KNOWLEDGE SYNTHESIS ON NEW VALUE CHAINS BY THERMOCHEMICAL CONVERSION OF DIGESTATE FOR INCREASED BIOFUEL PRODUCTION IN SWEDEN

Report from a project within the collaborative research program *Renewable transportation fuels and systems*

January 2018

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THE SWEDISH KNOWLEDGE CENTRE
FOR RENEWABLE TRANSPORTATION FUELS

PREFACE

This project has been carried out within the collaborative research program *Renewable transportation fuels and systems* (Förnybara drivmedel och system), Project no. 43682-1. The project has been financed by the Swedish Energy Agency and f3 – Swedish Knowledge Centre for Renewable Transportation Fuels.

f3 Swedish Knowledge Centre for Renewable Transportation Fuels is a networking organization which focuses on development of environmentally, economically and socially sustainable renewable fuels, and

- Provides a broad, scientifically based and trustworthy source of knowledge for industry, governments and public authorities
- Carries through system oriented research related to the entire renewable fuels value chain
- Acts as national platform stimulating interaction nationally and internationally.

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The f3 centre is financed jointly by the centre partners and the region of Västra Götaland. f3 also receives funding from Vinnova (Sweden's innovation agency) as a Swedish advocacy platform towards Horizon 2020. Chalmers Industriteknik (CIT) functions as the host of the f3 organization (see www.f3centre.se).

ACKNOWLEDGEMENT

This project has been carried out by Anna-Karin Jannasch (RISE Energy and Circular Economy), Kent Davidsson (RISE Energy and Circular Economy) and Mikael Lantz (Lund University). A reference group has been tied to the project, whose input during the work has been very valuable and whose contributions are hereby greatly acknowledged. The reference group consisted of the following persons:

- Peter Axegård (RISE Bioeconomy, formerly Innventia)
- Anneli Petersson (RISE Energy and Circular Economy)
- Tobias Richards (University of Borås)
- Caroline Steinwig (Avfall Sverige)
- Christopher Gruvberger (VA SYD)
- Anders Lagerqvist (Luleå University of Technology)
- Ola Solér (Region Skåne)

The project team also would like to thank Sudhanshu Pawar who contributed with the description of the Tool-box - Substrate handbook (Appendix E).

ADDITIONAL FUNDING

This study received additional funding from Region Skåne, which allowed for a more detailed study regarding the potentials, including locations, of the studied value chain in Skåne. The project group would like to thank Region Skåne.

This report should be cited as:

Davidsson, K., Jannasch, A-K. & Lantz, M. (2018) *Knowledge synthesis on new value chains by thermochemical conversion of digestate for increased biofuel production in Sweden*. Report No 2018:04, f3 The Swedish Knowledge Centre for Renewable Transportation Fuels, Sweden. Available at www.f3centre.se.

SUMMARY

To replace fossil fuels with second-generation biofuels, it is crucial to make available larger amounts of biomass material. While high-grade feedstocks are already used for this and other products, low-grade feedstocks, such as residues from forestry, agriculture, industry and households, have not yet been fully evaluated for this purpose. Residues may be more difficult to process but are generally much cheaper and could, individually or in combination with other raw materials, become an economic feedstock for biofuel production. In addition, a wider biomass material basis would lead to the contribution to an increased biofuel production from several sectors in the society while waste issues are being solved. Besides the biomass availability, sustainable biofuel production requires that the biomass feedstock is used in an effective way.

This project has investigated the techno-economic potentials of more effective utilisation of biogas feedstock by using digestate as raw material for thermochemical conversion for the production of biofuels and/or biochemicals. A study of this value chain is of interest for several reasons. First, the digestate contains an unneglectable amount of chemically bound energy that potentially can be converted into biofuels/biochemical, and thus increase the biofuel yield from the same amount of biomass. Second, the suggested value chain could simplify and /or enable a safer handling, storage, transport and use of the residue (ash *vs.* digestate). Finally, the value chain could be motivated when the digestate is not allowed or is less suitable to spread as fertilizer on farmland because of too high concentrations of toxic metals, hormones and/or different pathogens. The latter reason is becoming increasingly up-to-date as the public resistance to spreading digestate from wastewater treatment plants on farmland increases.

The present analysis covers the thermochemical methods gasification, pyrolysis and hydrothermal treatment (HT), and the aim has been to present and discuss theirs potentials in terms of

- Production yield biofuel (biomethane/bio-oil)
- Ash yield
- Heat demand
- Scale of economics
- Possibility to separate nutrients from toxic heavy metals and unwanted organic compounds

To analyse and illustrate the effect of utilized feedstock type (digestate from WWTP or co-digestion plants), scale of operation, transportation distance and local conditions such as available heat sources, a number of study cases were made (Table S1 below), where the situation as of today at the different locations was used as references. Given the fact that digestate from WWTP as of today generates a treatment fee while digestate from co-digestion plants gives an income for the biogas producer, these study cases focus on the treatment of digested sewage sludge.

Table S1. Description of the selected study cases.

Study case		Location for thermochemical conversion	Supplier of digestate	Digestate flow (t/yr), 25 % DS
1.	Local collection and conversion of digestate from one single WWTP.	Sjölunda in Malmö	Malmö (Sjölunda)	30 000
2.	Regional collection and conversion of digestate from several WWTPs.	Sjölunda in Malmö	Malmö, Helsingborg, Landskrona, Eslöv, Kävlinge	70 000
3.	Regional collection and conversion of digestate from several WWTPs and two larger co-digestions plants	Sjölunda in Malmö or at WWTP in Helsingborg	Similar as for case 2) + digestate from Helsingborg and Kristianstad	110 000
4.	National collection and conversion of digestate from a large number of WWTPs	Malmö, Jönköping, Göteborg or Stockholm	Digestate from WWTPS of the 24 largest Swedish municipalities	440 000

The main conclusions of the analysis are highlighted in the following:

- The economic analysis of variable costs and revenues shows that there is a significant room for investments for all three investigated thermochemical techniques (pyrolysis, gasification and HTL/G) (Figure S1). This is true even when transportation cost for collecting digestate from regions such as Scania (Case 2 and 3) or the whole of Götaland and Svealand (Case 4) is taken into account. (Figure S2).

- In the case of pyrolysis, the major contributions to the revenue are char and sludge reception (i.e. an avoided cost vs. the reference case), whereas the costs are dominated by the thermal drying.

- In case of gasification, more than 70 % of the revenues origins from CH_4 (in this case assumed to be the targeted biofuel product) and the rest from avoided sludge reception, whereas the composition of the costs is the same as for pyrolysis.

- In case of HTL/G, the revenue consists of about equal parts of bio-oil and sludge reception. The cost originates only from the heating, which is almost 4 times higher than is needed for pyrolysis and gasification because of 5 times more water. A substantial part of this heat could however most probably be recovered and could thereby reduce the cost for the heat net accordingly.

- The sensitivity analysis shows that when one variable at the time is varied, the largest impact is in the range of 20-30 % on the economic result. Even if the sensitivity of the parameter value is large, it does not seem to have any determining effect on the economic result and the given conclusions.

- From the perspective of the suggested value chains, biogas plants located nearby energy intensive industries such as pulp and paper or chemical industry holds a big advantage since the necessary with time non-variable low cost heat is at these locations generally available.

- Available in demonstration scale, gasification (including fuel upgrading to biofuel quality) is probably the fastest way forward to produce biofuels from digestate. Pyrolysis upgrading is still in pilot scale, whereas the equivalent for HTL/G is still in laboratory scale and which cost and performance data on larger scale are therefore still unknown.

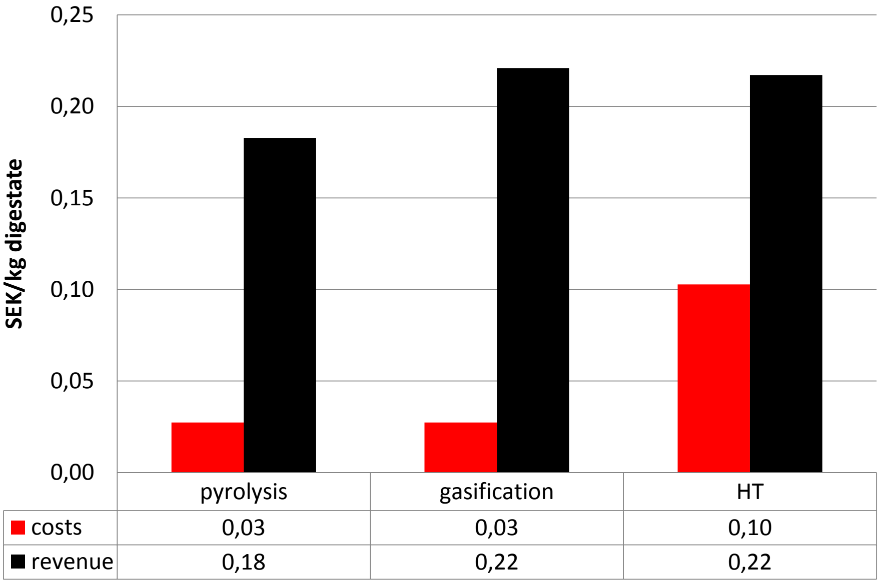
- For gasification plants for biofuel production, sludge from very large areas needs to be collected in order to reach economic scale (1,2 Mt/yr equivalent to ~85 $MW_{biomethane}$). The sludge available in the most populated areas of Sweden might therefore not be sufficient (0.4 Mt/yr). However, the estimation of economic scale is in this case given for wood-based feedstock, so there may still be a positive net in the case of sludge gasification. Another alternative for reaching profitability is to consider co-gasification with woody biomass feedstock.

- Sewage sludge will not be the major substrate in the production of fossil-free biofuel but it may constitute an important contribution.

- The literature shows that pyrolysis of sewage sludge could be a technique for separating cadmium from phosphorus, which can then be recycled via bio-fertilization to agriculture. Ammonia nitrogen, however, is in this case to the largest extent dissolved in the water fraction that is removed upstream of the process and its nutrient value would therefore be lost by the suggested value chain.

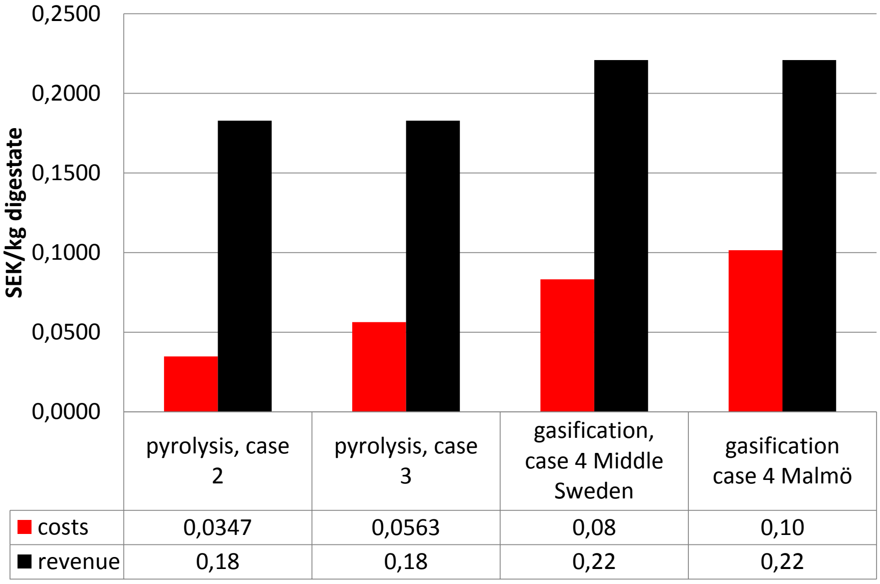
- In case of gasification, the phosphorous ends up in char or bottom ash and might therefore be possible to separate and recycle as nutrient to the agriculture. In the same way as in pyrolysis, the nutrient value of ammonia nitrogen is through the thermal drying process lost.

- There are indications in the literature that HTL/G of digestate from WWTPs might be a process for recovering both ammonia nitrogen and phosphorous to the farmland.



	pyrolysis	gasification	HT
🟥 costs	0,03	0,03	0,10
■ revenue	0,18	0,22	0,22

Figure S1. Variable costs and revenues in different treatment methods.



	pyrolysis, case 2	pyrolysis, case 3	gasification, case 4 Middle Sweden	gasification case 4 Malmö
🟥 costs	0,0347	0,0563	0,08	0,10
■ revenue	0,18	0,18	0,22	0,22

Figure S2. Costs and revenues for the different study cases and the thermochemical routes that come in question. Approximately the same result is obtained if Helsingborg instead of Malmö is chosen as location in case 3.

SAMMANFATTNING

För att ersätta fossila bränslen med andra generationens biobränslen är det avgörande att tillgängliggöra större mängder biomassabaserad råvara. Medan högkvalitativa råvaror redan används för detta och andra produkter har lågkvalitativa råvaror såsom rester från skogsbruk, jordbruk, industri och hushåll ännu inte utvärderats fullt ut för detta ändamål. Lågvärdiga biobaserade rester kan vara svåra att bearbeta men är i allmänhet mycket billigare och kan enskilt eller i kombination med andra råvaror bli ett ekonomiskt lönsamt råmaterial för produktion av biodrivmedel. Dessutom skulle en bredare biomassabaserade råvarubas leda till att fler sektorer i samhället bidrar till en ökad biodrivmedelsproduktion samtidigt som avfallsproblem inom samma sektorer minskar. Förutom tillgången på biomassa kräver en hållbar biobränsleproduktion att biomassan används på ett resurseffektivt sätt.

