0,1		Beregning
Gløderest	%	10,5	42,4			DS 204 (M029)
Glødetab (org. substans)	%	14,3	57,6	0,5		DS 204 (M029)
Glødetab (org. substans)	mg/kg	143000	576000	1000		DS 204 (M029)
Alkalinitet, som (CaCO3)	mg/kg	17000	69000	1000		AbfklärV 1992
Kulstof, total organisk TOC	%	7,09	28,6	0,1		DIN EN 15936 (Dumas)

Næringsstoffer

Kvælstof tot. (N)	mg/kg	11000	44000	100		DIN EN 13342 (M023)
Kvælstof tot. (N) i TS	mg/kg		44000			Beregning
Ammoniumkvælstof (NH4-N)	mg/kg	1170	4720	100		DIN 38406-5-2 (E 5-2)
Ammoniumkvælstof (NH4-N) i TS	mg/kg		4720			Beregning
Calcium total (Ca)	mg/kg	9750	39300	1		DIN EN ISO 11885 (M021)
Phosphor (P)	mg/kg	7700	31000	100		DIN EN ISO 11885 (M021)
Phosphor citratopløsning (P)	mg/kg	6750	27200	100		DIN EN ISO 11885 (M021)
Kalium (K) vandopløsning	mg/kg	350	1410	100		DIN EN ISO 11885 (M021)
Magnesium total (Mg)	mg/kg	1290	5190	500		DIN EN ISO 11885 (M021)

Metaller

Arsen	mg/kg	4,5	18	0,5		DIN EN ISO 17294-2 (E 29)
Bly	mg/kg	12	48	0,5	120	DIN EN ISO 11885 (M021)
Bly (Pb) pr. phosphorenhed	mg/kg TP	370	1500		10000	Beregning
Cadmium	mg/kg	0,2339	0,943	0,25	0,8	DIN EN ISO 11885 (M021)
Cadmium (Cd) pr. phosphorenhed	mg/kg TP	7,4	30		100	Beregning
Chrom	mg/kg	8,2	33	0,5	100	DIN EN ISO 11885 (M021)
Kobber	mg/kg	97	392	1	1000	DIN EN ISO 11885 (M021)
Nikkel	mg/kg	8,2	33	0,5	30	DIN EN ISO 11885 (M021)

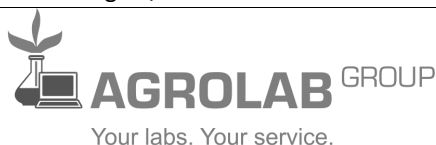
Side 1 af 3

DOC-27-1103742S-DA-P1

29.08.17 11:39
AG Hildesheim
HRB 200557
Ust./VAT-ID-Nr.
DE 198 696 523Geschäftsführer
Dr. Paul Wimmer
Dr. Jens RadickeDeutsche
Akkreditierungsstelle
D-PL-14047-01-00

AGROLAB Agrar und Umwelt GmbH

Dr.-Hell-Str. 6, 24107 Kiel, Germany
www.agrolab.de



Dato 29.08.2017

Kundenr. 20092402

ANALYSERAPPORT 1850286 - 280062

	Enhed	Værdi i OS	Værdi i TS	Kvantifi- ceringsgr.	Grænse- værdi	Metode
Nikkel (Ni) pr. phosphorenhed	mg/kg TP	270	1100		2500	Beregning
Kviksølv	mg/kg	0,27	1,1	0,1	0,8	DIN EN 1483
Kviksølv (Hg) pr. phosphorenhed	mg/kg TP	8,7	35		200	Beregning
Zink	mg/kg	246	993	1	4000	DIN EN ISO 11885 (M021)

Dioxinlignende PCB (dl-PCB)

PCB (118)	mg/kg		0,002	0,001		German Regulation for Waste Material and Sewage 1992(ZF) v)
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Non-dioxinlike PCB (ndl-PCB)

PCB (28)	mg/kg		0,003	0,001		German Regulation for Waste Material and Sewage 1992(ZF) v)
PCB (52)	mg/kg		0,004	0,001		German Regulation for Waste Material and Sewage 1992(ZF) v)
PCB (101)	mg/kg		0,005	0,001		German Regulation for Waste Material and Sewage 1992(ZF) v)
PCB (138)	mg/kg		0,005	0,001		German Regulation for Waste Material and Sewage 1992(ZF) v)
PCB (153)	mg/kg		0,005	0,001		German Regulation for Waste Material and Sewage 1992(ZF) v)
PCB (180)	mg/kg		0,003	0,001		German Regulation for Waste Material and Sewage 1992(ZF) v)
PCB-sum	mg/kg		0,025			AbfKlärV 1992

Polycyclic aromatic hydrocarbons (PAH)

Acenaphthen	mg/kg	<0,0124	<0,0500	0,05		VDLUF VII, 3.3.3(OB) u)
Benzo(a)-pyren	mg/kg	0,0494	0,199	0,05		VDLUF VII, 3.3.3(OB) u)
Benzo(b)fluoranthren	mg/kg	0,0652	0,263	0,05		VDLUF VII, 3.3.3(OB) u)
Benzo(ghi)perylene	mg/kg	0,0573	0,231	0,05		VDLUF VII, 3.3.3(OB) u)
Benzo(j)fluoranthren	mg/kg	0,0352	0,142	0,05		VDLUF VII, 3.3.3(OB) u)
Benzo(k)fluoranthren	mg/kg	0,0320	0,129	0,05		VDLUF VII, 3.3.3(OB) u)
Fluoranthren	mg/kg	0,148	0,596	0,05		VDLUF VII, 3.3.3(OB) u)
Indeno(1,2,3-cd)pyren	mg/kg	0,0365	0,147	0,05		VDLUF VII, 3.3.3(OB) u)
Phenanthren	mg/kg	0,142	0,573	0,05		VDLUF VII, 3.3.3(OB) u)
Fluoren	mg/kg	0,0162	0,0652	0,05		VDLUF VII, 3.3.3(OB) u)
Pyren	mg/kg	0,118	0,474	0,05		VDLUF VII, 3.3.3(OB) u)
Sum af PAH	mg/kg	0,70 x)	2,8		3	VDLUF VII, 3.3.3

Blødgørere

Di-Ethyl-Hexyl-Phthalat (DEHP)	mg/kg	0,47	1,9	0,5	50	GC/MSD(A8) v)
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NPE-forbindelser

Nonylphenol	mg/kg	<0,0248	<0,100	0,1		Egen metode GC/MS(A8) v)
Nonylphenolmonoethoxylat	mg/kg	<0,025	<0,100	0,1		Egen metode GC/MS(A8) v)
Nonylphenoldiethoxylat	mg/kg	<0,025	<0,100	0,1		Egen metode GC/MS(A8) v)
Sum af Nonylphenoler	mg/kg	<0,0248 x)	<0,100	0,1	10	Beregning

Andre undersøgelsesparametre

LAS *	mg/kg	57,0	230	50	1300	MeOH-Ekstraktion, HPLC/UV(A8)
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x) Enkelt værdier, som er under påvisnings- eller kvantificeringsgrænsen indgår ikke i beregningen

Symbolet "<" eller i.k. i kolonnen "Resultat" betyder, at stoffet ikke kan kvantificeres, da det ligger under kvantificeringsgrænsen

forklaring: Indhold: OS=Bruttoindhold, TS=Tørstofindhold

v) Analyseret på andet akkrediteret laboratorie

u) Analyseret på andet akkrediteret Agrolab-laboratorie

DOC-27-11037429-DA-42



AG Hildesheim
HRB 200557
Ust./VAT-ID-Nr:
DE 198 696 523

Geschäftsführer
Dr. Paul Wimmer
Dr. Jens Radicke



Deutsche
Akkreditierungsstelle
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ANALYSERAPPORT 1850286 - 280062Underleverancer eller outsourcingUndersøgt af

(A8) AnalyTech Miljølaboratorium A/S, Bøgildsmindevej 21, 9400 Nørresundby

Metode

MeOH-Ekstraktion, HPLC/UV

(A8) AnalyTech Miljølaboratorium A/S, Bøgildsmindevej 21, 9400 Nørresundby, akkrediteret til metoden citerede DANAK 401, Akkreditering certifikat: EN ISO 17025:2005

Metode

GC/MSD; Egen metode GC/MS

(ZF) ZFD, BERNECKERSTR. 17-21, 95448 BAYREUTH, akkrediteret til metoden citerede DIN EN ISO/IEC 17025:2005, Akkreditering certifikat: D-PL-19418-01-00

Metode

German Regulation for Waste Material and Sewage 1992

Agrolab grupper laboratorierUndersøgt af

(OB) AGROLAB Beliggenhed Bruckberg, Dr.-Pauling-Str. 3, 84079 Bruckberg, akkrediteret til metoden citerede ISO/IEC 17025:2005, Akkreditering certifikat: D-PL-14289_01_00

Metode

VDLUF VII, 3.3.3

De følgende parametre overskrider grænseværdien eller ligger uden for det påkrævede område

Analyseparametre	Værdi	Enhed	
Cadmium	0,943	mg/kg	Cadmium
Nikkel	33	mg/kg	Nikkel
Kviksølv	1,1	mg/kg	Kviksølv

Bemærkninger

Fordelingsliste: lha@vandcenter.dk, analyserapporter@vandcenter.dk

Testens begyndelse: 11.08.2017

Testens afslutning: 29.08.2017

Testresultaterne gælder udelukkende for testens genstande. Ved prøver af ukendt oprindelse er en plausibilitetskontrol kun mulig under visse forudsætninger. Mangfoldiggørelse af uddrag af rapporten er ikke tilladt uden vores skriftlige tilladelse.