Syftet med detta projekt har varit att undersöka den tekno-ekonomiska potentialen för ett mer effektivt utnyttjande av biogasens råvara genom att använda rötresten som råmaterial för termokemisk omvandling för biodrivmedelsproduktion. Aktuell värdekedja är av intresse utav flera orsaker. För det första innehåller rötresten en icke försumbar mängd kemiskt bunden energi som potentiellt kan omvandlas till biobränslen/biokemikalier och därigenom erhålla högre omvandlingsutbyten från en och samma mängd biomassa. För det andra kan den föreslagna värdekedjan förenkla och/eller möjliggöra en säkrare hantering, lagring, transport och användning av återstoden (aska jfr rötrest). Värdekedjan kan också vara motiverad när det inte är tillåtet eller mindre lämpligt att sprida rötresten som gödsel på åkermark på grund av höga koncentrationer av giftiga metaller, hormoner och/eller patogener. Det sistnämnda argumentet blir alltmer aktuellt eftersom det offentliga motståndet till att sprida rötrest från avloppsreningsverk (s.k. rötslam) på åkermark växer.

Projektets analys omfattar tre olika termokemiska omvandlingstekniker: förgasning, pyrolys och hydrotermisk behandling (HT). Målsättningen har varit att presentera och diskutera deras respektive potentialer med avseende på:

- Produktionsutbyte biobränsle (biometan/bioolja)
- Mängd aska
- Värmebehov
- Ekonomisk produktionsskala
- Möjlighet att separera näringsämnen från giftiga tungmetaller och oönskade organiska föreningar.

För att analysera och illustrera effekten av vilken typ av rötrest som används (rötrest från avloppsreningsverk eller samrötningsanläggning), driftskala, transportavstånd och lokala förhållanden såsom tillgängliga värmekällor genomfördes ett antal fallstudier (tabell S1), där rådande situation på de olika lokaliseringarna användes som referenser. Mot bakgrunden att rötslam från reningsverket idag genererar en mottagningsavgift, medan rötning från samrötningsanläggningar ger en inkomst för biogasproducenten, har vi valt att fokusera våra fallstudier på termokemisk omvandling av rötslam.

Tabell S1. Beskrivning av de olika fallstudierna.

Fallstudie		Lokalisering för termokemisk omvandling	Leverantör av rötrest	Flöde rötrest (ton/år), 25 % TS, d.v.s. avvattnat
1.	Lokal insamling och omvandling av rötslam från ett enskilt avloppsreningsverk	Sjölunda i Malmö	Malmö (Sjölunda)	30 000
2.	Regional insamling och omvandling av rötslam från flera avloppsreningsverk	Sjölunda i Malmö	Malmö, Helsingborg, Landskrona, Eslöv, Kävlinge	70 000
3.	Regional insamling och omvandling av rötslam från flera avloppsreningsverk samt två större samrötningsanläggningar	Sjölunda i Malmö or eller vid ett avloppsreningsverk i Helsingborg	Samma för fallstudie 2) + rötrest från Helsingborg och Kristianstad	110 000
4.	Nationell insamling och omvandling av rötslam från ett stort antal avloppsreningsverk	Malmö, Jönköping, Göteborg eller Stockholm	Rötslam från avloppsreningsverk i de 24 största kommunerna i Sverige	440 000

De huvudsakliga slutsatserna sammanfattade i punktform:

- Den ekonomiska analysen av variabla kostnader och intäkter visar att det finns ett betydande investeringsutrymme för samtliga undersökta termokemiska omvandlingstekniker (pyrolys, förgasning och HTL/G) (Figur S1). Detta gäller även då man tar hänsyn till transportkostnaderna för insamling av rötrest från delar av Skåne (Fallstudie 2-3) eller hela Götaland och Svealand (Fallstudie 4) (Figur S2).

- Vid pyrolys kommer de viktigaste intäktsbidragen från biokol och slammottagning (här beskriven som en undviken kostnad jämfört med referensfallet), medan kostnaderna domineras av termisk torkning.

- Vid förgasning kommer mer än 70 % av intäkterna från metan (CH_4), vilket är den antagna huvudprodukten, och resten från undviken slammottagning. Sammansättningen av kostnaderna är densamma som för pyrolys.

- Vid HTL/G består intäkterna av ungefär lika stora delar bioolja och undviken slammottagning. Kostnaden härstammar enbart från uppvärmningen, vilken är nästan fyra gånger mer än vad som krävs vid pyrolys och förgasning till följd av fem gånger mer vatten i ingående flöde (5 jfr med 25 vikt% torr substans). En väsentlig del av denna värme förväntas dock kunna återvinnas, och därigenom minska kostnaderna för det behövliga värmenettot i samma grad.

- Känslighetsanalysen visar att när man ändrar en variabel i taget påverkas det ekonomiska resultatet med maximalt 20-30 %. Även om känsligheten för parametervärdet är stor verkar det inte ha någon avgörande effekt på det ekonomiska resultatet och de givna slutsatserna.

- Utifrån de föreslagna värdekedjornas perspektiv innehar biogasanläggningar i närheten av energiintensiva industrier såsom massa- och papper eller kemisk industri en stor fördel eftersom den behövliga med tiden icke-variabla, billiga restvärmen är tillgänglig vid dessa lokaliseringar.

- Förgasning (inklusive uppgradering till drivmedelskvalité) är förmodligen det i tid snabbaste sättet att producera biodrivmedel från rötrest. Uppgradering av pyrolysolja är fortfarande på pilotstadiet, medan motsvarande för HTL/G befinner sig i labbskala och vars kostnads- och prestandadata fortfarande inte finns tillgängliga.

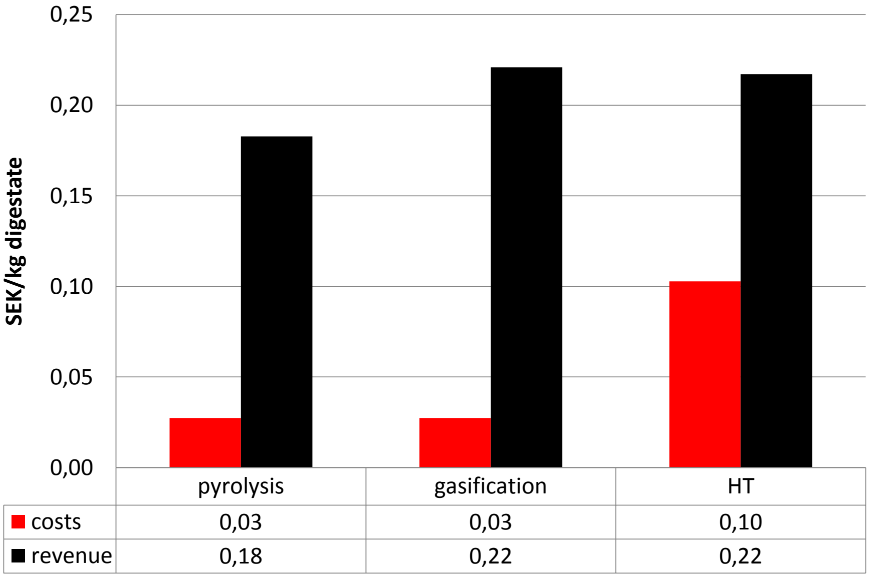
- För att erhålla ekonomisk lönsam skala för förgasningsanläggningar för biodrivmedelsproduktion måste slam från mycket stora områden samlas in (1,2 Mt/år motsvarande ~85 $MW_{biometan}$). Det slam som finns tillgängligt i Sveriges mest tätbefolkade område är därför inte tillräckligt (0,4 Mt/år). I detta fall är uppskattningen av ekonomisk skala dock angiven för träbaserad biomassa så ett positivt netto vid slamförgasning skulle ändå kunna vara möjlig. Ett annat tänkbart tillvägagångsätt för att uppnå lönsamhet i detta fall är samförgasning med träbaserad biomassa.

- Avloppsslam kommer inte att vara det viktigaste substratet vid framställning av biodrivmedel, även om det kan utgöra ett viktigt bidrag.

- Litteraturen visar att pyrolys av avloppsslam kan vara en teknik för att separera kadmium från fosfor, som sedan kan återvinnas, via biogödsel, till jordbruket. Ammoniumkvävet däremot är i detta fall mestadels löst i vattenfraktionen som avlägsnas uppströms processen vilket medför att dess näringsvärde skulle gå förlorad genom den föreslagna värdekedjan.

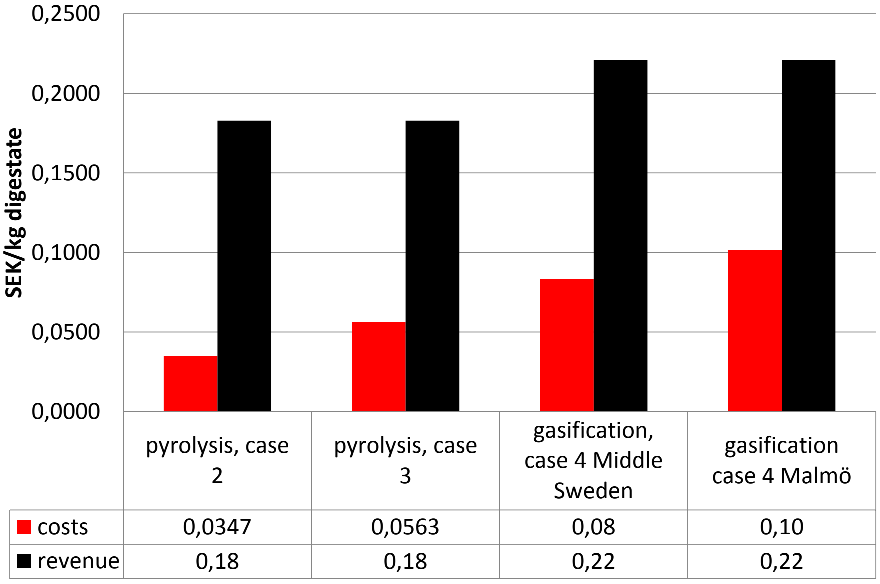
- Vid förgasning hamnar fosfor i biokolen eller bottenaskan och kan därför vara möjlig att separera och återvinna som näringsämne till jordbruket. På samma sätt som vid pyrolys går näringsvärdet bundet till ammoniumkvävet i detta fall förlorad.

- Det finns i litteraturen indikationer på om att HTL/G av rötslam kan vara en process för att återvinna både ammoniumkväve och fosfor till jordbruket.



	pyrolysis	gasification	HT
🟥 costs	0,03	0,03	0,10
⬛ revenue	0,18	0,22	0,22

Figur S1. Variabla kostnader och intäkter vid användande av olika termokemiska tekniker i kombination med rötslam.



	pyrolysis, case 2	pyrolysis, case 3	gasification, case 4 Middle Sweden	gasification case 4 Malmö
🟥 costs	0,0347	0,0563	0,08	0,10
⬛ revenue	0,18	0,18	0,22	0,22

Figur S2. Kostnader och intäkter för de olika fallstudierna och termokemiska omvandlingsteknikerna som bedöms aktuella i de fallen. Ungefär samma resultat erhålls om Helsingborg, istället för Malmö, väljs som lokalisering i fallstudie 3.

CONTENTS

1 INTRODUCTION

1.1 BACKGROUND

To replace fossil fuels with second-generation biofuels, it is crucial to make available larger amounts of biomass material. While high-grade feedstocks are already used for this and other products, low-grade feedstocks, such as residues from forestry, agriculture, industry and households, have not yet been fully evaluated for this purpose. Residues may be more difficult to process but are generally much cheaper and could, individually or in combination with other raw materials, become an economic feedstock for biofuel production. In addition, a wider biomass material basis would lead to the contribution to an increased biofuel production from several sectors in the society while waste issues are being solved. Besides the biomass availability, sustainable biofuel production requires that the biomass feedstock is used in an effective way.

So far, the second-generation biofuel project portfolio has primarily been based on converting one type of lignocellulose raw material to one type of biofuel with the exception of concepts with bioethanol and biogas as biofuel products. Process integration and in particular combinations of biochemical and thermochemical conversion routes has not yet received the same attention. On the contrary, alternative uses of biomass have sometimes even led to discussions about competitive situations between thermochemical and biochemical routes. Similar competition has been discussed between biomaterial and biofuel production, as well as food and biofuels. A general conclusion is in fact that there is a lack, with some exception (e.g. Börjesson *et al.* 2013[1]), of objective studies that provide the industry and the government with a broad knowledge base of what their organic residue streams can be used for, the pros and cons of different processes, and how these can be combined into new value chains contributing with added and/or new values.

This study has investigated the techno-economic potentials of using biogas feedstocks more efficiently by using the digestate as raw material for thermochemical conversion for the production of biofuels and/or biochemicals. There are several motives for studying this value chain. First, the digestate contains an unneglectable amount of energy that potentially can be converted into biofuels/biochemicals, which means that the thermochemical process can potentially increase the biofuel yield from the same amount of biomass. The more difficult it is to biodegrade the biogas feedstock, the higher amount of organic yield in the digestate becomes. Second, the suggested value chain might simplify and /or enable a safer handling, storage, transport and use of the residue (ash *vs.* digestate). Finally, the value chain could be motivated when the digestate is not allowed or is less suitable to spread as fertilizer on farmland due to high concentrations of toxic heavy metals, hormones and/or different pathogens. This is probably today the strongest reason why this value chain is of interest as the public resistance to spreading digestate from sewage sludge on farmland increases. For example, Lantbrukarnas Riksförbund (LRF) has with their new cycle policy taken standstill against the use of sewage sludge as a source of nutrition in agriculture. For the same reason, LRF is now considering ending their participation in the purification plants certification system, REVAQ [2].

To our knowledge, there is very limited information about this value chain or related in the open literature [3][4][5][6][7][8]. Another example with similar purpose and goals is the EUPD project PURSUC, that is aimed to develop an energy efficient drying module for manure (no digestion in this case) to be gasified, so also to develop new gasifier concepts optimized for raw materials such as dried manure and/or sewage sludge [9].

1.2 PURPOSE AND GOALS OF STUDY

The overall aim of this study is to contribute to a fossil fuel independent vehicle fleet by 2030 [10][11]. More specifically, the aim is to investigate the techno-economic potential of thermochemical conversion of digestate for the production of biofuels and/or biochemicals and if there are gaps in knowledge on this issue. The analysis covers the thermochemical methods gasification, pyrolysis and hydrothermal methods (HT), and the aim has been to present and discuss theirs potentials in terms of

- Production yield biofuel (biomethane/bio-oil)
- Yield ashes
- Heat demand
- Scale of economics
- Possibility to separate nutrients from toxic heavy metals and unwanted organic compounds

To analyse and illustrate the effect of utilized feedstock type (digestate from WWTP or co-digestion plants), scale of operation, transportation distance and local conditions such as available heat sources, a number of study cases were made using Swedish locations where biogas production takes place today. The biogas production situation as of today for the chosen locations was used as references.

1.3 SYSTEM BOUNDARIES

The present study considers different treatments of digestates. In general, a system with ingoing and outgoing flows is considered. The ingoing flow passes the system boundary, and is subject to treatment that results in outgoing flows that pass the boundary. The results for a certain system consist of a mass and energy balance and yields of products. In addition, an economic evaluation is made based on the costs and value of the products. Figure 1 shows a general schematic picture of the systems considered. The ingoing digestate, which is the starting point for the subsequent analysis, consists of solids suspended in 95 % water. The solids mainly consist of organic substances, such as cellulose, but also some inorganic compounds. The outgoing mass flows arise from possible drying and thermal treatment of the digestate. The drying results in outgoing steam and liquid water.

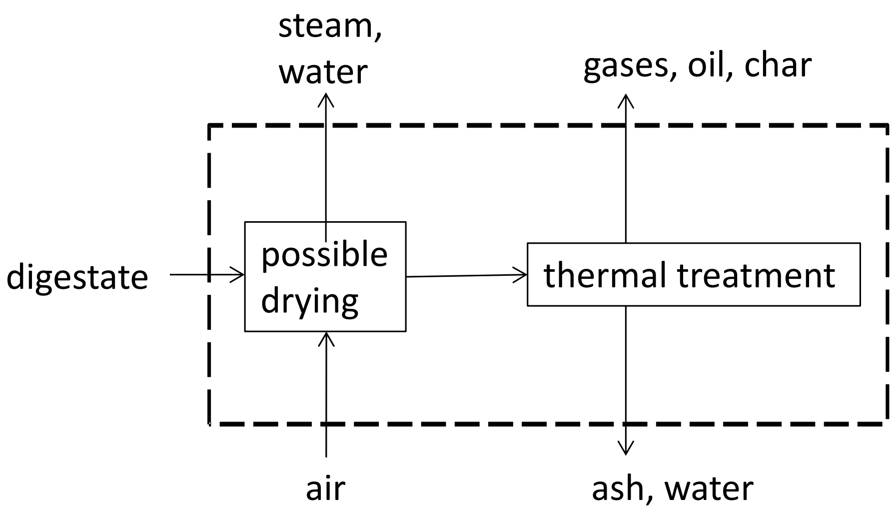


Figure 1. Schematic drawing showing the general system boundaries (dashed) and mass flows (arrows) in the present project.

2 ANAEROBIC DIGESTION

Anaerobic digestion is a biological process where various microorganisms degrade organic material in the absence of oxygen. The process generates biogas, which mainly consists of methane and carbon dioxide, as well as a digestate that contains all material not converted into biogas. In general, it is possible to use any organic material as feedstock for biogas production but the most common in Sweden are sewage sludge, manure, municipal solid organic waste and various industrial waste. The choice of feedstock affect the design of the process as well as the amount and characteristics of the biogas and digestate produced.

Given the scope of this study, the process of anaerobe digestion as such is not included within the system boundaries (Figure 1). Instead, we focus on the digestate produced.

2.1 PRODUCTION AND UTILIZATION OF DIGESTATE

As mentioned above, the digestate contains everything in the feedstock that is not converted into biogas in the anaerobic process. Thus, it contains lignin and other organic substances that have not been degraded as well as nutrients such as nitrogen, phosphorus and potassium. If the feedstock contains impurities such as heavy metals, these will also end up in the digestate and potentially affect its utilization.

In 2015, the total production of digestate in Sweden was approximately 2.7 million tons. The digestate is mainly produced at co-digestions plants and wastewater treatment plants (WWTP), but also on farm-scale biogas plants and a few plants located at industries, see Table 1. Given the total production of digestate as well as the production at each site, this study focuses on digestate from co-digestion plants and WWTP.

Table 1. Biogas plants and production of biogas and digestate in 2015.[12]

	Number of plants	Biogas production (GWh)	Digestate production (ton)
Waste Water Treatment	140	697	650 000[a]
Co-digestion	35	854	1 710 000
Farm scale	40	50	310 000
Industry	6	121	10 000
Landfill	60	187	e.t.
Gasification	1	38	not applicable
Total	**282**	**1 947**	**2 690 000**

[a] **Dewatered sludge.**

2.1.1 Digestate from co-digestion plants

As presented in Table 1, there are 35 co-digestion plants in Sweden producing 1.7 million tons of digestate annually. The digestate production at each plant ranges from approximately 2–120 000 tons annually with an average of 50 000 tons (Figure 2).

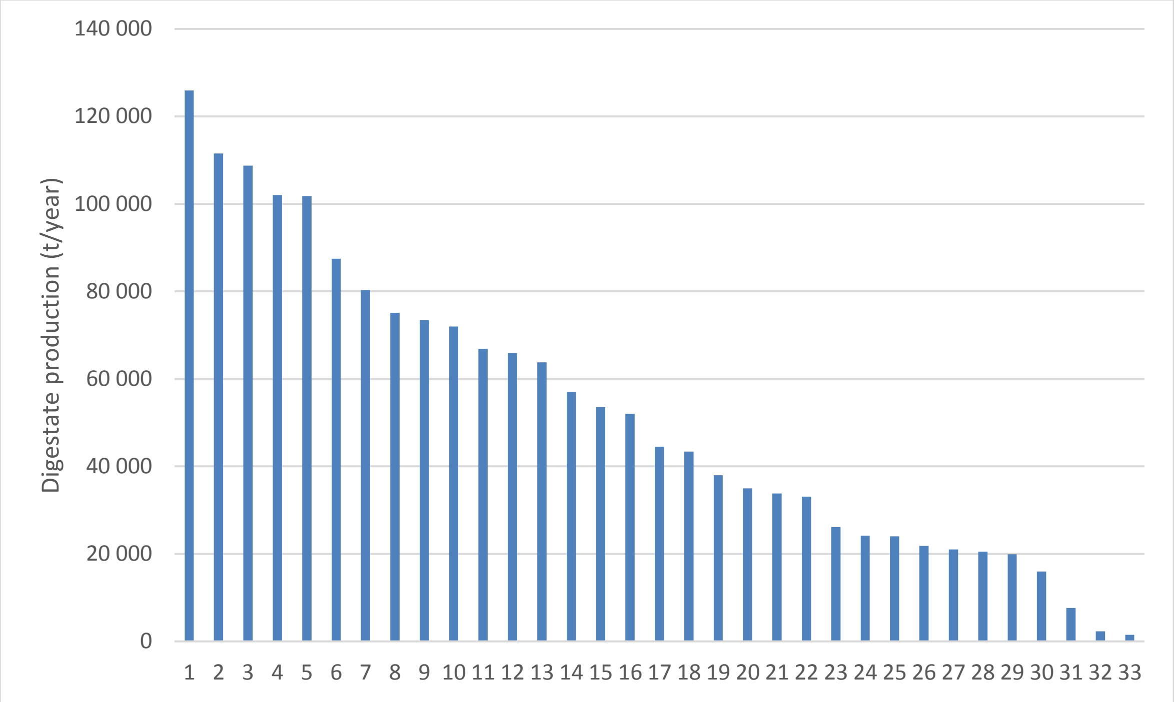


Figure 2. Annual digestate production at co-digestion plants [13].

On a wet weight basis, co-digestion plants mainly use manure, municipal solid organic waste (MSOW) separated at source and different kinds of industrial waste [12]. Comparing specific plants, there are however substantial differences in feedstock composition which might also affect the digestate. For example, the dry matter content ranges from 1.5 % to 8.5 % with an average of 4.6 % at the biogas plants presented in Figure 2. In Table 2, the digestate composition at two of the larger co-digestion plants in Sweden are also presented. In general, digestate from co-digestion is used as a fertilizer with an economic value that varies depending on local conditions. For the digestates presented in Table 2, the nutrient value as such is approximately 56 and 48 SEK/ton, respectively. For assumptions and background data, see Appendix A.

Table 2. Digestate composition at two of the larger co-digestion plants in Sweden.

	Helsingborg	Kristianstad
DM (%)	3,5	3.6
VS (% of DM)	62	69.4
NH_4-N (kg/t)	3.8	3.1
N-tot (kg/t)	5.4	4.7
P (kg/t)	0.5	0.4
K (kg/t)	1.5	1.5
Pb (g/t)	0.07	0.08
Cd (g/t)	0.01	0.01
Hg (mg/t)	1.1	0.9

2.1.2 Digestate from waste water treatment

In Sweden, there are more than 400 wastewater treatment plants with a capacity of > 2 000 pe (population equivalents) that generate 200 000 tons of sewage sludge (dry matter) annually [14].

Larger plants use anaerobic digestion to treat the sewage sludge and produce 650 000 tons digestate (wet weight). Since these plants mainly use sewage sludge as feedstock, the composition is probably more similar when comparing different plants than it is for digestate from co-digestion plants. In Table 3, data on typical sludge composition at VA SYD is presented as an example.

In the same way as digestate from co-digestions plants, digested sewage sludge contains nutrients such as nitrogen and phosphorus. However, sludge might also contain various contaminants, limiting the possibility to use it as a fertilizer. Only 25 % of the sludge is spread on farmland (2014). The rest is e.g. used to cover landfills (24 %) and to produce construction soil (19 %) [14].

Currently, producers of digested sewage sludge normally pay a fee for the disposal of the sludge. The size of this fee may vary between different WWTPs. As an example, VA SYD pays approximately 300 SEK/ton [15]. This is relatively low and the fee can vary between 200–600 SEK/ton depending on local conditions for each WWTP [16].

Table 3. Typical data on dewatered sludge composition, recalculated from mg/kg DM based on data given by VA SYD [15].

	VA SYD
DM (%)	22
VS (% of DM)	62.6
NH_4-N (kg/t)	3.1
N-tot (kg/t)	9.5
P (kg/t)	7.8
Pb (g/t)	5.3
Cd (g/t)	0.2
Hg (g/t)	0.1

3 THERMOCHEMICAL CONVERSION

Thermochemical conversion is the process of subjecting a feedstock to a temperature high enough to chemically alter the feedstock. The alteration, and consequently the products, depends, among other parameters, on temperature, atmosphere, retention time, and pressure. Short descriptions of different thermochemical treatments are given below with focus on the requirements that the treatment in question sets on the feedstock. The treatments considered are pyrolysis, combustion, gasification, and HT methods.

3.1 PYROLYSIS

Pyrolysis is the process of subjecting a feedstock to a temperature high enough to crack chemical bonds in organic molecules of the feedstock without the addition of an oxidising agent. This could be obtained by maintaining a nitrogen atmosphere or by limiting the access of air so that the oxygen present at the start of the process is consumed. Among the chemical bonds that break during pyrolysis, the most abundant are C-H and C-O bonds. The breaking of these results in three main products: char, gas and tar. The char is a solid, porous and carbon-rich structure, which shows that C-C bonds are less affected by the thermal treatment. The gases are so called permanent gases; i.e. they will remain gaseous at room temperature. Typical product gases from pyrolysis are CO, CO_2, H_2O, CH_4 and other light hydrocarbons. The tar – a brownish, sticky, hydrophobic and viscous substance – consists of those substances that condense at room temperature. This includes hundreds of species, such as aromatic, polyaromatic and other heavier hydrocarbons, in a wide range of molecular weights. The distribution of products between char, gas and tar can be controlled by the pyrolysis temperature and retention time. Heat has to be provided to the feedstock to reach the pyrolysis temperature. If the feedstock contains water, the vaporisation of the water will prevent the temperature to reach significantly above 100 °C until the feedstock has been dried. A slightly endothermic process, pyrolysis requires that heat be provided also after the pyrolysis temperature has been reached.

Sewage sludge has been subject to pyrolysis treatment. In a bench-scale fluidised bed, the maximum tar yield in the pyrolysis of dried sludge was found to reach a maximum at 400-450°C whereas the gas yield increased throughout the whole temperature range to above 40 % at 700°C [17]. In this case, the retention time was very short and the heating rate very fast – so called flash pyrolysis. Nonetheless, the retention time was of importance for the product yields. Experiments in a slightly larger scale showed that the tar yield was highest at around 550°C, and was also affected by feedstock size and heating rate.[18] The gas yield increased with temperature to above 40 % at 650°C. It was also found that cadmium was released to the gas phase at 600°C while chromium, copper, lead and zinc stayed in the char. The maximum yields of tar of 30-40 % at around 540°C, and that the gas yield increases with temperature in fluidised bed pyrolysis have been confirmed [19]. The resulting tar can be separated in different phases with lower heating values in the range 15.5 to 41 MJ/kg, and with different qualities for use as fuel with respect to the content of water and contaminants.[20] Sewage sludge has also been pyrolysed in a centrifugal reactor yielding 41 % organic oil at 575°C [21]. The gas yield reached only 19 % at 625°C. In a spiral-feeding reactor with residence times as long as 23 minutes, the maximum bio-oil yield was found to be around 17 % at 700°C. The char from sludge pyrolysis may be a useful product [22], e.g. applied as fertilizer [23]. In order to produce a bio-char with low content of toxic metals, sewage sludge was pyrolysed in a small fixed bed reactor [24]. The Cd/P ratio was found to decrease by a factor of

20-25, which suggests that pyrolysis may be a very suitable process to recover phosphorus while unwanted organic molecules, pathogens and hormones are destroyed.