K. Hesseler

AGROLAB Umwelt Kiel Frau Hesseler, Tlf. 0431/22138-517
Kundeservice slam

DOC-27-11037429-DA-P3



29.08.17 11:38
AG Hildesheim
HRB 200557
Ust./VAT-ID-Nr:
DE 198 696 523

Geschäftsführer
Dr. Paul Wimmer
Dr. Jens Radicke



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Vandværksvej 7
5000 Odense C
DÅNEMARK

Dato 29.08.2017

Kundenr. 20092402

ANALYSERAPPORT 1850285 - 280049

Ordre **1850285 Ejby Mølle slam - Tørret afvandet primær slam fra AquaGreen**
 Analyse nr. **280049 Spildevandsslam**
 Projekt **5518 Ejby Mølle Renseanlæg, EAN nr. 5798006610945, att. Lise Havsteen**
 Prøvens ankomst **11.08.2017**
 Prøvetagning **01.08.2017**
 Prøvetager **Ordregiver (IP)**
 Kunde-prøvebetegnelse **30429850**
 Prøvetagning start (dato,kl.) **01.08.2017 00:00**
 Udtagningssted **14610003 Ejby Mølle Renseanlæg; Møllevej 20 - 22 Aqua Green**

Bemærk:

Tørret afvandet slam fra pilotanlæg ved Aqua Green.

	Enhed	Værdi i OS	Værdi i TS	Kvantifi- ceringsgr.	Grænse- værdi	Metode
Fysisk-kemisk Parameter						
Tørstof	%	100		0,1		DS 204 (M029)
Tørstof	mg/kg	1000000	1000000	1000		DS 204 (M029)
Vandindhold	%	<0,100		0,1		Beregning
Gløderest	%	44,9	44,9			DS 204 (M029)
Glødetab (org. substans)	%	55,1	55,1	0,5		DS 204 (M029)
Glødetab (org. substans)	mg/kg	551000	551000	1000		DS 204 (M029)
Alkalinitet, som (CaCO3)	mg/kg	55000	55000	1000		AbfklärV 1992
Kulstof, total organisk TOC	%	28,7	28,7	0,1		DIN EN 15936 (Dumas)
Næringsstoffer						
Kvælstof tot. (N)	mg/kg	40000	40000	100		DIN EN 13342 (M023)
Kvælstof tot. (N) i TS	mg/kg		40000			Beregning
Ammoniumkvælstof (NH4-N)	mg/kg	752	752	100		DIN 38406-5-2 (E 5-2)
Ammoniumkvælstof (NH4-N) i TS	mg/kg		752			Beregning
Phosphor (P)	mg/kg	32000	32000	100		DIN EN ISO 11885 (M021)
Phosphor citratopløsning (P)	mg/kg	30000	30000	100		DIN EN ISO 11885 (M021)
Kalium (K) vandopløsning	mg/kg	1470	1470	100		DIN EN ISO 11885 (M021)
Magnesium total (Mg)	mg/kg	5640	5640	500		DIN EN ISO 11885 (M021)
Metaller						
Arsen	mg/kg	17	17	0,5		DIN EN ISO 17294-2 (E 29)
Bly	mg/kg	54	54	0,5	120	DIN EN ISO 11885 (M021)
Bly (Pb) pr. phosphorenhed	mg/kg TP	1700	1700		10000	Beregning
Cadmium	mg/kg	1,03	1,03	0,25	0,8	DIN EN ISO 11885 (M021)
Cadmium (Cd) pr. phosphorenhed	mg/kg TP	32	32		100	Beregning
Chrom	mg/kg	37	37	0,5	100	DIN EN ISO 11885 (M021)

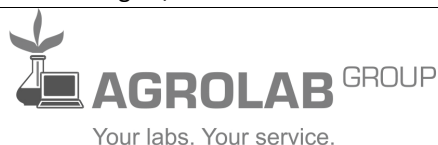
Side 1 af 3

DOC-27-11037387-DA-P1

AG Hildesheim
HRB 200557
Ust./VAT-ID-Nr.:
DE 198 696 523Geschäftsführer
Dr. Paul Wimmer
Dr. Jens RadickeDeutsche
Akkreditierungsstelle
D-PL-14047-01-00

AGROLAB Agrar und Umwelt GmbH

Dr.-Hell-Str. 6, 24107 Kiel, Germany
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Dato 29.08.2017

Kundenr. 20092402

ANALYSERAPPORT 1850285 - 280049

	Enhed	Værdi i OS	Værdi i TS	Kvantifi- ceringsgr.	Grænse- værdi	Metode
Kobber	mg/kg	424	424	1	1000	DIN EN ISO 11885 (M021)
Nikkel	mg/kg	35	35	0,5	30	DIN EN ISO 11885 (M021)
Nikkel (Ni) pr. phosphorenhed	mg/kg TP	1100	1100		2500	Beregning
Kviksølv	mg/kg	1,2	1,2	0,1	0,8	DIN EN 1483
Kviksølv (Hg) pr. phosphorenhed	mg/kg TP	38	38		200	Beregning
Zink	mg/kg	1070	1070	1	4000	DIN EN ISO 11885 (M021)

Dioxinlignende PCB (dl-PCB)

PCB (118)	mg/kg	<0,001	0,001			German Regulation for Waste Material and Sewage 1992(ZF) v)
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Non-dioxinlike PCB (ndl-PCB)

PCB (28)	mg/kg	<0,001	0,001			German Regulation for Waste Material and Sewage 1992(ZF) v)
PCB (52)	mg/kg	0,001	0,001			German Regulation for Waste Material and Sewage 1992(ZF) v)
PCB (101)	mg/kg	0,002	0,001			German Regulation for Waste Material and Sewage 1992(ZF) v)
PCB (138)	mg/kg	0,002	0,001			German Regulation for Waste Material and Sewage 1992(ZF) v)
PCB (153)	mg/kg	0,002	0,001			German Regulation for Waste Material and Sewage 1992(ZF) v)
PCB (180)	mg/kg	0,002	0,001			German Regulation for Waste Material and Sewage 1992(ZF) v)
PCB-sum	mg/kg	x)	0,009			AbfKlärV 1992

Polycyclic aromatic hydrocarbons (PAH)

Acenaphthen	mg/kg	<0,0500	<0,0500	0,05		VDLUF VII, 3.3.3(OB) u)
Benzo-(a)-pyren	mg/kg	0,0732	0,0732	0,05		VDLUF VII, 3.3.3(OB) u)
Benzo(b)fluoranthen	mg/kg	0,118	0,118	0,05		VDLUF VII, 3.3.3(OB) u)
Benzo(ghi)perylene	mg/kg	0,118	0,118	0,05		VDLUF VII, 3.3.3(OB) u)
Benzo(j)fluoranthen	mg/kg	0,0696	0,0696	0,05		VDLUF VII, 3.3.3(OB) u)
Benzo(k)fluoranthen	mg/kg	0,0795	0,0795	0,05		VDLUF VII, 3.3.3(OB) u)
Fluoranthen	mg/kg	0,0872	0,0872	0,05		VDLUF VII, 3.3.3(OB) u)
Indeno(1,2,3-cd)pyren	mg/kg	0,0687	0,0687	0,05		VDLUF VII, 3.3.3(OB) u)
Phenanthren	mg/kg	0,0604	0,0604	0,05		VDLUF VII, 3.3.3(OB) u)
Fluoren	mg/kg	<0,0650 m)	<0,0650	0,065		VDLUF VII, 3.3.3(OB) u)
Pyren	mg/kg	0,0877	0,0877	0,05		VDLUF VII, 3.3.3(OB) u)
Sum af PAH	mg/kg	0,76 x)	0,76		3	VDLUF VII, 3.3.3

Blødgørere

Di-Ethyl-Hexyl-Phthalat (DEHP)	mg/kg	1,5	1,5	0,5	50	GC/MSD(A8) v)
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NPE-forbindelser

Nonylphenol	mg/kg	<0,100	<0,100	0,1		Egen metode GC/MS(A8) v)
Nonylphenolmonoethoxylat	mg/kg	<0,100	<0,100	0,1		Egen metode GC/MS(A8) v)
Nonylphenoldiethoxylat	mg/kg	<0,100	<0,100	0,1		Egen metode GC/MS(A8) v)
Sum af Nonylphenoler	mg/kg	<0,100 x)	<0,100	0,1	10	Beregning

Andre undersøgelsesparametre

LAS *	mg/kg	350	350	50	1300	MeOH-Ekstraktion, HPLC/UV(A8)
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x) Enkelt værdier, som er under påvisnings- eller kvantificeringsgrænsen indgår ikke i beregningen

m) På grund af prøvens beskaffenhed er detektions- og kvantificeringsgrænserne forhøjede