Pyrolysis of sewage sludge at higher temperatures in a fludised bed showed that the gas yield may reach over 70 % at 900°C [25]. Partly, this high gas yield is a result of thermal cracking of primary tars. It was also showed that the yields of different tar compounds may depend strongly of the pyrolysis temperature. The heating rate – at least indirectly – may also have influence on the products from pyrolysis [26][27]. The heating rate is determined by the particle size of the feedstock and the pyrolysis temperature it is exposed to.

To summarise, bio-oil and gas in yields of more than 40 % and more than 70 %, respectively, may result from pyrolysis of sewage sludge. The oil yield is less than what has been achieved under fast pyrolysis of wood [28]. Pyrolysis may also be a suitable process to make a valuable bio-char. Not much is found in the literature about pyrolysis of digestate from biogas processes, or other feedstocks of interest in the present project, but what has been said about sewage sludge qualitatively holds for any organic feedstock. The general trends in rapid pyrolysis are illustrated in Figure 3. The yields of char and gas decreases and increases, respectively, while that of tar exhibits a maximum. Note that significant deviations from the yields in Figure 3 may occur because of other parameters than temperature.

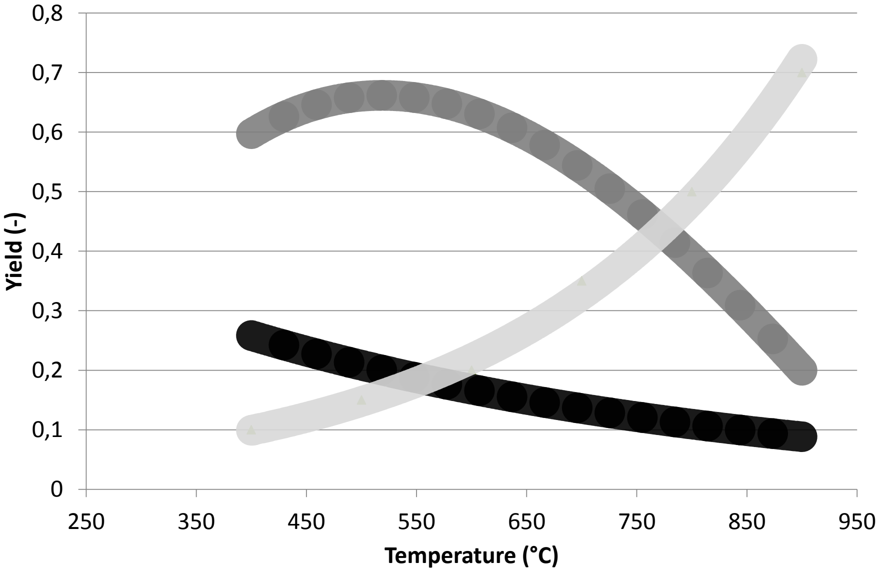


Figure 3 General trends of the yields of rapid pyrolysis. Black = char, grey = tar/oil, and light grey = gas.

3.2 COMBUSTION

Combustion is the process of completely oxidising the organic molecules in the feedstock with gaseous oxygen. Complete oxidation results in CO_2 and water. A solid residue in the form of ash is also obtained. Combustion does not result in any organic chemicals.

Since combustion does not produce any valuable organic molecules, and consequently no biofuel, it is of less importance than the other thermochemical methods mentioned. Therefore, it will not be considered in economic evaluation of the treatment methods. Still, it may serve as a supporting alternative in a sludge-to-biofuel process if e.g. not all sludge can be used but still has to be treated.

Advantages with combustion may be to get rid of the sludge, phosphorus recovery, destruction of organic molecules, hormones and medicine, and a better combustion process.

Sewage sludge may be combusted but one has to consider its special features of high moisture and ash contents, and that its content of phosphorus should be recovered. The moisture content of dewatered sewage sludge is in the range of 70 to 75 %, which results in a heating value of around zero. Therefore drying is required prior to combustion if it is to be combusted alone. This is done in some facilities with the major purpose of cutting down the volumes [29]. Alternatively, sludge may be co-combusted with a fuel that has higher heating value. The water has to be evaporated in this case too, but it does not require a drying facility. If the combustion plant can handle the increased ash flow, sewage sludge has been found to enhance the combustion performance by strongly decreasing the risk for agglomeration in fluidised beds and by decreasing the formation of corrosive deposits on heat exchanger surfaces [30]. The phosphorus in the fuel would be found in the ash after combustion. Phosphorus recovery includes struvite precipitation [31], electrochemical methods [32], leaching methods [33][34], and thermochemical methods [35].

3.3 GASIFICATION

Gasification is the process of transferring the chemically energy bound in the solid feedstock to gaseous species. This is done by a combination of pyrolysis and partial oxidation. The pyrolysis should be aimed at producing high yields of permanent gases rather than tar. Unlike combustion, the char is not fully oxidised. Instead, substoichiometric amounts of oxygen, CO_2 or steam are supplied to react with the char producing mostly CO, H_2 and CH_4. Thus, the product gas becomes a mixture of these and other gases, and tar. To become more useful, the product gas needs upgrading to CH_4 or H_2 or some better defined mixture. This end product may serve as a raw material for production of electricity, fuels, materials or anything that these gases are used for.

Gasification may be applied in different scales and in the form of different techniques, and with different biomass. The prerequisites for economically viable biomass gasification have been thoroughly analysed [36]. It was concluded that tars constitute a major obstacle. In large-scale gasification both primary and secondary catalysts are therefore recommended. Of different small-scale gasifiers, the fixed bed downdraft gasifier seemed most suitable; possibly with the use of secondary catalysts to cut down the tar yield. Also the operational parameters such as temperature, steam content and residence time play a major role for the formation of tars. Small-scale gasification for a number of different types of biomass has been analysed [37]. The downdraft gasifiers are usually operated in combination with internal combustion engines to produce electricity [38]. To really cut down the tar formation, a gasifier temperature of 1200-1300°C has been shown to be sufficient [39]. No CH_4, but instead high yields of H_2 and CO were obtained. Temperatures in this range are used in entrained-flow gasifiers in which the feedstock is entrained by the gaseous oxidant and converted to a tar-free product gas [40]. The drawback is that the feedstock has to be finely ground, which is not suitable for all feedstocks. Plasma gasification is a relatively new type of gasification, which may produce mainly H_2, CO and CO_2 [41]. It has been considered for different waste streams including sewage sludge.

Fluidised bed gasification is a more complicated technique than fixed bed, but its profitability increases with scale [42]. Both fluidised bed and fixed bed (updraft and downdraft) techniques would become more competitive if the gas quality were enhanced and installation costs cut. Therefore, new concepts and combinations of these techniques have been described [43]. This includes process integration with gasification and gas cleaning in one reactor. The separation of pyrolysis and gasification in two different reactors is another possibility [44][45][46], as well as a number of polygeneration strategies such as the combined production of biofuel, heat and power.

Dry woody biomass is suitable for gasification, but less valuable feedstocks have been considered. Moist wood has been successfully gasified in a fixed bed gasifier [47]. Manure and sludge, unless dried [48][49], give product gas with low heating values, which make these feedstocks difficult to use alone. In a direct comparison, gasification of sawdust resulted in a gas with significantly higher heating value than manure [50]. One of the reasons may be the moisture content, which most often exceeds 30 %, which is an approximate limit for when the product gas becomes of too low value [38]. However, less valuable feedstocks can be used as supplement with e.g. woody biomass [51][52][53][54]. Co-gasification of wood and sewage sludge would be economically superior to incineration [54].

Sewage sludge has been co-gasified with other feedstocks in a lab-scale fixed bed [55]. The sludge resulted in a gas with a lower heating value of 10,1 MJ/m^3. It produced emission precursors such as NH_3 and COS, but was quite possible to co-gasify with paper and plastics.

Because sewage sludge cannot be completely digested and because of the heat required to dry it, combinations of digestion and gasification have been suggested to raise the electrical output. A combined digestion and gasification scheme to produce gas for a solid fuel cell and a gas turbine was analysed. Experiments [56] and modelling [57] have reached the electrical efficiency of 42 and 52 % respectively.

Sewage sludge and char from pyrolysis of sludge was gasified in a lab-scale fluidised bed [44]. The resulting product gas from char had a lower heating value of 4-6 MJ/m^3, which is rather low. However, the tar yield was much lower.

In all thermal conversion, the toxicity of the solid residues should be considered. Metals and other constituents may be detrimental to human health or the environment [58].

To summarise, gasification of sewage sludge or digestate in medium scale to produce electricity is quite possible. For biofuel production, it is probably better to use fluidised bed gasification in considerably larger scale, which depends on a local supply of considerable amounts of feedstock. The highly moist feedstock has to be dried in any kind of gasification. Therefore, the economics depend on a cheap heat source being used.

3.4 HYDROTHERMAL CONVERSION

HT is the process of transferring the chemically bound energy in a solid feedstock to solid (hydrochar), gaseous and/or liquid form. This is done in water at moderate temperatures compared with pyrolysis, combustion and gasification, and high pressure; circumstances at which the properties of water may change. Especially near and above the critical point (374,3°C and 22.1 MPa) the reaction rates of different processes may be significantly more rapid because of e.g. the high increase of the solubility of hydrocarbons in water [59]. As opposed to pyrolysis, combustion and gasification, since hydrothermal conversion takes place in water, drying of the feedstock is not necessary. The products depend on temperature and pressure. Hydrothermal carbonisation (HTC) to produce hydrochar is performed in the range 180-250°C. Hydrothermal liquefaction (HTL) in the range

4–30 MPa and 200-370°C results in heavy oils. Hydrothermal gasification (HTG) is performed in near-critical conditions and produces a hydrogen-rich gas [59]. The yields of char, liquid and gas can be modified by oxidising agents and catalysts; e.g. K_2CO_3 promotes the gas yield [60]. Apart from being reaction-promoting, near-critical water constitutes a reactant containing hydrogen for the production of H_2. Operational parameters that affect the H_2 yield are temperature, pressure, feedstock concentration and residence time in order of importance. Catalysts may affect the yields. Alkali favours the water-gas shift reaction [60] while inhibiting the formation of tar [59]. Iron has been shown to enhance the bio-oil yield in HTL of biomass [61]. While alkali is used as homogeneous catalyst, nickel-based catalysts and noble metal catalysts are used heterogeneously.

The HT treatment of sewage sludge has been shown to be economically feasible compared with incineration [59]. Small-scale studies have shown high yields of H_2 in sludge with a solid content of up to 5 %. At higher contents, as in an industrial case, the yields become worse. Therefore pretreatments such as pre-liquefaction have been suggested [59][62]. In addition to low H_2 yield, other issues must be addressed to make large-scale HT treatment of sludge profitable. Those are corrosion, operating costs, reactor plugging and catalyst deactivation.

Lab-scale experiments of HTG of sewage sludge have been carried out with near and super-critical water [60][63]. The yields of gases, liquid and solids were more temperature-dependent than time dependent. The organic matter of the sludge was almost completely hydrolysed at 425°C. The liquid yield was more than 80 % and decreasing with temperature, while the gas yield was only a few percent and increased up to 450°C [60]. Higher gas yields were obtained with alkali catalysts, which converted around 45 % of the carbon to gas [60]. Even gas yields of around 70 % have been reported [63]. HTG combined with phosphorus recovery was examined at different temperatures and retention times in an autoclave. The carbon gasification efficiency was 60 % at 600°C, and 80-95 % of the phosphorus could be recovered. Other feedstocks such as card board [64], softwood [65] and algae [66] have been studied, and the yields depend on the same parameters as in HT treatment of sludge.

Since HT takes place in water, some of the organic product will be dissolved in the aqueous phase. This phase can be considered a byproduct that has to be disposed of because of difficulties of extracting the valuable compounds and because of its content of toxic metals. However, it may also be of considerable value due to its content of nutrients and organic compounds [67]. It may for instance be suitable for cultivating algae.

Most of the literature on HT processes describes lab-scale batch units. A somewhat larger and continuous system has been developed for the HTL of stillage from bioethanol production [68]. The oil yield was found to be around 40 %. However, further upscaling, while maintaining the yields and proper disposal of the aqueous phase, would be required for use in industry.

To summarise, HT may seem an attractive method due to its capacity to convert moist feedstocks. Other advantages may be the recovery of phosphorus. However, commercial-scale HT is only, to a small extent, available as HTC, which is not suitable for biofuel production, whereas HTL and HTG are not yet available at all. In the present study, HTL and HTG (HTL/G) will be considered.

Table 4 summarises the findings regarding pyrolysis, gasification and HTL/G.

Table 4. Summary of the main features of thermochemical conversion methods considered in this analysis.

	Pyrolysis	**Gasification**	**HTL/G**
Operation conditions	400-900°C, 1 bar.	800-1300°C, ≤ 30 bar	200-500°C, 50-400 bar
Pretreatment	Drying	Drying, milling (milling is required in suspension gasification. Depending on substrate, it may also be required in fluidised bed gasification.)	Pre-liquefaction? (Pre-liquefaction may be advantageous in large-scale applications.)
Scale	Variable	Large	n.a.
Phosphorus	Ends up in char	Ends up in char or bottom ash	Ends up in water fraction or precipitates
Nitrogen in NH_4	The majority ends up in water fraction that is removed upstreams process	The majority ends up in water fraction that is removed upstreams process	Ends up in water fraction
Toxic metals	End up in gas or char	End up in ash or char	End up in water fraction or precipitated
Unwanted organic compounds	Destroyed	Destroyed	Probably destroyed to some extent
Investments	Low (upgrading of the pyrolysis oil will be needed)	High	High (probably lower than for gasification)
Technical availability for biofuel production	Pilot	Demo	Laboratory
Technology tested with digestate/ sludge as feedstock	In pilot and lab-scale	In pilot and lab-scale	In lab-scale

4 SELECTED STUDY LOCATIONS

As presented in Chapter 3, different technologies could be available for thermochemical conversion of digestate for biofuel production, each with different characteristics. However, the overall feasibility of these conversion routes is also affected by what kind of feedstock that is utilized (digestate from WWTP or co-digestion plants), scale of operation, transportation distance and local conditions such as available heat sources. The impact of these different aspects is demonstrated in four case studies presented below. Given the fact that digestate from WWTP already generates a treatment fee while digestate from co-digestion plants gives an income for the biogas producer, these case studies here focus on the treatment of digested sewage sludge.

4.1 LOCAL TREATMENT OF DIGESTATE FROM WWTP (CASE1)

In *Case 1*, it is assumed that the thermochemical conversion plant is located at Sjölunda in Malmö, which is one of Sweden’s larger WWTP. Thus, there is no transportation needed and no transportation cost. Currently, the digested sludge is dewatered to approximately 25 % DM and then handed over to an external contractor that takes responsibility for the disposal of the sludge. The fee for this service is set to 300 SEK/ton dewatered digestate.

The total amount of dewatered digestate amounts in this case to 30 000 tons/yr.

Treating the digestate in a thermochemical process instead, it is assumed to have no impact on the WWTP. Thus, the owner of the WWTP still dewaters the digestate and still pays 300 SEK/ton for its disposal. The only exception is when the digestate is treated with HTL, which requires a low DM content. In that case, no dewatering is needed. To reflect this, the cost savings for the WWTP is included as an income for the thermochemical process. Based on an estimation provided by Tham (2017) [69], the cost for dewatering is set to 12 SEK/ton wet weight.

4.2 REGIONAL TREATMENT OF DIGESTATE FROM WWTP (CASE 2)

In *Case 2*, the thermochemical conversion process is still located at Sjölunda in Malmö. However, in order to increase the amount of digestate and benefit from a potential efficiency of scale regarding the thermochemical process, additional digestate is transported to Sjölunda. Here, it is assumed that another 40 000 tons/y of digested sewage sludge are transported from WWTP in the southwest of Scania. Thus, the difference between *Case 1* and *2* is that some of the digestate must be transported.

The average transportation distance is calculated to 21 km and the transportation cost is calculated to 31-44 SEK/ton. Background data and assumptions are given in Appendix B.

4.3 REGIONAL TREATMENT OF DIGESTATE FROM WWTP AND CO-DIGESTION (CASE 3)

In *Case 3*, the thermochemical process still takes place at Sjölunda in Malmö or at the WWTP in Helsingborg. However, in addition to the digestate from WWT that is treated in *Case 2*, it is also assumed that digestate from two large co-digestion plants in Scania is transported to Malmö as well. Thus, the total amount of digestate is increased to 110 000 tons.

Since digestate from co-digestion is currently handled as a slurry, the economic calculations for the thermochemical process includes not only the transportation cost given in Appendix B but also a cost for dewatering which is set to 12 SEK/ton wet weight [69]. Since the digestate from co-digestion plants are currently used as a fertilizer with an economic value, the co-digestion plant must also be compensated for the nutrients that are removed in the dewatered digestate. This value is calculated to 100–120 SEK/ton dewatered digestate (see Appendix A). On the other hand, there is also a cost for transport and spreading of digestate, which is now reduced. Given an assumed transportation distance of 10 km, the net cost for the digestate is estimated to approximately 200 SEK/ton dewatered digestate.

For the location in Malmö, the average transportation distance for all dewatered digestate is calculated to 46 km and the transportation cost is calculated to 56–72 SEK/ton. For the location in Helsingborg, the average transport distance is calculated to 52 km and the cost to 64–84 SEK/ton respectively.

In the following calculations, the net feedstock cost, including transportation and compensation to the biogas producer, is set to 145 SEK/ton and 153 SEK/ton respectively.

4.4 NATIONAL TREATMENT OF DIGESTATE FROM WWTP (CASE 4)

In *Case 4*, we demonstrate the possibility to establish a large-scale plant utilizing the majority of the digested sewage sludge produced in Sweden. The total amounts of dewatered digestate is set to 440 000 tons originating from 24 municipalities including Stockholm, Göteborg and Malmö, which together represents more than 50 % of the total volume.

As a base case scenario, this national treatment plant is located to Malmö, which gives an average transportation distance of approximately 400 km and a transportation cost of 360–82 SEK/ton.

For comparison, the transportation cost is approximately 302, 282 and 254 SEK/ton if this conversion plant is instead located to Göteborg, Stockholm or Jönköping, respectively.

5 HEAT SOURCES

As pointed out in Chapter 3, highly moist feedstock such as digestate and sewage sludge needs to be dried in any kind of gasification or pyrolysis process. For the digestate flows estimated for the four study cases described in Chapter 4, as much as 3 up to 48 GWh/yr heat is needed (Table 5). Against these figures, it becomes clear that the availability of low cost heat, generally industrial waste heat, is a decisive parameter for the economy of these value chains. The specific value of an existing heat source for this purpose is in turn dependent on several parameters such as its temperature and pressure (high or low grade heat), heat medium (liquid, gas), variation with time (continuous or seasonal production) and distance from the biogas plant(s) or the thermochemical conversion plant where the digestate would be processed, etc.

Today, the cost of waste heat varies in practice from 0 to approximately 600 SEK/MWh (excl. VAT, Energiföretagen) [70][71]. where the highest value is generally obtained for those heat production sites that are located in adjacent to a district heating network, which in turn opens up for heat storage, distribution and a market and thereby a higher alternative heat cost. Waste heat bounded to liquid mediums is generally easier recuperated than heat bounded to fumes, and thereby generally of higher value. In those cases where no heat infrastructure exists and the heat source to be used varies with time, heat storage will be a necessity. For storing smaller amounts of heat for shorter times (hours-days), pressurized heat tanks (accumulators) are generally used, whereas large-scale seasonal heat storage is most often made in boreholes or caverns at close to atmospheric pressure and low temperatures (15-20°C). In the case with drying digestate for gasification or pyrolysis, utilization of the latter heat storage alternative would call for complementary energy consuming heat upgrading (e.g. heat pump).

Table 5. Estimated amount of heat required for drying the digestate from 75 to 0 % humidity for the study cases described in Chapter 4, plus larger sources of waste heat identified in the vicinity of the thermochemical production plant and/or any of the biogas plants supplying digestate to the thermochemical conversion plant.

Study case	Digestate produced (tons/yr), 75 wt% water	Estimated heat amount required for drying the digestate (GWh/yr)
Case 1.	30 000	3
Case 2.	70 000	8
Case 3.	110 000	12
Case 4.	440 000	48

According to reference [72], about 3-4 TWh of waste heat is delivered annually in Sweden. This is estimated to represent just over half of our total waste heat potential. It is the energy-intensive industry (i.e. the pulp and paper, the iron, the chemical and the mining industry) that accounts for the largest share of this waste heat utilization, and from the perspective of this study's purpose and goals, the biogas plants located nearby any of these energy-demanding industries hold a big advantage (Figure 4). The selected location of this study, i.e. Sjölunda, Malmö, is singled out [73].

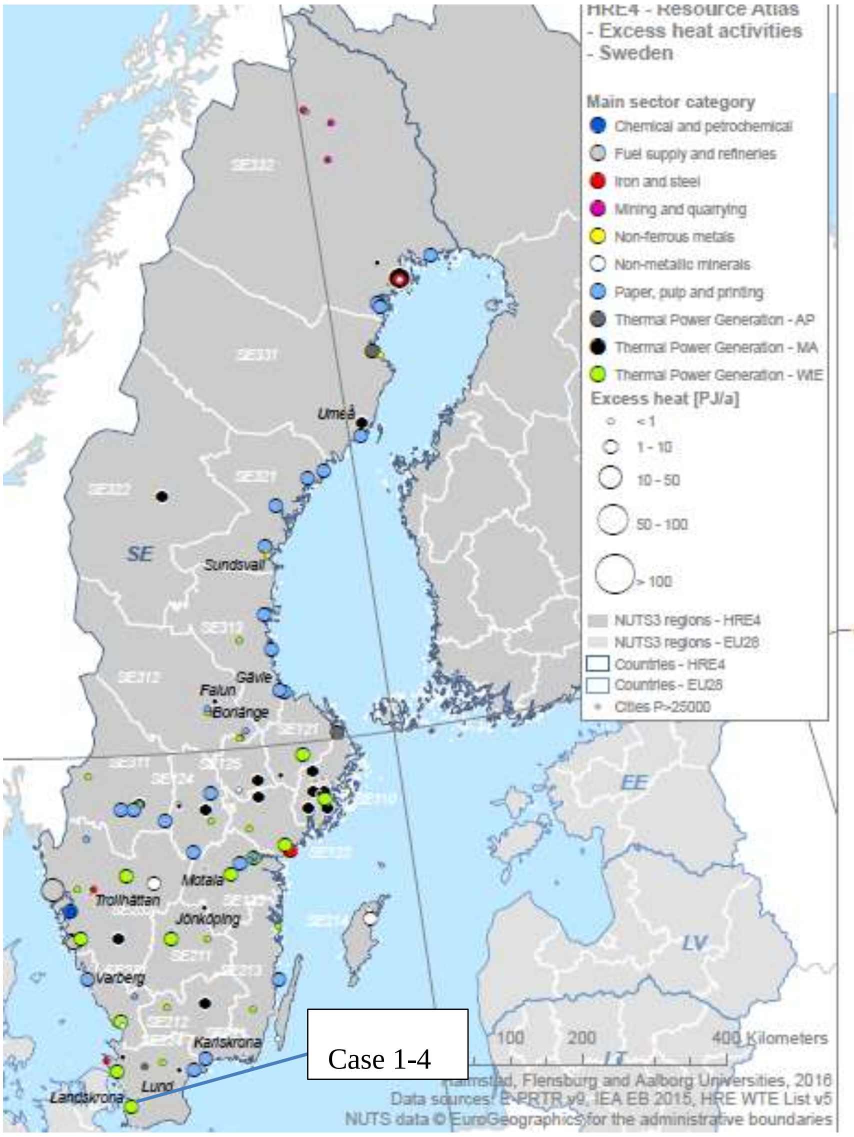


Figure 4. Heat roadmap Sweden [73]. 1 PJ = 280 GWh. The selected location of this study, i.e. Sjölunda, Malmö, is singled out in the map (i.e. Case 1-4).

Furthermore, for pointing out the potential of the selected study cases described in chapter 4, the mapping of waste heat made by Länsstyrelsen Skåne (2014) is of high interest [72]. According to this reference, ~1,3 TWh of waste heat is available in Skåne, out of which approximately 50 % is supplied to and used as district heating and the other 50 % is vented. In comparison to the estimations of heat demands given in Table 5, it can, based on the given magnitudes in MWh, be concluded that there seems to be by large enough low cost heat available in the region for enable digestate pyrolysis or gasification. In addition, a large portion of this heat seems to be available in or close to Malmö, Helsingborg and/or in the different digestate catchment areas considered for Case 1-4 (Table 5, Figure 5). Among the latter, the high value heat produced by NorbCarb in Malmö and Kemira in Helsingborg, respectively, are of especial interest in this study. For case 3, the waste heat produced in the eastern part of Scania (i.e. Nymölla paper mill, Stärkelsen, Lyckeby) is also of interest since this heat could potentially be used for drying the digestate and thereby reduce the transportation cost of the digestate from Kristianstad’s co-digestion plant to Sjölunda, Malmö or the WWTP in Helsingborg. However, the majority of these identified waste heat sources are connected to district heating networks which in practice implies that theirs availability and utility for other purposes than district heating, such as digestate drying demanding heat all year long, would be more doubtful. Having said that, in combination with the knowledge of the complexity of storing large amounts of high value heat over longer periods, it could therefore be motivated to consider other locations having significantly larger, less variable, excess of high value heat available. On such location alternative could be next to GRYAB WWTP, Göteborg, having the chemical and petrochemical industry close by (Figure 4). Another alternative could be to establish and operate a biomass heating plant adjacent to the thermochemical plant in question, at least during the colder season when waste heat is supplied to the district heating networks and for digestate flows as considered for Case 4.

Table 6. Examples of heat sources at or very near the WWTP of Sjölunda, Malmö , WWTP in Helsingborg and in the considered digestate catchment areas (case 2, 3, 4), respectively.

At or very near WWTP Sjölunda, Malmö [74]	In the digestate catchment areas considered in case 2/3/4.
VA-SYD* – up to 200 GWh low-grade heat in the form of waste water at 10-20°C. NorCarb* – 140 tons/yr (180°C water vapor) + up to 90 GWh/yr other heat losses from heat exchangers. Lantmännen* – low grade heat in the form of ≤ 440 000 m^3/h vented air at 35 °C SYSAV*– up to 8 GWh/yr low grade heat (process water, 24-38 °C)	Örtofta sugar mill, Lund* – 55-60 MW (50°C, water vapor) from Sept-Jan**. Research facility MAX IV* – up to 3 MW low-grade heat, in the future estimated to increase up to 5 MW [76]. In the future, research facility ESS* – up to 9 MW (62/50 °C) + 9 MW (30/25 °C).[76] Kemira-Industry Park of Sweden, Helsingborg* – up to 300 GWh high grade heat in the form of water vapor at 93 °C that is used as district heating winter time, non-utilised summer time [77]. Höganäs* – up to 7-8 MW and 1-2 MW high grade waste available heat summer and winter time, respectively [78]. Absolut and Stärkelsen, Lyckeby (10 km from Kristianstad biogas plant) – up to 10 GWh high grade heat at 120 °C + up to 10 GWh low grade heat (40-55 °C) [72]. Nymölla Stora Enso paper mill (ca 30 km from the Kristianstad biogas plant) – up to 30 GWh /yr high grade heat [72].