Symbolet "<" eller i.k. i kolonnen "Resultat" betyder, at stoffet ikke kan kvantificeres, da det ligger under kvantificeringsgrænsen

forklaring: Indhold: OS=Bruttoindhold, TS=Tørstofindhold

v) Analyseret på andet akkrediteret laboratorium

u) Analyseret på andet akkrediteret Agrolab-laboratorie

DCC-27-11037387-DA-P2



29.08.17 11:23
AG Hildesheim
HRB 200557
Ust./VAT-ID-Nr:
DE 198 696 523

Geschäftsführer
Dr. Paul Wimmer
Dr. Jens Radicke



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ANALYSERAPPORT 1850285 - 280049Underleverancer eller outsourcingUndersøgt af

(A8) AnalyTech Miljølaboratorium A/S, Bøgildsmindevej 21, 9400 Nørresundby

Metode

MeOH-Ekstraktion, HPLC/UV

(A8) AnalyTech Miljølaboratorium A/S, Bøgildsmindevej 21, 9400 Nørresundby, akkrediteret til metoden citerede DANAK 401, Akkreditering certifikat: EN ISO 17025:2005

Metode

Egen metode GC/MS; GC/MSD

(ZF) ZFD, BERNECKERSTR. 17-21, 95448 BAYREUTH, akkrediteret til metoden citerede DIN EN ISO/IEC 17025:2005, Akkreditering certifikat: D-PL-19418-01-00

Metode

German Regulation for Waste Material and Sewage 1992

Agrolab grupper laboratorierUndersøgt af

(OB) AGROLAB Beliggenhed Bruckberg, Dr.-Pauling-Str. 3, 84079 Bruckberg, akkrediteret til metoden citerede ISO/IEC 17025:2005, Akkreditering certifikat: D-PL-14289_01_00

Metode

VDLUF VII, 3.3.3

De følgende parametre overskrider grænseværdien eller ligger uden for det påkrævede område

Analyseparametre	Værdi	Enhed	
Cadmium	1,03	mg/kg	Cadmium
Nikkel	35	mg/kg	Nikkel
Kviksølv	1,2	mg/kg	Kviksølv

Bemærkninger

Fordelingsliste: analyserapporter@vandcenter.dk, lha@vandcenter.dk

Testens begyndelse: 11.08.2017

Testens afslutning: 29.08.2017

Testresultaterne gælder udelukkende for testens genstande. Ved prøver af ukendt oprindelse er en plausibilitetskontrol kun mulig under visse forudsætninger. Mangfoldiggørelse af uddrag af rapporten er ikke tilladt uden vores skriftlige tilladelse.

K. Hesseler

AGROLAB Umwelt Kiel Frau Hesseler, Tlf. 0431/22138-517
Kundeservice slam

DOC-27-11037367-DA-P3



29.08.17 11:23
AG Hildesheim
HRB 200557
Ust./VAT-ID-Nr:
DE 198 696 523

Geschäftsführer
Dr. Paul Wimmer
Dr. Jens Radicke



Deutsche
Akkreditierungsstelle
D-PL-14047-01-00

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Vandværksvej 7
5000 Odense C
DÅNEMARK

Dato 29.08.2017

Kundenr. 20092402

ANALYSERAPPORT 1850658 - 280878

Ordre **1850658 Ejby Mølle slam - pyroliseret afvandet/tørret slam fra pilotanlæg ved Aqua Green**

Analyse nr. **280878 Spildevandsslam**

Projekt **5518 Ejby Mølle Renseanlæg, EAN nr. 5798006610945, att. Lise Havsteen**

Prøvens ankomst **14.08.2017**

Prøvetagning **01.08.2017**

Prøvetager **Ordregiver (IP)**

Kunde-prøvebetegnelse **30429870**

Prøvetagning start (dato,kl.) **01.08.2017 00:00**

Udtagningssted **14610003 Ejby Mølle Renseanlæg; Møllevej 20 - 22 Aqua Green**

Fysisk-kemisk Parameter

	Enhed	Værdi i OS	Værdi i TS	Kvantifi- ceringsgr.	Grænse- værdi	Metode
Tørstof	%	100		0,1		DS 204 (M029)
Tørstof	mg/kg	1000000	1000000	1000		DS 204 (M029)
Vandindhold	%	<0,100		0,1		Beregning
Gløderest	%	74,4	74,4			DS 204 (M029)
Glødetab (org. substans)	%	25,6	25,6	0,5		DS 204 (M029)
Glødetab (org. substans)	mg/kg	256000	256000	1000		DS 204 (M029)
Alkalinitet, som (CaCO ₃)	mg/kg	140000	140000	1000		AbfklarV 1992
Kulstof, total organisk TOC	%	22,6	22,6	0,1		DIN EN 15936 (Dumas)

Næringsstoffer

Kvælstof tot. (N)	mg/kg	21000	21000	100		DIN EN 13342 (M023)
Kvælstof tot. (N) i TS	mg/kg		21000			Beregning
Ammoniumkvælstof (NH ₄ -N)	mg/kg	187	187	100		DIN 38406-5-2 (E 5-2)
Ammoniumkvælstof (NH ₄ -N) i TS	mg/kg		187			Beregning
Phosphor (P)	mg/kg	50000	50000	100		DIN EN ISO 11885 (M021)
Phosphor citratopløsning (P)	mg/kg	35400	35400	100		DIN EN ISO 11885 (M021)
Kalium (K) vandopløsning	mg/kg	639	639	100		DIN EN ISO 11885 (M021)
Magnesium total (Mg)	mg/kg	9520	9520	500		DIN EN ISO 11885 (M021)

Metaller

Arsen	mg/kg	16	16	0,5		DIN EN ISO 17294-2 (E 29)
Bly	mg/kg	87	87	0,5	120	DIN EN ISO 11885 (M021)
Bly (Pb) pr. phosphorenhed	mg/kg TP	1700	1700		10000	Beregning
Cadmium	mg/kg	1,69	1,69	0,25	0,8	DIN EN ISO 11885 (M021)
Cadmium (Cd) pr. phosphorenhed	mg/kg TP	34	34		100	Beregning
Chrom	mg/kg	62	62	0,5	100	DIN EN ISO 11885 (M021)
Kobber	mg/kg	656	656	1	1000	DIN EN ISO 11885 (M021)
Nikkel	mg/kg	64	64	0,5	30	DIN EN ISO 11885 (M021)

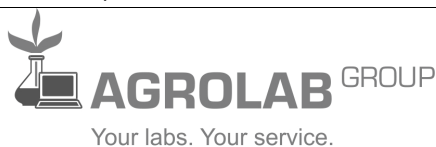
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DOC-27-11037430-DA-P1

AG Hildesheim
HRB 200557
Ust./VAT-ID-Nr:
DE 198 696 523Geschäftsführer
Dr. Paul Wimmer
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Akkreditierungsstelle
D-PL-14047-01-00

AGROLAB Agrar und Umwelt GmbH

Dr.-Hell-Str. 6, 24107 Kiel, Germany
www.agrolab.de



Dato 29.08.2017

Kundenr. 20092402

ANALYSERAPPORT 1850658 - 280878

	Enhed	Værdi i OS	Værdi i TS	Kvantifi- ceringsgr.	Grænse- værdi	Metode
Nikkel (Ni) pr. phosphorenhed	mg/kg TP	1300	1300		2500	Beregning
Kviksølv	mg/kg	<0,030 (LOD)	<0,030 (LOD)	0,1	0,8	DIN EN 1483
Kviksølv (Hg) pr. phosphorenhed	mg/kg TP	0,60 ^{xx)}	0,60		200	Beregning
Zink	mg/kg	1780	1780	1	4000	DIN EN ISO 11885 (M021)

Dioxinlignende PCB (dl-PCB)

PCB (118)	mg/kg		<0,001	0,001		German Regulation for Waste Material and Sewage 1992(ZF) ^{v)}
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Non-dioxinlike PCB (ndl-PCB)

PCB (28)	mg/kg		<0,001	0,001		German Regulation for Waste Material and Sewage 1992(ZF) ^{v)}
PCB (52)	mg/kg		<0,001	0,001		German Regulation for Waste Material and Sewage 1992(ZF) ^{v)}
PCB (101)	mg/kg		<0,001	0,001		German Regulation for Waste Material and Sewage 1992(ZF) ^{v)}
PCB (138)	mg/kg		<0,001	0,001		German Regulation for Waste Material and Sewage 1992(ZF) ^{v)}
PCB (153)	mg/kg		<0,001	0,001		German Regulation for Waste Material and Sewage 1992(ZF) ^{v)}
PCB (180)	mg/kg		<0,001	0,001		German Regulation for Waste Material and Sewage 1992(ZF) ^{v)}
PCB-sum	mg/kg		< LOD			AbfKlärV 1992

Polycyclic aromatic hydrocarbons (PAH)