*** Connected to district heating network.**
**** Equal to the heat supply to the district heating network prior to that Örtofta biomass plant was commissioned.**

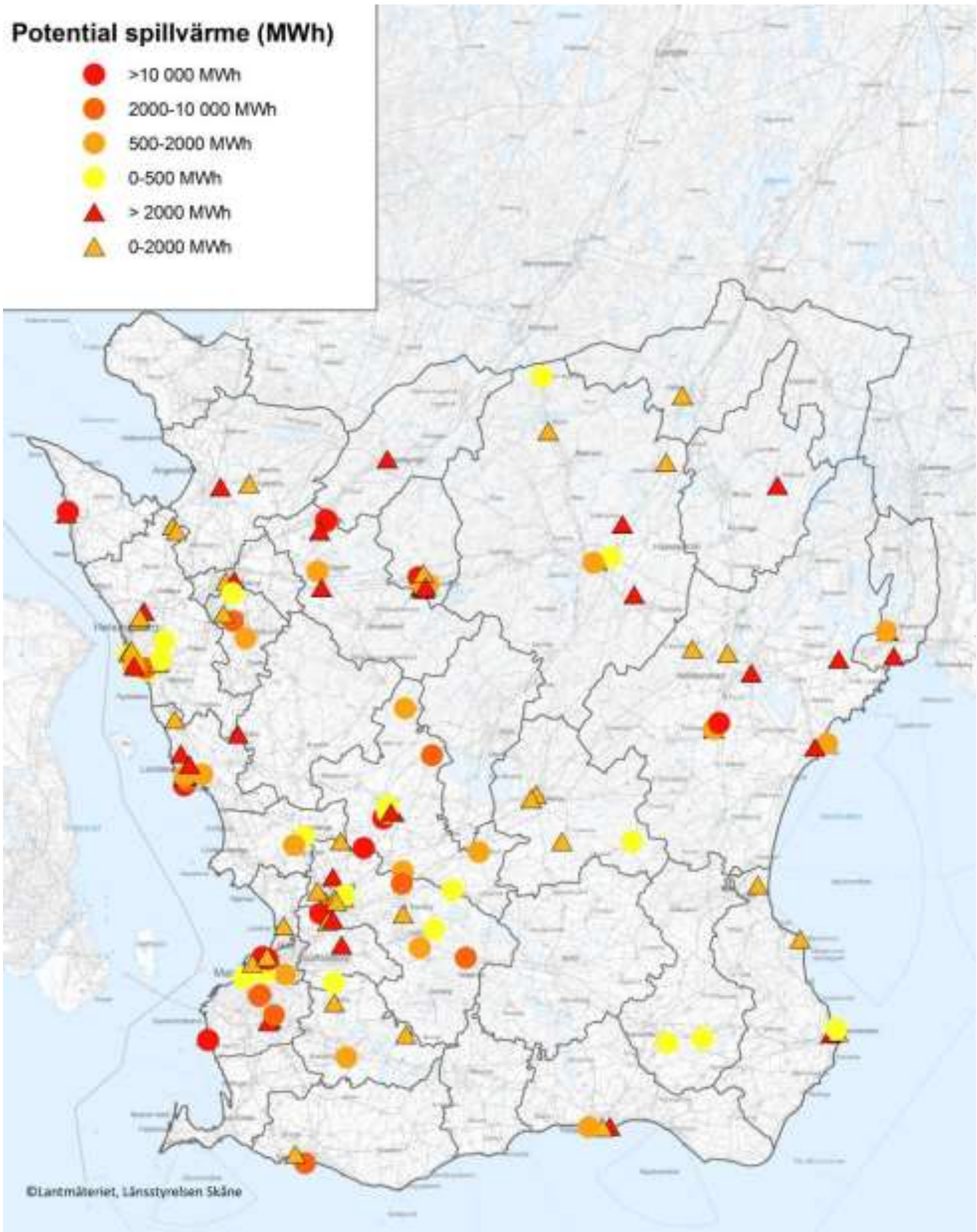


Figure 5. Mapping of estimated non-utilised waste heat sources in Skåne, published with the permission of Länsstyrelsen Skåne 2014 [79]. Circles indicate potentials estimated by separate organisations, and the triangles are estimated potentials based on purchased energy for those organisations that have announced that they have non-utilised waste heat that they have not quantified.

6 MASS AND ENERGY BALANCES

To make possible a quantitative comparison of different methods to convert digestate, their effects have to be reduced to one parameter. One such parameter could be the economic result. In such a case, the effect of a certain method on e.g. emissions of greenhouse gases and generation of phosphorus would correspond to an economic value and thereby be directly comparable. However, this would be an extensive task suffering from large uncertainties. In the present case, the variable costs and revenues are determined. If the net of revenues and costs is positive it may cover investment cost and other costs. To this end, the mass balances must be established in each treatment method. The mass balances consist of mass flows across the system boarder. Each mass flow corresponds to an energy flow, and therefore a cost or revenue, in terms of heat or chemically bound energy.

The mass balances sum the ingoing and outgoing mass flows, $dm/dt = \dot{m}$, where m is mass and t is time. Because of the preservation of mass, these sums are equal. The easiest way to illustrate this is by a schematic outline and an equation.

6.1 PYROLYSIS

Figure 6 illustrates the mass flows in the pyrolysis process.

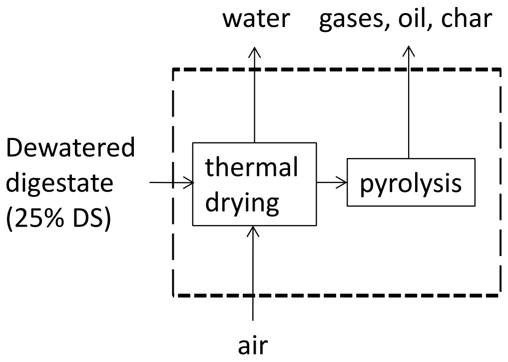


Figure 6 Schematic outline of the pyrolysis process in terms of mass flows (arrows) across the system boarder (dashed).

The ingoing mass flow of digestate and air is equal to the outgoing flows of water, steam (in air), gases, char and pyrolysis oil:

$$\dot{m}_d + \dot{m}_a = \dot{m}_w + \dot{m}_g + \dot{m}_c + \dot{m}_o + \dot{m}_s,$$

where indices d, a, w, g, c, o and s denote digestate, air, water, gas, char, oil and steam, respectively.

6.2 GASIFICATION

Figure 7 illustrates the mass flows in the gasification process.

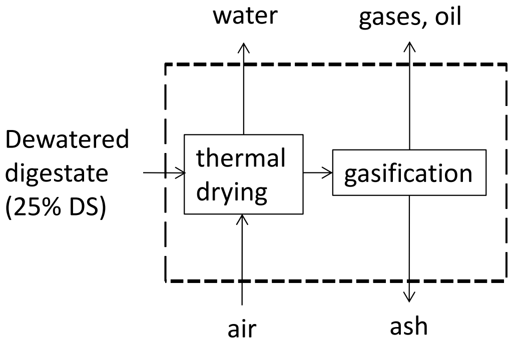


Figure 7. Schematic outline of the gasification process in terms of mass flows (arrows) across the system boarder (dashed).

The ingoing mass flow of digestate and air is equal to the outgoing flows of saturated steam (in air), gases and ash:

$$\dot{m}_d + \dot{m}_a = \dot{m}_w + \dot{m}_g + \dot{m}_s + \dot{m}_{ash},$$

where index *ash* denotes ash.

6.3 HTL/G

Figure 8 illustrates the mass flows in the HTL/G process.

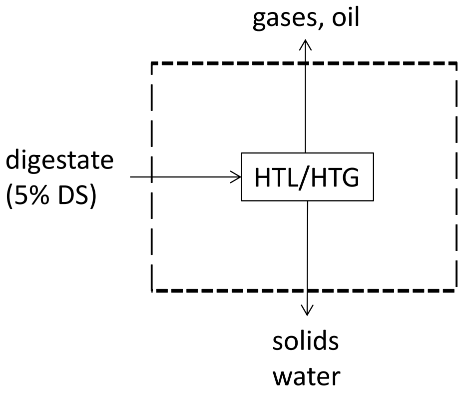


Figure 8. Schematic outline of the HTL/G process in terms of mass flows (arrows) across the system boarder (dashed).

The ingoing mass flow of digestate and is equal to the outgoing flows of bio-oil, gases and water phase:

$$\dot{m}_d = \dot{m}_o + \dot{m}_g + \dot{m}_w.$$

7 ECONOMIC ANALYSIS

In this section, the economic model and its parameters are described. Thereafter the model is used on the different treatment methods. Finally, a sensitivity analysis is made.

7.1 MODEL

The energy balances sum the energy in the ingoing and outgoing mass flows. Because of the preservation of energy, these sums are equal. In the present case, only energy flows that have impact on the economic result of the process are taken into account. This limits the analysis to electricity and heat needed to dry the ingoing flow and chemically bound energy in the outgoing flows of gas and liquid. The starting point of the economic analysis is a flow of 1 kg/s of digestate with 5 % dry substance. In pyrolysis and gasification this has to be mechanically dewatered. The incoming dewatered digestate to pyrolysis and gasification has a dry content of 25 %, which makes the flow 0,2 kg/s. Since dewatering is part of the process even if neither pyrolysis nor gasification are in place, this cost has been excluded. In HTL/G dewatering is not necessary, so to be able to compare the different treatment methods the cost of dewatering has been added as revenue. All costs and revenues are given per kg of the digestate with 5 % dry substance.

7.1.1 Pyrolysis

Prior to pyrolysis, the water has to be completely removed. This is done thermally by raising the temperature to 100 °C and evaporating the water. The heat needed for this constitutes a cost. The water produced in the drying processes is assumed to be fed into the WWTP. The cost for water treatment constitutes an additional cost of the pyrolysis. Hence, the sum of costs, C, is

$$C = \dot{m}_{dw} w_{dw} \left(p_{heat}\left(C_p(100 - T_{in}) + H\right) + c_{wt}\right),$$

where $\dot{m}_{dw}$ is the mass flow of dewatered digestate, w_{dw} is the water content of the dewatered digestate, p_{heat} is the price of heat, C_p is the heat capacity of water, T_{in} is the temperature of the ingoing digestate, H is the heat of vaporisation of water, and c_{wt} is the cost of water treatment.

The revenue consists of the sum of the values of the produced char, gas and oil. This is determined by the prices and yields on dry basis of these products and the flow of dry matter. If the sewage sludge is not destructed, it has to be gotten rid of which implies a cost. Pyrolysis saves this cost why the fee to get rid of dewatered sewage sludge is added as revenue. Hence, the revenue, R, is

$$R = (p_c y_c + p_g y_g + p_o y_o)(\dot{m}_{dw} - \dot{m}_{dw} w_{dw}) + p_s \dot{m}_{dw},$$

where p and y are the prices and yields on dry basis, respectively, of char, gas and oil, and p_s is the fee to get rid of sludge. The composition and value of the gas may be specified for each gas, but in the present case CO and H_2 were assumed to be converted to CH_4.

7.1.2 Gasification

As in pyrolysis, gasification requires complete drying. Hence

$$C = \dot{m}_{dw} w_{dw} \left(p_{heat}\left(C_p(100 - T_{in}) + H\right) + c_{wt}\right).$$

The revenue consists of the sum of the values of the outgoing gases and, possibly, the ash. Also, as in pyrolysis, the fee to get rid of the sewage sludge is added as revenue. Therefore

$$R = (p_g y_g + p_{ash} y_{ash})(\dot{m}_{dw} - \dot{m}_{dw} w_{dw}) + p_s \dot{m}_{dw},$$

where index *ash* and *s* denote ash and sewage sludge, respectively. As in pyrolysis, CO and H_2 were assumed to be converted to CH_4.

7.1.3 HTL/G

No drying is needed in HTL/G, but the digestate has to be heated to 200-400 °C. Since 95% of it is water, the whole mass can be assumed to have the heat capacity of water. The water fraction downstream of the treatment is assumed to be fed back to the water treatment plant. This water volume would have been processed the same way directly, had there been no HT process, why this does not induce an additional cost. The cost then becomes

$$C = p_{heat} \dot{m}_d C_p (T_{out} - T_{in}),$$

where T_{out} is the temperature of the outgoing flows.

The value of the outgoing gases and bio-oil contribute to the revenue. It should also be possible to recover some of the heat of the outgoing flow by lowering the temperature to e.g. 150 °C. As in pyrolysis and gasification, the fee to get rid of the sewage sludge is added as revenue. This however pertains to dewatered digestate and has to be recalculated accordingly. Therefore

$$R = p_g y_g (\dot{m}_d - \dot{m}_d w_d) + p_o y_o (\dot{m}_d - \dot{m}_d w_d) + p_{heat} \dot{m}_d w_d C_p (T_{out} - 150) + p_s \dot{m}_{dw}.$$

8 RESULTS

The model described in Chapter 7 is used to calculate variable costs and revenues. The difference, $R - C$, between these should cover some variable costs that have not been taken into account by the model. Such costs are e.g. salaries directly coupled to the conversion of digestate. Financial costs, because of the investments that have to be made in the different treatment methods, should also be covered, as should the costs that are in common for the whole enterprise. The latter includes administrative costs and facilities. After all these costs have been subtracted, the net is a profit that is hopefully larger than zero. To summarise, the model provides the financial space to cover the investment costs and others. It is important to recognize that

- a larger $R - C$ in one of the methods does not necessarily mean that the economic basis is better since that method may imply higher investment costs.
- the quality of the result of the model is dependent of the data it uses. Some of the treatment methods discussed here are not very mature regarding large-scale technique or regarding the market in which it is assumed to operate. This makes it more difficult to obtain established market prices.

In this section, the parameters are discussed first. Thereafter the total economic result and revenue and costs in the different treatment methods are given. Then the compositions of the revenues and costs are analysed.

8.1 PARAMETERS

The parameters used in the calculations are listed in Appendix C. Some of them, e.g. physical properties, have well known values. Other parameters such as the yields and, as mentioned, prices vary between different sources, techniques, and means of operation. Consequently the result, $R - C$, varies. Parameters that exhibit different values depending on source were taken as the average of these sources. However, some source may have been considered unreliable and was therefore neglected. The values used and their sources are stated in Appendix D.

8.2 REVENUE AND COSTS

Figure 9 shows the variable costs, revenue and alternative revenue for pyrolysis, gasification and HT. In all treatment methods the revenue is larger than the costs ($R - C > 0$). This shows that all methods have a potential to produce biofuels. The revenue was calculated assuming that all CO and H_2 were transformed to CH_4 via

$$CO + H_2O \rightarrow CO_2 + H_2$$

and

$$CO + 3\,H_2 \rightarrow CH_4 + H_2O.$$

This means that the ideal ratio of amount of substance between H_2 and CO is 3, and that CO can be converted to H_2. It is also assumed that the process does not produce excess H_2. It is likely that the equipment needed for upgrading of the gas from a gasifier would require large scale. HTL/G, which is unknown in commercial scale, would probably also require significant investments since the facility would have to process a large flow of highly pressurised digestate with 95 % water content. Pyrolysis, on the other hand, requires smaller equipment and less upgrading of the gases. The oil is of worse quality than that of gasification and HT.

The revenues are in the range of 0,18 and 0,22 SEK/kg. The costs of pyrolysis and gasification are of 0,03 SEK/kg while the costs of HTL/G are 0,10 SEK/kg. This gives an economic result of 0,15-0,17 SEK/kg for pyrolysis and gasification, and 0,11 SEK/kg for HTL/G.

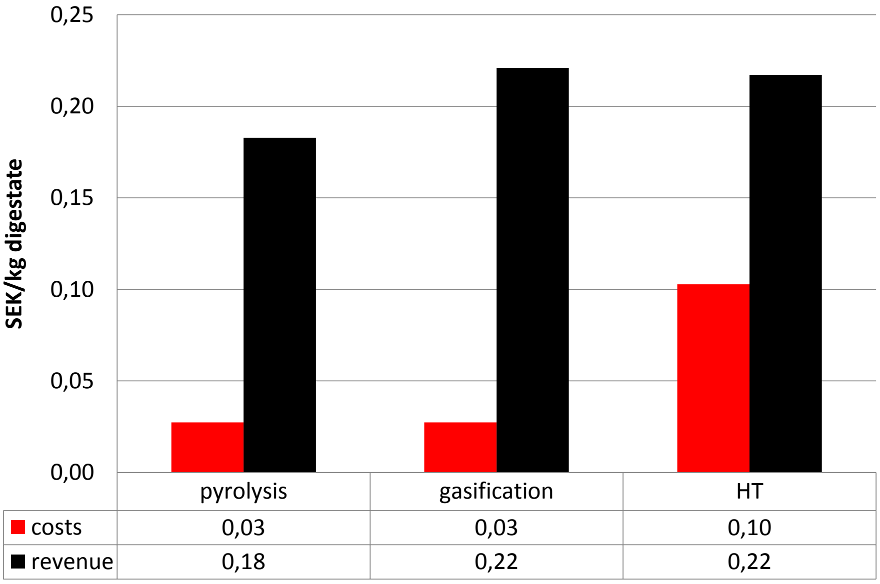


Figure 9. Variable costs and revenues in different treatment methods.

8.2.1 *Pyrolysis*

Figure 10 shows the composition of revenues and costs in pyrolysis. The major contributions to the revenue are char and sludge reception. However, almost 30 % of the total revenue comes from CH_4. To maximise the biofuel potential, the char production should be as low as possible, but the sludge reception revenue is independent of the products and constitutes an important income for the whole process. The costs are dominated by the thermal drying of the water. It is thus, as has been established in previous chapters, essential that the heat source is cheap. Furthermore, it can be concluded that dewatering also constitutes of a substantial fraction of the total costs.

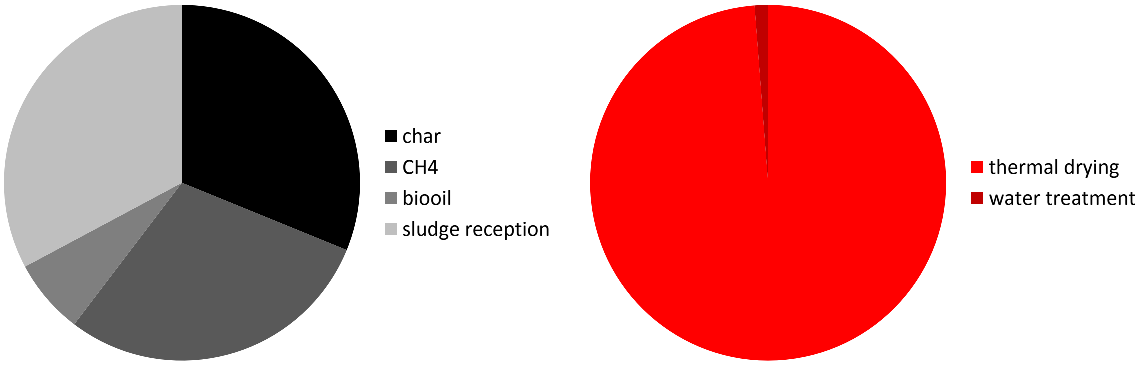


Figure 10. Composition of revenues and costs in pyrolysis.

8.2.2 *Gasification*

Figure 11 shows the composition of revenues and costs in gasification. More than 70 % of the revenue comes from CH_4. The rest is income from sludge reception. This means that there are no competing products of which it is impossible to make biofuel. The composition of the costs is the same as for pyrolysis.

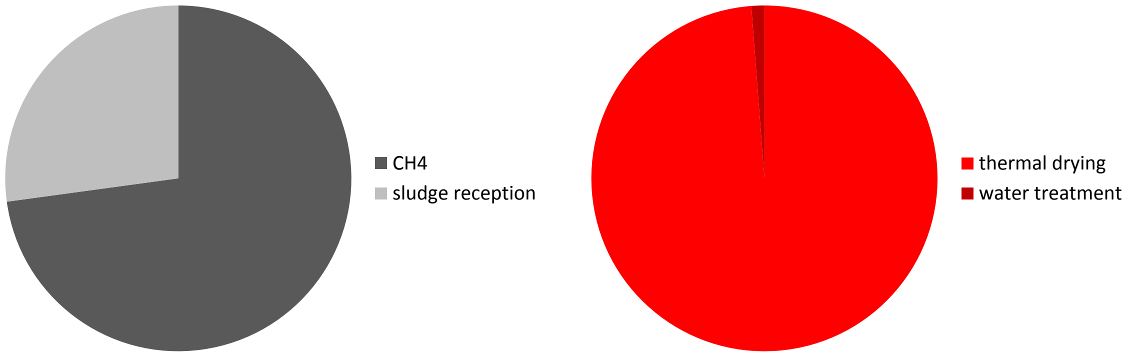


Figure 11. Composition of revenues and costs in gasification.

8.2.3 *Hydrothermal treatment*

Figure 12 shows the composition of revenues in HT. The costs only consist of heating and are therefore not bestowed with a diagram. The revenue consists of about equal parts of bio-oil, recovered heat and sludge reception. This means that, except for a little char, all of the feedstock can be converted to biofuel.

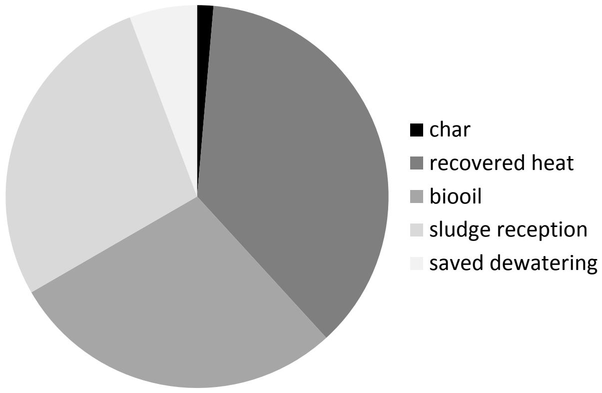


Figure 12. Composition of revenues and costs in HT.

8.3 SENSITIVITY ANALYSIS

8.3.1 *Theory*

To take the variation of the parameters into account, a sensitivity analysis was made where one parameter at a time was varied and a new $R - C$ was calculated. Thus, the absolute as well as the relative impact of a change of a parameter were calculated.

Consider a parameter, P, which affects the revenue or the costs. They could then be written as functions of the parameter:

$$R = R(P) \text{ and } C = C(P).$$

If P were varied, the economic result, $R - C$, would change. The extent of this change would be the sensitivity in absolute terms, S_A, of the model with respect to P. Hence

$$S_A(f) = (R(fP) - C(fP)) - (R(P) - C(P)),$$

where f is the sensitivity factor > 1 by which the parameter was varied. A positive value of S_A would correspond to the case that an increase of the factor has a positive impact on the result.

It might also be interesting to relate $R(fP) - C(fP)$ to $(R(P) - C(P))$ yielding a relative sensitivity, S_R:

$$S_R(f) = (R(fP) - C(fP))/(R(P) - C(P)).$$

$S_R = 1$ would correspond to the case that $S_A = 0$; i.e. not sensitive at all. If $S_A > 0$ then $S_R > 1$.

If all parameters, P, were changed by the same factor, then a judgement of S_A and S_R could be made directly. However, this is not the case. f is set to 1,1 – a 10 % increase – if the variation of P is not known. If the variation of P is known, f is set to that variation; *e.g.* 1 + *standard deviation*/*average*. To make possible a direct comparison of the impact of a certain parameter, a normalised sensitivity, S_N, was defined

$$S_N(f) = (S_R(f) - 1)/(f - 1),$$

which relates the relative increase of the economic result to the relative variation of P.

In the following sections some parameters were varied one at a time.

8.3.2 Pyrolysis

The result of the sensitivity analysis for pyrolysis is shown in Figure 13 and Table 7. Unless the variation of a parameter was known, it was varied +10 %. The price of heat varies more so its variation was set to +100 %. The price of biochar and bio-oil was increased by factor of *standard deviation*/*average* of the acquired prices. The water content of the digestate is 95 % to start with so it was only increased with 1 %.

The absolute sensitivity is low to any of the variations. The relative sensitivity to different parameters is illustrated in Figure 13. It is highest for the price of heat, price of char and water content of the digestate, respectively. Obviously, an increase of the price of heat strongly increases the costs for thermal drying, while that of char increases the revenue. The effect of the water content of the digestate is more difficult to explain. The incoming flow to the pyrolysis process is dewatered digestate at 25 % dry substance by definition in the model, but this flow is calculated based on the water content of 1 kg of the original digestate. If the water content of this is increased by 1 %, the dry content decreases from 5 to 4,05 which would yield much less of valuable products. This is why the normalised sensitivity is so strongly affected by a change of the water content. In this case, a 1 % increase results in 19 % lower economic result. Clearly, it is important not to dilute the digestate, but it should be noted that to achieve the same amount of dewatered digestate as when the digestate has 5 % dry substance, one would simply have to dewater more digestate.

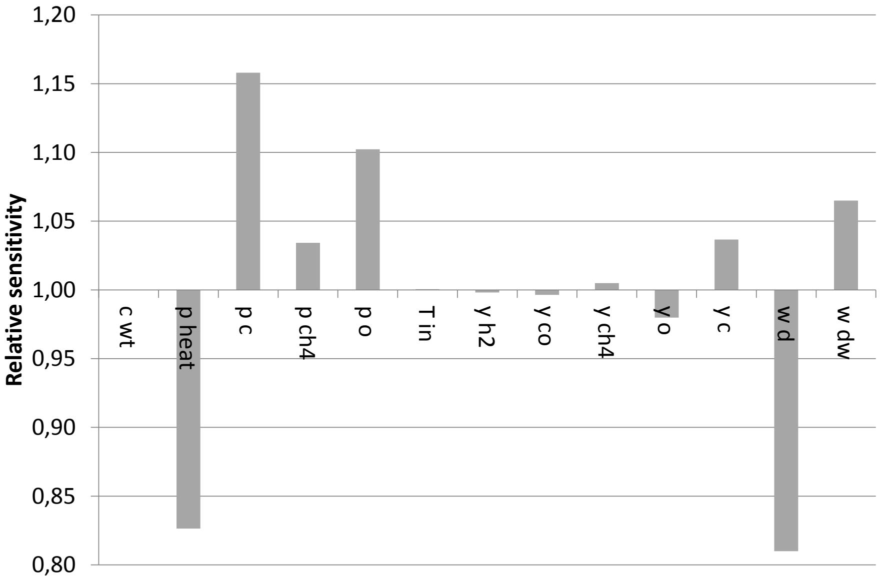


Figure 13 The relative sensitivity, S_R, of the economic result in pyrolysis for a number of parameters. $S_R = 1$ means no effect on the economic result, $S_R > 1$ means positive effect, and $S_R < 1$ means negative effect.