Acenaphthen	mg/kg	<0,150 ^{m)}	<0,150	0,15		VDLUF VII, 3.3.3(OB) ^{u)}
Benzo-(a)-pyren	mg/kg	<0,0500	<0,0500	0,05		VDLUF VII, 3.3.3(OB) ^{u)}
Benzo(b)fluoranthren	mg/kg	<0,0500	<0,0500	0,05		VDLUF VII, 3.3.3(OB) ^{u)}
Benzo(ghi)perylene	mg/kg	<0,0500	<0,0500	0,05		VDLUF VII, 3.3.3(OB) ^{u)}
Benzo(j)fluoranthren	mg/kg	<0,0500	<0,0500	0,05		VDLUF VII, 3.3.3(OB) ^{u)}
Benzo(k)fluoranthren	mg/kg	<0,0500	<0,0500	0,05		VDLUF VII, 3.3.3(OB) ^{u)}
Fluoranthren	mg/kg	<0,0500	<0,0500	0,05		VDLUF VII, 3.3.3(OB) ^{u)}
Indeno(1,2,3-cd)pyren	mg/kg	<0,0500	<0,0500	0,05		VDLUF VII, 3.3.3(OB) ^{u)}
Phenanthren	mg/kg	<0,0500	<0,0500	0,05		VDLUF VII, 3.3.3(OB) ^{u)}
Fluoren	mg/kg	<0,150 ^{m)}	<0,150	0,15		VDLUF VII, 3.3.3(OB) ^{u)}
Pyren	mg/kg	<0,0500	<0,0500	0,05		VDLUF VII, 3.3.3(OB) ^{u)}
Sum af PAH	mg/kg	i.k.	i.k.		3	VDLUF VII, 3.3.3

Blødgørere

Di-Ethyl-Hexyl-Phthalat (DEHP)	mg/kg	<0,50	<0,50	0,5	50	GC/MSD(A8) ^{v)}
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NPE-forbindelser

Nonylphenol	mg/kg	<0,100	<0,100	0,1		Egen metode GC/MS(A8) ^{v)}
Nonylphenolmonoethoxylat	mg/kg	<0,100	<0,100	0,1		Egen metode GC/MS(A8) ^{v)}
Nonylphenoldiethoxylat	mg/kg	<0,100	<0,100	0,1		Egen metode GC/MS(A8) ^{v)}
Sum af Nonylphenoler	mg/kg	<0,100 ^{x)}	<0,100	0,1	10	Beregning

Andre undersøgelsesparametre

LAS *	mg/kg	<50,0	<50,0	50	1300	MeOH-Ekstraktion, HPLC/UV(A8)
-------	-------	-------	-------	----	------	-------------------------------

x) Enkelt værdier, som er under påvisnings- eller kvantificeringsgrænsen indgår ikke i beregningen

xx) Ved enkeltbestemmelser under LOD er LOD anvendt ved beregning, og ved enkeltbestemmelser mellem LOD og LOQ er LOQ anvendt ved beregning.

m) På grund af prøvens beskaffenhed er detektions- og kvantificeringsgrænserne forhøjede

Symbolet "<" eller i.k. i kolonnen "Resultat" betyder, at stoffet ikke kan kvantificeres, da det ligger under kvantificeringsgrænsen

Symbolet "<...(LOD)" eller i.d. i kolonnen "Resultat" betyder, at stoffet ikke kan detekteres, da det ligger under detektionsgrænsen.

forklaring: Indhold: OS=Bruttoindhold, TS=Tørstofindhold

v) Analyseret på andet akkrediteret laboratorie

u) Analyseret på andet akkrediteret Agrolab-laboratorie

DOC-27-11037430-DA-42



AG Hildesheim
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D-PL-14047-01-00

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AGROLAB Agrar und Umwelt GmbH

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Your labs. Your service.

Dato 29.08.2017

Kundenr. 20092402

ANALYSERAPPORT 1850658 - 280878Underleverancer eller outsourcingUndersøgt af

(A8) AnalyTech Miljølaboratorium A/S, Bøgildsmindevej 21, 9400 Nørresundby

Metode

MeOH-Ekstraktion, HPLC/UV

(A8) AnalyTech Miljølaboratorium A/S, Bøgildsmindevej 21, 9400 Nørresundby, akkrediteret til metoden citerede DANAK 401, Akkreditering certifikat: EN ISO 17025:2005

Metode

Egen metode GC/MS; GC/MSD

(ZF) ZFD, BERNECKERSTR. 17-21, 95448 BAYREUTH, akkrediteret til metoden citerede DIN EN ISO/IEC 17025:2005, Akkreditering certifikat: D-PL-19418-01-00

Metode

German Regulation for Waste Material and Sewage 1992

Agrolab grupper laboratorierUndersøgt af

(OB) AGROLAB Beliggenhed Bruckberg, Dr.-Pauling-Str. 3, 84079 Bruckberg, akkrediteret til metoden citerede ISO/IEC 17025:2005, Akkreditering certifikat: D-PL-14289_01_00

Metode

VDLUF VII, 3.3.3

De følgende parametre overskrider grænseværdien eller ligger uden for det påkrævede område

Analyseparametre	Værdi	Enhed
Cadmium	1,69	mg/kg
Nikkel	64	mg/kg

Cadmium
NikkelBemærkninger

Fordelingsliste: lha@vandcenter.dk, analyserapporter@vandcenter.dk

Testens begyndelse: 15.08.2017

Testens afslutning: 29.08.2017

Testresultaterne gælder udelukkende for testens genstande. Ved prøver af ukendt oprindelse er en plausibilitetskontrol kun mulig under visse forudsætninger. Mangfoldiggørelse af uddrag af rapporten er ikke tilladt uden vores skriftlige tilladelse.

AGROLAB Umwelt Kiel Frau Hesseler, Tlf. 0431/22138-517
Kundeservice slam

DOC-27-11037430-DA-P3



29.08.17 11:38
AG Hildesheim
HRB 200557
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Deutsche
Akkreditierungsstelle
D-PL-14047-01-00

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Appendix 2: AquaGreen system, material use

Primary data provided by Michael Olsson, Project Engineer (in Danish):

Materialeforbrug til AG-anlæg på VandCenter Syd								
kg	Rustfrit stål AISI 304	Stål SJ 235	Bronze	Kobber	Polymere div	Støbejern	Aluminium	Rockwool
gas/gas		780						
Isolering							200	200
Ledninger				40				
Lejehuse			20					
Gear/motor						205		
Blæsere		368						
Skruer		1580						
Elektriske					20			
Chassis damp	450							
Chassis pyro	250							
tørrekasse	400							
Pyrolovn	300							
Røggaskredsløb	300							
Indfødning	160							
Kondens kredsløb	130							
Rest af maskine	300							

To this is added 2x 20 feet containers summing up to 7.5 t steel

Dataset scaled, simplified and aggregated for implementation in Easetech:

	Construction phase	End-Of-Life phase
	Material use	Recycling
Material fraction:	kg/kg TS	kg/kg TS
Steel (Σ steel, stainless steel and cast iron)	2.1E-03	1.6E-03 (50-75% of input)
Aluminum (Σ bronze, copper and aluminum)	5.5E-05	4.3E-05 (75-90% of input)
Rockwool	4.2E-05	1.1E-05 (25% of input)
Computers (Σ computers and polymers)	1.0E-05	5.7E-07 (0-10% of input)
		Total landfilling
		kg/kg TS
		5.9E-04

Appendix 3: AquaGreen system, lifetime, operational hours and consumption of utilities during operation

Estimated values by agreement with AquaGreen, Claus Dalsgaard Jensen, Project Engineer:

Plant lifetime	Years	15	Estimation
Operational time	Hours/year	8000	Estimation
Propane gas consumption	MJ/FU	14	Assumed 2 hours consumption (1886 MJ) per week (start-up)
Water consumption	L/FU	345	Assumed 5 L/min for temperature control and char cooling

Determination power consumption during operation of AG plant at Ejby Mølle, by Michael Olsson, Project Engineer (in Danish):

Forbrug på PCP Damptørrer og Pyrolyse proces

	Nom effekt, watt	% af 50 HZ		Forbrug i effekt.
Indfødning motor	750	65	Watt	487.5
Dobbeltgear og motor	1500	60	Watt	900
Dampkreds cirkulations motor	5000	75	Watt	3750
Vakumpumpe	2200	4	Watt	88
Cellesluse	500	20	Watt	100
Conveyor 1	250	85	Watt	212.5
Conveyor 2	250	25	Watt	62.5
Conveyor 3	250	20	Watt	50
Pyrolyseovn	1500	3	Watt	45
Røggas cirkulation	4300	45	Watt	1935
Røggas udluft	3700	16	Watt	592
Effektforbrug i alt ved kontinuerlig drift.			Watt	8222.5

Appendix 4: Transfer functions, Reference 1 encompassing anaerobic sludge digestion

Transfor coefficients for Anaerobic Digestion			
	Biogas	Digestate	Reference
	%	%	
Water	1.7	98.3	Yoshida (2018) [39]
Total solids	19.2	68.1	Calculated
Organic carbon	44	56	Calc based on Kirkeby et al (2013) [5]
Total N	12.9	87.1	Yoshida (2018) [39]
NH4-N	0	100	Assumption
Total P	0	100	Assumption
Total K	0	100	Assumption
Total Mg	0	100	Assumption
Total S	5	95	Dewil (2007) 95% S recovery [56]
REST of TS (org+inorg)	0	73	Fittet to get 32% TS reduction [5]
Chemical energy potential	49.5	50.5	Calc based on Kirkeby et al 2013 + fit sludge energy [5]
Additional:	Biogas loss	3 vol%	Yoshida (2018) [39]
	Biogas CH4/CO2	65/35 vol%	Kirkeby et al (2013) [5]

Transfor coefficients for mechanical dewatering			
	Reject	Dewatered sludge	Reference
	%	%	
Water	86.5	13.5	Fit to get water content to 77%
Total solids	6.4	93.6	Calculated
Organic carbon	7.64	92.36	Assumption: as for undigested sludge in Ref 2
Total N	7.04	92.96	Assumption: as for undigested sludge in Ref 2
NH4-N	6.38	93.62	Assumption: as for undigested sludge in Ref 2
Total P	6.38	93.62	Assumption: as for undigested sludge in Ref 2
Total K	10.94	89.06	Assumption: as for undigested sludge in Ref 2
Total Mg	27.46	72.54	Assumption: as for undigested sludge in Ref 2
Total S	8	92	Dewil et al + Larsen et al* [7,56]
REST of TS (org+inorg)	5	95	Assumption
Chemical energy potential	0	100	Fitted

*Assumed to follow the distribution of Fe since most S is bounf to Fe after digestion
Based on Fe distribution from Larsen and S speciation from Dewil et al

Transfor coefficients during sludge storage			
	Air	Stored sludge	Reference
	%	%	
Water	1	99	Assumption: as for undigested sludge in Ref 2
Total solids	5.0	95.0	Calculated
Organic carbon	12	88	Assumption: as for undigested sludge in Ref 2
Total N	3	97	Assumption: as for undigested sludge in Ref 2
NH4-N	100	0	Assumption: as for undigested sludge in Ref 2
Total P	0	100	Assumption: as for undigested sludge in Ref 2
Total K	0	100	Assumption: as for undigested sludge in Ref 2
Total Mg	0	100	Assumption: as for undigested sludge in Ref 2
Total S	0	100	Assumption: as for undigested sludge in Ref 2
REST of TS (org+inorg)	0	100	Assumption: as for undigested sludge in Ref 2
Additional:	CO2: 48.5% of total C		Assumption: as for undigested sludge in Ref 2
	CH4: 51.5% of total C		Assumption: as for undigested sludge in Ref 2
	N2O: 25.5% of total N		Assumption: as for undigested sludge in Ref 2

Transfor coefficients during in-soil degradation (100 years)			
	Air	Stored sludge	Reference
	%	%	
Water	100	0	Assumption
Total solids	30.1	69.9	Calculated
Organic carbon	94.4	5.6	Yoshida (2018) [39]
Total N	4.9	95.1	Yoshida (2018) [39]
NH4-N	100	0	Assumption
Total P	0	100	Assumption
Total K	0	100	Assumption
Total Mg	0	100	Assumption
Total S	0	100	Assumption
REST of TS (org+inorg)	0	100	Assumption
Additional:	CO2: 99.9% of total C		Yoshida (2018) [39]
	CH4: 0.01% of total C		Yoshida (2018) [39]
	N2O: 24.5% Net of total N		Yoshida (2018) [39]

Appendix 5: Transfer functions, Reference 2 encompassing aerobic sludge stabilization

Transfor coefficients for aerobic stabilization			
	Air	Stabilized sludge	Reference
	%	%	
Water	1.7	98.3	Assumed as AD process
Total solids	10.0	90.0	Calculated
Organic carbon	22	78	Fittet to get 36% C in stabilized sludge [5]
Total N	12.9	87.1	Assumed as AD process
Total P	0	100	Assumed as AD process
Total K	0	100	Assumed as AD process
Total Mg	0	100	Assumed as AD process
Total S	5	95	Assumed as AD process
REST of TS (org+inorg)	0	100	Assumed as AD process
Additional:	100% C to CO ₂		Assumption
	0% N to N ₂ O		Assumption

Transfor coefficients for mechanical dewatering			
	Reject	Dewatered sludge	Reference
	%	%	
Water	87.5	12.5	Fit to get water content to 77%
Total solids	6.7	93.3	Calculated
Organic carbon	7.64	92.36	Larsen (2018) [7]
Total N	7.04	92.96	Larsen (2018) [7]
Total P	6.38	93.62	Larsen (2018) [7]
Total K	10.94	89.06	Larsen (2018) [7]
Total Mg	27.46	72.54	Larsen (2018) [7]
Total S	33	67	Dewil et al* [56]
REST of TS (org+inorg)	5	95	Assumption

*34% S water soluble. Soluble S distributed evenly in water

Approximately 1% of water and soluble S remain in solids

Transfer coefficients during sludge storage

	Air	Stored sludge	Reference
	%	%	
Water	1	99	Larsen (2018) [7]
Total solids	5.0	95.0	Calculated
Organic carbon	12	88	Larsen (2018) [7]
Total N	3	97	Larsen (2018) [7]
Total P	0	100	Assumption
Total K	0	100	Assumption
Total Mg	0	100	Assumption
Total S	0	100	Assumption
REST of TS (org+inorg)	0	100	Assumption
Additional:	CO ₂ : 48.5% of total C		Larsen (2018) [7]
	CH ₄ : 51.5% of total C		Larsen (2018) [7]
	N ₂ O: 25.5% of total N		Larsen (2018) [7]

Transfer coefficients during in-soil degradation (100 years)

	Air	Stored sludge	Reference
	%	%	
Water	100	0	Assumption
Total solids	32.0	68.0	Calculated
Organic carbon	94.9	5.1	Yoshida (2018) [39]
Total N	6	94	Yoshida (2018) [39]
Total P	0	100	Assumption
Total K	0	100	Assumption
Total Mg	0	100	Assumption
Total S	0	100	Assumption
REST of TS (org+inorg)	0	100	Assumption
Additional:	CO ₂ : 99.9% of total C		Yoshida (2018) [39]
	CH ₄ : 0.01% of total C		Yoshida (2018) [39]
	N ₂ O: 35% Net of total N		Yoshida (2018) [39]

Appendix 6: Transfer functions, Scenario 1 - anaerobic sludge digestion, steam drying and thermal pyrolysis

Transfer coefficients for Anaerobic Digestion			
	Biogas %	Digestate %	Reference
Water	1.7	98.3	Yoshida (2018) [39]
Total solids	31.9	68.1	Calculated
Organic carbon	44	56	As Reference system 1
Total N	12.9	87.1	Yoshida (2018) [39]
NH ₄ -N	0	100	Assumption
Total P	0	100	Assumption
Total K	0	100	Assumption
Total Mg	0	100	Assumption
Total S	5	95	Dewil (2007) 95% S recovery [56]
REST of TS (org+inorg)	27	73	Fitted to get 32% TS reduction [5]
Additional:	Biogas loss	3 vol%	Yoshida (2018) [39]
	Biogas		
	CH ₄ /CO ₂	65/35 vol%	Kirkeby et al (2013) [5]

Transfer coefficients for mechanical dewatering			
	Reject %	Dewatered sludge %	Reference
Water	86.5	13.5	Fit to get water content to 77%
Total solids	6.4	93.6	Calculated
Organic carbon	7.64	92.36	Assumption: as for undigested sludge in Ref 2
Total N	7.04	92.96	Assumption: as for undigested sludge in Ref 2
NH ₄ -N	6.38	93.62	Assumption: as for undigested sludge in Ref 2
Total P	6.38	93.62	Assumption: as for undigested sludge in Ref 2
Total K	10.94	89.06	Assumption: as for undigested sludge in Ref 2
Total Mg	27.46	72.54	Assumption: as for undigested sludge in Ref 2
Total S	8	92	Dewil et al + Larsen et al* [7,56]
REST of TS (org+inorg)	5	95	Assumption
Chemical energy potential	0	100	Fitted

*Assumed to follow the distribution of Fe since most S is bound to Fe after digestion
Based on Fe distribution from Larsen and S speciation from Dewil et al

Transfor coefficients during steam drying			
	Condensate	Dry sludge	Reference
	%	%	
Water	100	0	Calc. Based on Agrolab analysis data
Total solids	1.2	98.8	Calculation
Organic carbon	0	100	Calc. Based on Agrolab analysis data
Total N	9	91	Calc. Based on Agrolab analysis data
NH4-N	84	16	Calc. Based on Agrolab analysis data
Total P	0	100	Assumption
Total K	0	100	Assumption
Total Mg	0	100	Assumption
Total S	0	100	Saleh et al (2014) [57]
REST of TS (org+inorg)	0	100	Assumption

Transfor coefficients during thermal pyrolysis			
	Pyrolysis gas	Char	Reference
	%	%	
Water	100	0	Calc. Based on Agrolab analysis data
Total solids	44.0	56.0	Calculated
Organic carbon	55	45	Agrolab analysis + char recovery estimate
Total N	70	30	Agrolab analysis + char recovery estimate
NH4-N	86	14	Agrolab analysis + char recovery estimate
Total P	10	90	Agrolab analysis + char recovery estimate
Total K	10	90	Agrolab analysis + char recovery estimate
Total Mg	6	94	Agrolab analysis + char recovery estimate
Total S	45	55	Agrolab analysis + char recovery estimate
REST of TS (org+inorg)	37.5	62.5	Fittet to match total char recovery of 57%
Total energy (chem +heat)*	49	36.7	Calc based on agrolab analysis and DNA modelling

*The remaining 14.3% are thermal losses

Transfor coefficients during char storage			
	Air	Stored sludge	Reference
	%	%	
Water	0	100	Assumption
Total solids	0	100	Assumption
Organic carbon	0	100	Assumption
Total N	0	100	Assumption
NH4-N	0	100	Assumption
Total P	0	100	Assumption
Total K	0	100	Assumption
Total Mg	0	100	Assumption
Total S	0	100	Assumption
REST of TS (org+inorg)	0	100	Assumption

Transfer coefficients during in-soil degradation (100 years)			
	Air	Stored sludge	Reference
	%	%	
Water	0	100	Assumption
Total solids	2.8	97.2	Calculated
Organic carbon	10	90	Assumption based on Budai et al [44]
Total N	1	100	Assumption
NH4-N	0	100	Assumption
Total P	0	100	Assumption
Total K	0	100	Assumption
Total Mg	0	100	Assumption
Total S	0	100	Assumption
REST of TS (org+inorg)	0	100	Assumption
Additional:	N emission as N2 only		Assumption
	C emissions as CO2 only		Assumption

Transfor coefficients for mechanical dewatering

	Reject	Dewatered sludge	Reference
	%	%	
Water	87.5	13.5	Fit to get water content to 77%
Total solids	6.8	93.6	Calculation
Organic carbon	7.64	92.36	Larsen (2018) [7]
Total N	7.04	92.96	Larsen (2018) [7]
NH4-N	6.38	93.62	Larsen (2018) [7]
Total P	6.38	93.62	Larsen (2018) [7]
Total K	10.94	89.06	Larsen (2018) [7]
Total Mg	27.46	72.54	Larsen (2018) [7]
Total S	33	92	Dewil et al* [56]
REST of TS (org+inorg)	5	95	Assumption

*34% S water soluble. Soluble S distributed evenly in water

Approximately 1% of water and soluble S remain in solids

Transfor coefficients during steam drying

	Condensate	Dry sludge	Reference
	%	%	
Water	100	0	Assumed to be as in SCE 1
Total solids	0.9	99.1	Calculation
Organic carbon	0	100	Assumed to be as in SCE 1
Total N	9	91	Assumed to be as in SCE 1
NH4-N	84	16	Assumed to be as in SCE 1
Total P	0	100	Assumed to be as in SCE 1
Total K	0	100	Assumed to be as in SCE 1
Total Mg	0	100	Assumed to be as in SCE 1
Total S	0	100	Assumed to be as in SCE 1
REST of TS (org+inorg)	0	100	Assumed to be as in SCE 1

Transfor coefficients during thermal pyrolysis			
	Pyrolysis gas	Char	Reference
	%	%	
Water	100	0	Assumed to be as in SCE 1
Total solids	28.2	71.8	Calculation
Organic carbon	55	45	Assumed to be as in SCE 1
Total N	70	30	Assumed to be as in SCE 1
NH4-N	86	14	Assumed to be as in SCE 1
Total P	10	90	Assumed to be as in SCE 1
Total K	10	90	Assumed to be as in SCE 1
Total Mg	6	94	Assumed to be as in SCE 1
Total S	45	55	Assumed to be as in SCE 1
REST of TS (org+inorg)	2	98	Assumed to be as in SCE 1
Total energy (chem +heat)*	49	36.7	Assumed to be as in SCE 1

*The remaining 14.3% are thermal losses as in SCE 1

Transfor coefficients during char storage			
	Air	Stored sludge	Reference
	%	%	
Water	0	100	Assumption
Total solids	0	100	Assumption
Organic carbon	0	100	Assumption
Total N	0	100	Assumption
NH4-N	0	100	Assumption
Total P	0	100	Assumption
Total K	0	100	Assumption
Total Mg	0	100	Assumption
Total S	0	100	Assumption
REST of TS (org+inorg)	0	100	Assumption

Transfor coefficients during in-soil degradation (100 years)			
	Air	Stored sludge	Reference
	%	%	
Water	0	100	Assumption
Total solids	2.6	97.4	Calculated
Organic carbon	10	90	Assumption based on Budai et al [44]
Total N	1	100	Assumption
NH4-N	0	100	Assumption
Total P	0	100	Assumption
Total K	0	100	Assumption
Total Mg	0	100	Assumption
Total S	0	100	Assumption
REST of TS (org+inorg)	0	100	Assumption
Additional:	N emission as N2 only		Assumption
	C emissions as CO2 only		Assumption

Appendix 8: Sludge and char composition estimates for Easetech implementation

REFERENCE 1: ANAEROBIC DIGESTION AND DIRECT SLUDGE APPLICATION TO SOIL

Phase		As FU	After AD	After dewatering	After storage	After soil application, 100 years
Composition		Raw Sludge	Digested sludge	Dewatered sludge	Stored sludge	Degraded sludge
Water	wt% AR	95.0	96.5	79.8	80.5	0.0
TS	wt% AR	5.0	3.5	20.2	19.5	100.0
TOC	wt% DRY	42.0	34.5	34.1	31.6	2.5
Total N	wt% DRY	5.1	6.5	6.5	6.6	9.0
Total P	wt% DRY	3.1	4.6	4.6	4.8	6.9
Total K	wt% DRY	0.4	0.6	0.5	0.6	0.8
Total Mg	wt% DRY	0.7	1.0	0.8	0.8	1.2
Total S	wt% DRY	1.2	1.7	1.7	1.8	2.5
REST (org+inorg)	wt% DRY	47.0	50.4	51.2	53.9	77.1

REFERENCE 2: AEROBIC STABILIZATION AND DIRECT SLUDGE APPLICATION TO SOIL

Phase		As FU	After aerobic stabilization	After dewatering	After storage	After soil application, 100 years
Composition		Raw Sludge	Stabilized sludge	Dewatered Stabilized sludge	Stored sludge	Degraded sludge
Water	wt% AR	95.0	95.4	73.5	74.3	73.5
TS	wt% AR	5.0	4.6	26.5	25.7	26.5
TOC	wt% DRY	42.0	36.4	36.0	33.4	56.1
Total N	wt% DRY	5.1	4.9	4.9	5.0	7.7
Total P	wt% DRY	3.1	3.5	3.5	3.6	5.4
Total K	wt% DRY	0.4	0.4	0.4	0.4	0.6
Total Mg	wt% DRY	0.7	0.7	0.6	0.6	0.9
Total S	wt% DRY	1.2	1.3	0.9	1.0	1.5
REST (org+inorg)	wt% DRY	47.0	52.2	53.2	56.0	82.9

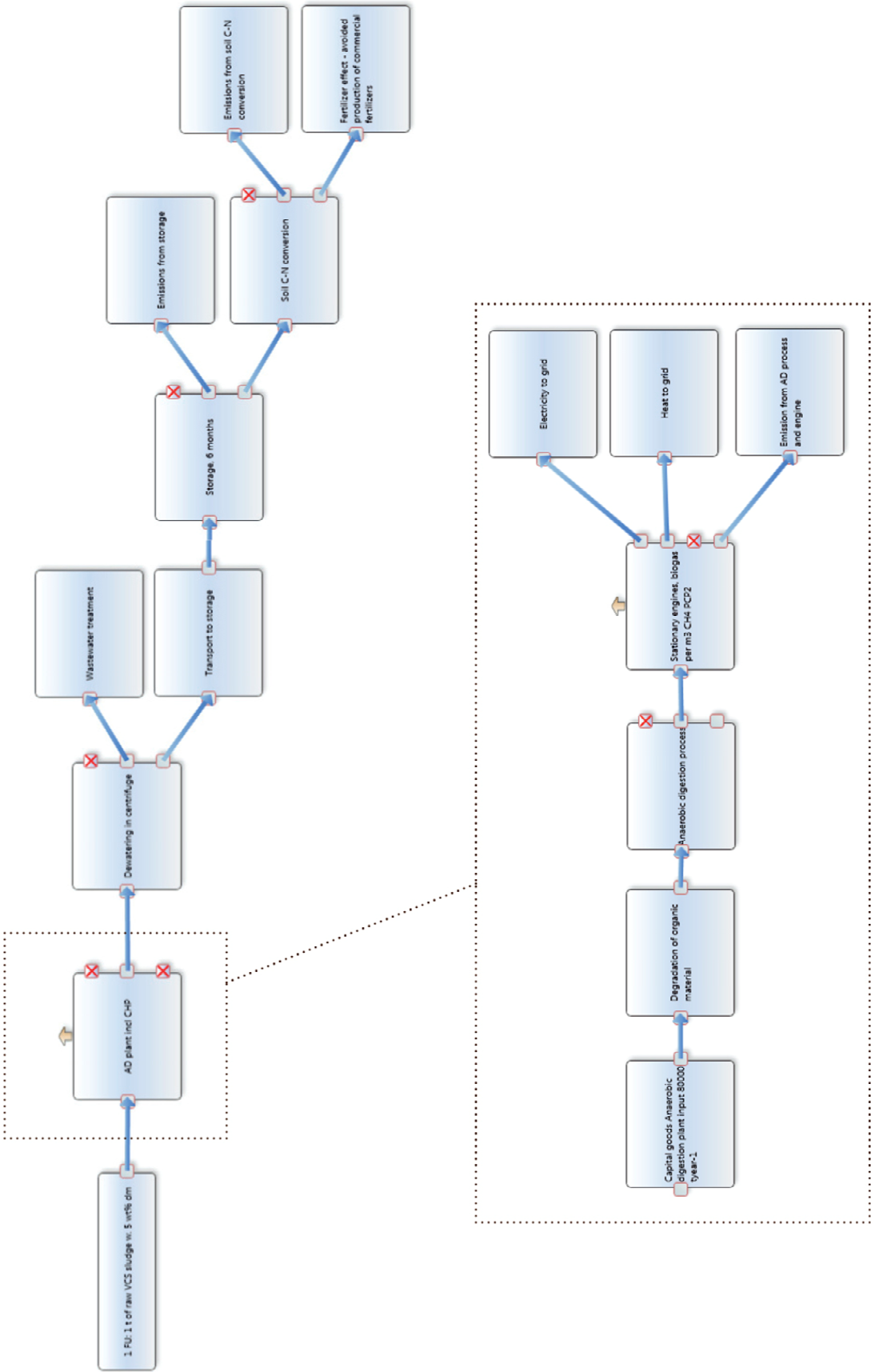
SCENARIO 1: STEAM DRYING AND PYROLYSIS OF ANAEROBICALLY DIGESTED SLUDGE AND CHAR APPLICATION TO SOIL

Phase		As FU	After AD	After dewatering	After steam	After	After	After soil application,
Composition		Raw Sludge	Digested sludge	Dewatered sludge	drying	pyrolysis	storage	100 years
					Dry sludge	Fresh Char	Stored char	Degraded char
Water	wt% AR	95.0	95.9	76.9	0.0	0.0	0.0	0.0
TS	wt% AR	5.0	4.1	23.1	100.0	100.0	100.0	100.0
TOC	wt% DRY	42.0	29.1	28.7	28.9	22.8	22.8	21.0
Total N	wt% DRY	5.1	5.5	5.5	5.0	2.6	2.6	2.7
Total P	wt% DRY	3.1	3.8	3.8	3.9	6.1	6.1	6.3
Total K	wt% DRY	0.4	0.5	0.4	0.4	0.7	0.7	0.7
Total Mg	wt% DRY	0.7	0.8	0.6	0.6	1.1	1.1	1.1
Total S	wt% DRY	1.2	1.4	1.4	1.4	1.4	1.4	1.4
REST (org+inorg)	wt% DRY	47.0	58.2	59.0	59.5	65.2	65.2	66.8

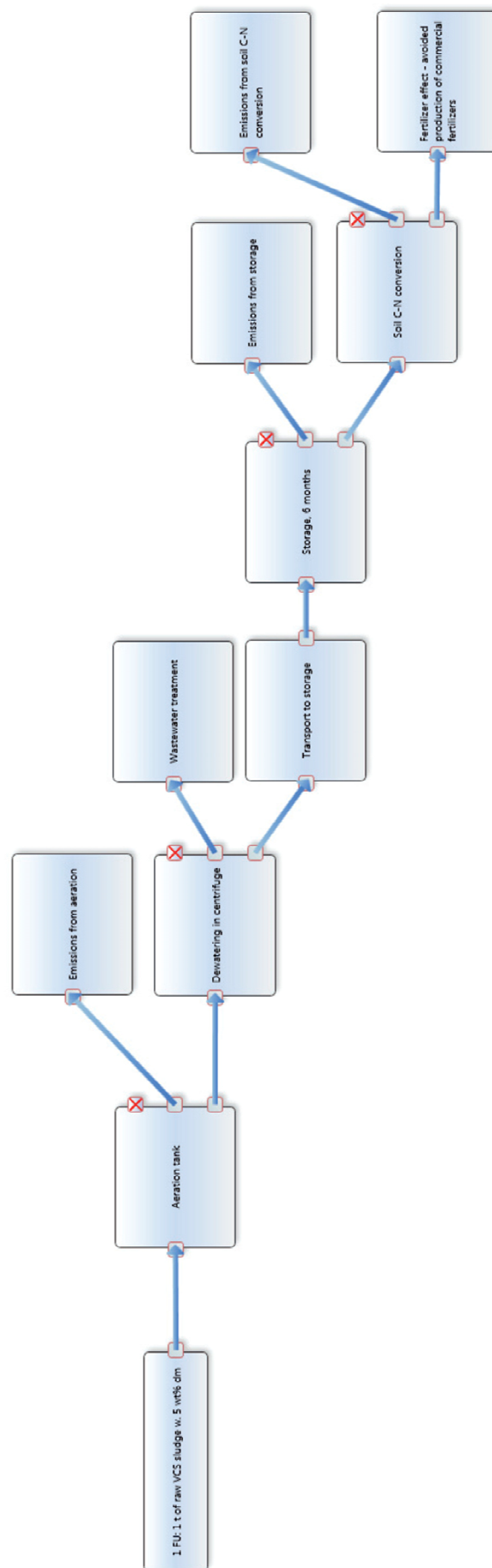
SCENARIO 2: STEAM DRYING AND PYROLYSIS OF UN-STABILIZED SLUDGE AND CHAR APPLICATION TO SOIL

Phase		As FU	After dewatering	After steam	After	After char	After soil application,
Composition		Raw Sludge	Dewatered sludge	drying	pyrolysis	storage	100 years
				Dry sludge	Char	Stored Char	degraded char
Water	wt% AR	95.0	71.8	0.0	0.0	0.0	0.0
TS	wt% AR	5.0	28.2	100.0	100.0	100.0	100.0
TOC	wt% DRY	42.0	41.6	42.0	26.3	26.3	24.3
Total N	wt% DRY	5.1	5.1	4.7	2.0	2.0	2.0
Total P	wt% DRY	3.1	3.1	3.1	3.9	3.9	4.1
Total K	wt% DRY	0.4	0.4	0.4	0.5	0.5	0.5
Total Mg	wt% DRY	0.7	0.5	0.5	0.7	0.7	0.7
Total S	wt% DRY	1.2	0.9	0.9	0.7	0.7	0.7
REST (org+inorg)	wt% DRY	47.0	47.9	48.3	66.0	66.0	67.7

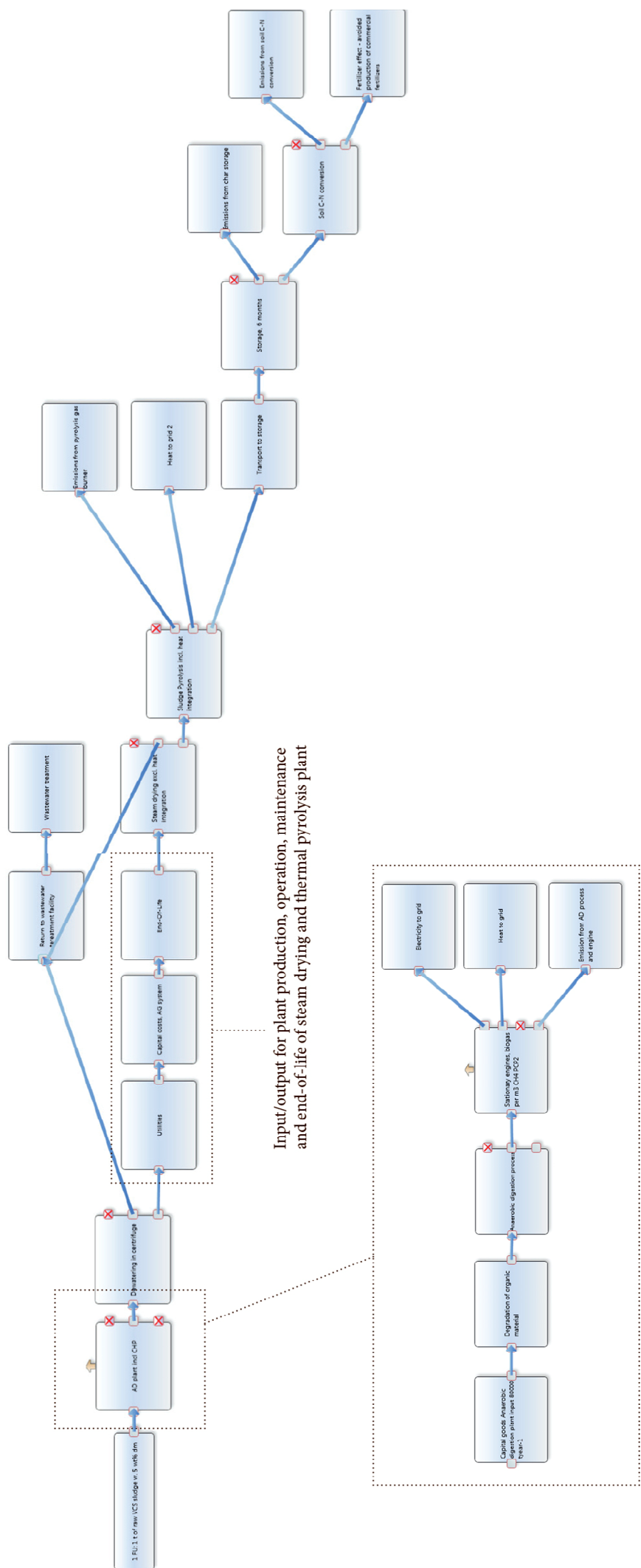
Reference system 1



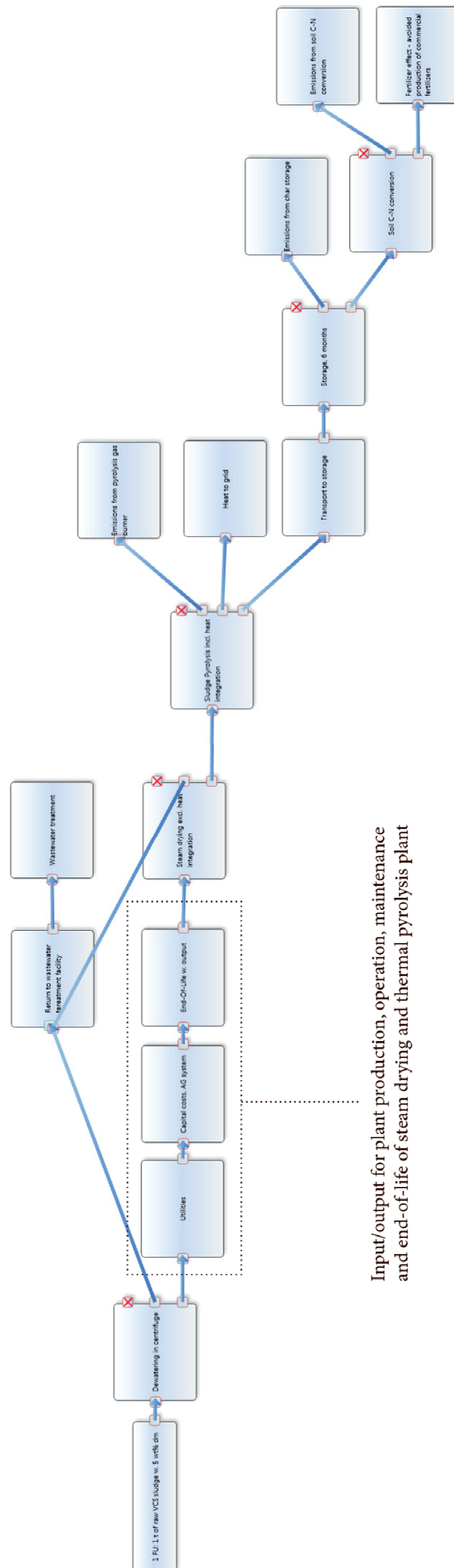
Reference system 2



Scenario system 1



Scenario system 2



Input/output for plant production, operation, maintenance and end-of-life of steam drying and thermal pyrolysis plant

LCIA method: IPCC 2013, climate change, GWP 100a with LT_with ccfb kg CO₂-Eq

Energy marginal, electricity:

"Wind"

"Coal"

Easetech process:

Electricity from Off-shore wind, DK 2010

Marginal Electricity Consumption incl. Fuel Production, Coal, Energy Quality, DK, kWh, 2006

Energy marginal, district heating:

"WnW"

"Coal"

Easetech process:

Heat from wood, DK 2010

Electricity from Off-shore wind, DK 2010

District Heating, marginal average, (DK), kWh 2012 - predominately coal

Reference 1 (AD)

Energy marginal, electricity

"Wind"

"Coal"

Energy marginal, district heating

"WnW"

"Coal"

Unit	kg CO ₂ -eq/FU	kg CO ₂ -eq/FU
Sum	139.54	88.38
AD plant incl CHP	39.87	-11.42
Dewatering in centrifuge	0.00	0.13
Emissions from soil C-N conversion	46.06	46.06
Emissions from storage	41.34	41.34
Fertilizer effect - avoided production of commercial fertilizers	-11.51	-11.51
Transport to storage	0.51	0.51
Wastewater treatment	23.28	23.28

Reference 2 (AER)

Energy marginal, electricity

"Wind"

"Coal"

Energy marginal, district heating

"WnW"

"Coal"

Unit	kg CO ₂ -eq/FU	kg CO ₂ -eq/FU
Sum	150.05	152.67
Aeration tank	0.05	2.66
Dewatering in centrifuge	0.06	0.06
Emissions from aeration	16.96	16.96
Emissions from soil C-N conversion	66.08	66.08
Emissions from storage	53.06	53.06
Fertilizer effect - avoided production of commercial fertilizers	-10.23	-10.23
Transport to storage	0.51	0.51
Wastewater treatment	23.57	23.57

Scenario 1 (AD)		
Energy marginal, electricity	"Wind"	"Coal"
Energy marginal, district heating	"WnW"	"Coal"
	kg CO2-	
Unit	eq/FU	kg CO2-eq/FU
Sum	86.66	36.01
AD plant incl CHP	39.63	-9.20
Capital costs, AG system	0.26	0.26
Dewatering in centrifuge	0.00	0.13
Emissions from char storage	0.00	0.00
Emissions from pyrolysis gas burner	21.93	21.93
Emissions from soil C-N conversion	1.79	1.79
End-Of-Life	-0.74	-0.74
Fertilizer effect - avoided production of commercial fertilizers	-4.95	-4.95
Heat to grid 2	-0.41	-9.15
Transport to storage	0.05	0.05
Utilities	2.22	9.01
Wastewater treatment	26.89	26.89

Scenario 2 (NO)		
Energy marginal, electricity	"Wind"	"Coal"
Energy marginal, district heating	"WnW"	"Coal"
	kg CO2-	
Unit	eq/FU	kg CO2-eq/FU
Sum	66.98	60.74
Capital costs, AG system	0.38	0.38
Dewatering in centrifuge	0.01	1.33
Emissions from char storage	0.00	0.00
Emissions from pyrolysis gas burner	39.17	39.17
Emissions from soil C-N conversion	3.20	3.20
End-Of-Life w. output	-0.78	-0.78
Fertilizer effect - avoided production of commercial fertilizers	-4.94	-4.94
Heat to grid	-0.74	-18.12
Transport to storage	0.08	0.08
Utilities	3.21	13.03
Wastewater treatment	27.38	27.38

Thermal Processing of sludge	Scenario 1 (AD)	Scenario 2 (NO)
Energy marginal, electricity	"Wind"	"Wind"
Energy marginal, district heating	"WnW"	"WnW"
Unit	kg CO2-eq/FU	kg CO2-eq/FU
Capital costs, AG system	0.27	0.39
Emissions from pyrolysis gas burner	21.93	39.17
AG system End-Of-Life	-0.15	-0.22
District heating	-0.41	-0.74
Power consumption	0.12	0.17
Natural gas consumption	0.62	0.89
Process water consumption	1.48	2.14

Sludge stabilization in Reference systems	Reference 1 (AD)	Reference 2 (AER)
Energy marginal, electricity	"Wind"	"Wind"
Energy marginal, district heating	"WnW"	"WnW"
Unit	kg CO2-eq/FU	kg CO2-eq/FU
Sum	39.87	17.19
Capital goods Anaerobic digestion plant	1.56	0.00
Biogas combustion and avoided energy production	30.29	0.00
CH4 Leakage	8.01	0.00
Power use	0.23	0.23
Emissions from aeration tank	0.00	16.96

Emissions from sludge storage	Reference 1 (AD)	Reference 2 (AER)
Unit	kg CO2-eq/FU	kg CO2-eq/FU
Sum	40.33	53.06
Nitrous Oxide	8.65	7.53
Carbon dioxide	2.32	3.23
Methane	29.36	42.30

Emissions from sludge and char degradation in soil	Reference 1 (AD)	Reference 2 (AER)	Scenario 1 (AD)	Scenario 2 (NO)
Unit	kg CO2-eq/FU	kg CO2-eq/FU	kg CO2-eq/FU	kg CO2-eq/FU
Sum	46.06	66.08	1.79	3.20
Carbon dioxide	33.10	46.34	1.79	3.20
Methane	0.04	0.06	0	0
Nitrous Oxide	12.92	19.69	0	0

Emissions from fertilizer value of sludge and char	Reference 1 (AD)	Reference 2 (AER)	Scenario 1 (AD)	Scenario 2 (NO)
Unit	kg CO2-eq/FU	kg CO2-eq/FU	kg CO2-eq/FU	kg CO2-eq/FU
Sum	-11.51	-10.23	-4.95	-4.94
K Fertilizer	-0.12	-0.12	-0.11	-0.11
N Fertilizer	-9.24	-7.96	-2.73	-2.73
P Fertilizer	-2.36	-2.36	-2.12	-2.12
Farm tractor	0.21	0.20	0.02	0.03