Table 7. The result of the sensitivity analysis for pyrolysis.

parameter	f	S_A (SEK/kg)	S_R	S_N
c_{wt}	1.1	0.00	1.00	-0.0021
p_{heat}	2	-0.03	0.83	-0.17
pc	1.43	0.02	1.16	0.37
p_{ch4}	1.1	0.01	1.03	0.34
p_o	2.27	0.02	1.10	0.08
T_{in}	1.1	0.00	1.00	0.01
y_{h2}	1.1	0.00	1.00	-0.02
y_{co}	1.1	0.00	1.00	-0.04
y_{ch4}	1.1	0.00	1.00	0.05
y_o	1.1	-0.003	0.98	-0.20
y_c	1.1	0.006	1.04	0.37
w_d	1.01	-0.030	0.81	-19.00
w_{dw}	1.1	0.010	1.06	0.65

8.3.3 Gasification

The result of the sensitivity analysis for pyrolysis is shown in Table 8. The parameters were varied in the same way as in pyrolysis.

The absolute sensitivity is low. The economic result is not strongly affected by any of the changes. The relative sensitivity is illustrated in Figure 14, and is high for the price of heat and CH_4, which is no surprise since gasification, as pyrolysis, requires drying, and that CH_4 constitutes >70% of the revenues. For the same reasons as in pyrolysis, the sensitivity is also large the water content of the digestate.

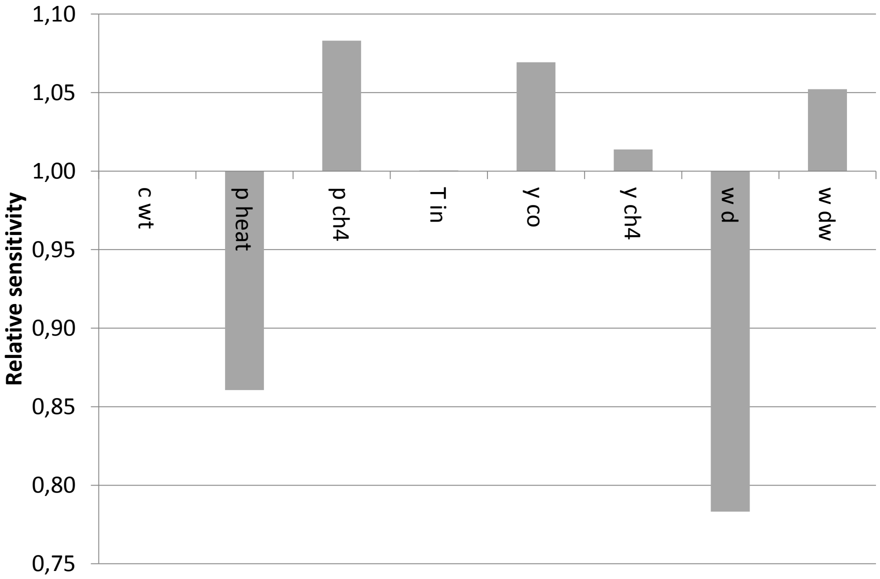


Figure 14 The relative sensitivity, S_R, of the economic result in gasification for a number of parameters. $S_R = 1$ means no effect on the economic result, $S_R > 1$ means positive effect, and $S_R < 1$ means negative effect.

Table 8. The result of the sensitivity analysis for gasification.

parameter	f	S_A (SEK/kg)	S_R	S_N
c_{wt}	1.1	0.00	1.00	0.00
p_{heat}	2	-0.03	0.86	-0.14
p_{ch4}	1.1	0.02	1.08	0.83
T_{in}	1.1	0.00	1.00	0.00
y_{co}	1.1	0.01	1.07	0.69
y_{ch4}	1.1	0.00	1.01	0.14
w_d	1.01	-0.04	0.78	-21.68
w_{dw}	1.1	0.01	1.05	0.52

8.3.4 HTL/G

The result of the sensitivity analysis for pyrolysis is shown in Table 9. The parameters were varied in the same way as in pyrolysis.

The absolute sensitivity is low to all variations. The relative sensitivity is illustrated in Figure 15, and is considerable to the price of oil, which stands for a significant part of the revenue. The price of heat is also important for the relative sensitivity. The normalised sensitivity is again sensitive to the water content of the digestate.

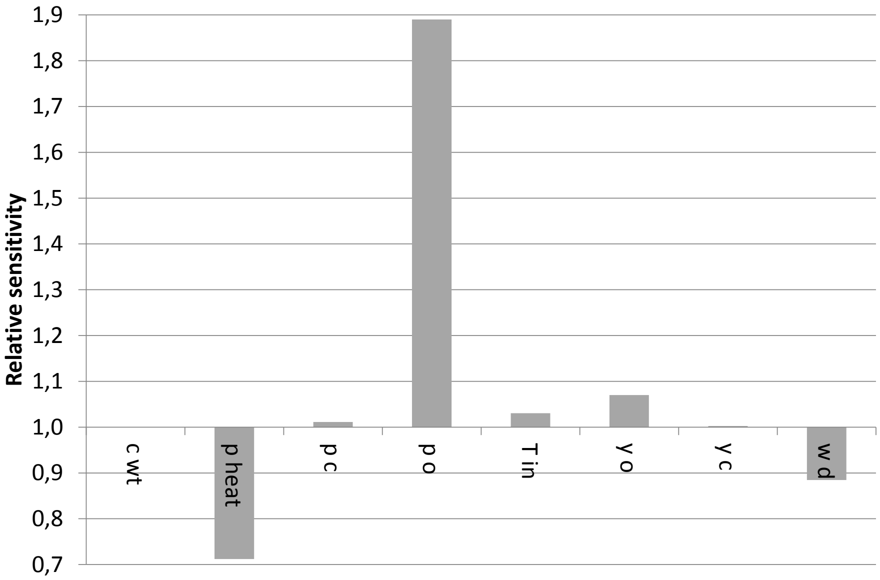


Figure 15. The relative sensitivity, S_R, of the economic result in HTL/G for a number of parameters. $S_R = 1$ means no effect on the economic result, $S_R > 1$ means positive effect, and $S_R < 1$ means negative effect.

Table 9. The result of the sensitivity analysis for hydrothermal treatment.

parameter	f	S_A (SEK/kg)	S_R	S_N
p_{heat}	2.00	-0.03	0.71	-0.29
pc	1.43	0.00	1.01	0.03
p_o	2.27	0.10	1.89	0.70
T_{in}	1.10	0.00	1.03	0.30
y_o	1.10	0.01	1.07	0.70
y_c	1.10	0.00	1.00	0.03
w_d	1.10	-0.01	0.88	-11.54

8.4 POTENTIAL OF BIOFUEL PRODUCTION

The yields of the different treatment methods and the amount of digestate available in the different cases (Chapter 4) result in a potential production of biofuels. Table 10 summarises this potential production of biofuels.

Table 10. Potential production of biofuels in different cases.

Case and method	Mass of biofuel (kt/year)
1, pyrolysis	3,4
1, HTL/G	3
2, pyrolysis	8
3, pyrolysis	13
4, gasification	69

9 DISCUSSION

The discussion is based on the result of the economic model, the transportation costs in different cases and the technical features of the treatment methods. Some comments on the investment space and capital costs are made, as well as some on the biofuel production potential.

9.1 CASE 1

In case 1, around 30 000 t/year dewatered sewage sludge is thermally processed at WWTP Sjölunda in Malmö. It includes no transportations and hence no such costs. Case 1 is preferable if transportation costs are high and/or the facility can be of economic scale with respect to the amount of digestate available at the site in question.

Pyrolysis could be performed in small scale. The pyrolysis oil could be used directly as fuel for peak load or balance. For the use of biofuel, it need however to be up-graded. Such upgrading usually requires expensive catalysts and other special equipment. Therefore it is likely that there are scale effects; i.e. the larger the upgrading facility the smaller the cost per unit biofuel. A possible solution to this might be to transport pyrolysis oil from several smaller units to an upgrading unit of economic scale. This transportation cost has not been taken into account in the present project, but since the pyrolysis unit is fairly uncomplicated it is possible that this solution is more efficient than transporting dewatered, but still water-laden, digestate to a large pyrolysis unit.

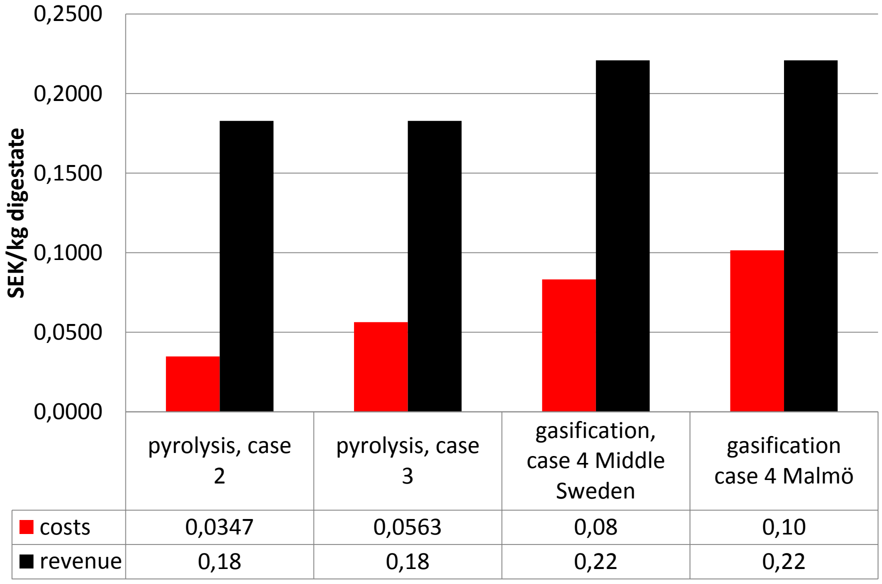
Gasification for biofuel production should probably be performed in large scale to become economic. It appears far too expensive to have small gasification units at each site where digestate is produced. The main product, being gas (herein assumed as CH_4), is not as easily transported as pyrolysis oil. The economic scale of a gasification unit can be estimated by considering the dual fluidised bed facility GoBiGas in which the economic scale was calculated to be a gas production in the range 80-100 $MW_{biomethane}$. At 65% efficiency, this would correspond to a biomass flow of 131 MWth based on low heating value (LHV). If the heating value of dry sewage sludge is set to 13.3 MJ/kg, then the required biomass flow would be 9.8 kg/s, which corresponds to 6.2 Mt/year of sludge and 1.24 Mt/year of dewatered sludge. No site in Sweden produces such amounts of sludge.

HTL/G uses the digestate without dewatering. The transportation of digestate seems highly inefficient. Therefore, HTL/G may appear more suitable to case 1 than pyrolysis and gasification. However, a rather immature process, it is unclear if enough digestate is available anywhere to perform HTL/G in economic scale. Of course, solutions such as dewatering prior to transport and then dilution again at the HTL/G site cannot be excluded, but technical problems, such as mixing, may be larger than expected.

9.2 CASE 2

In case 2, transportation of dewatered sewage sludge from the nearby region to the WWTP Sjölunda in Malmö is considered making the total amount of dewatered sludge to approximately 70 000 t/year.

Pyrolysis, as described above, may be more efficient if the oil is transported. However, in a densely populated area with short distances case 2 may be suitable. Figure 16 shows the costs and revenues with transportation costs included. Obviously, the costs are higher than in case 1, but there is still a considerable positive net and the scale of the process is larger.



	pyrolysis, case 2	pyrolysis, case 3	gasification, case 4 Middle Sweden	gasification case 4 Malmö
🟥 costs	0,0347	0,0563	0,08	0,10
■ revenue	0,18	0,18	0,22	0,22

Figure 16. Costs and revenues in the different cases for the treatment methods that come in question. Approximately the same result is obtained if Helsingborg instead of Malmö is chosen as location in case 3.

Gasification requires too large scale for this case to be realistic.

HTL/G is not considered suitable for transportation because of the high water content of the sludge.

9.3 CASE 3

In case 3, digestate from two large co-digestion plants in Scania is added to the dewatered sludge considered in case 2 resulting in a total of 110 000 t/year.

Pyrolysis, as seen in Figure 16, results in a positive net, which is smaller than in cases 1 and 2. However, the scale is larger, so the economical outcome depends on this net in relation to scale effects.

Gasification requires too large scale for this case to be realistic.

HTL/G is not considered suitable for transportation because of the high water content of the sludge and digestate.

9.4 CASE 4

In case 4, all dewatered sewage sludge in Svealand and Götaland is collected to Malmö, Stockholm, Göteborg or Jönköping. The cost to transport the sludge is similar in the three latter locations, why these have been lumped together as Middle Sweden. Transportation to Malmö is more expensive and has been considered as a separate calculation case.

The total amount of dewatered sludge available in this case is around 440 000 t/year, which is less than the estimated 1.24 Mt/year required for a gasifier of economic scale (Chapter 9.1.3). However, this estimation was based on a wood-based feedstock, so there may still be a positive net considering sludge that you even get paid for to take care of.

When it comes to the determination of location, the availability of low cost heat and other biomass feedstock for potential co-gasification are, in addition to the transportation cost, crucial parameters to consider. Among the three locations considered in this case, Göteborg, being close to the petrochemical industry, is probably the most suitable location with respect to the heat availability. Jönköping on the other hand is surrounded by forests of high annual growth [81] which should make the transportation of a wood-based additional feedstock to the gasifier cheaper. Furthermore, Malmö does not come out well in this comparison as neither enough low-cost heat (Chapter 5) nor forests are available to the same degrees. On the other hand, Malmö, like Göteborg, has a high-capacity harbour through which an additional biomass feedstock could be taken in. Table 11 summarises the findings for the considered locations of this case study.

Table 11. Summary of relative advantages (+) and disadvantages (-) on placing a sewage sludge gasifier at different locations.

Location	transportation costs	waste heat available (continuous supply)	additional biomass feedstock for co-gasification	harbour
Göteborg	+	+	-	+
Jönköping	+	-	+	-
Malmö	-	-	-	+
Stockholm	+	-	-	+

9.5 CAPITAL COSTS

Capital costs lie outside the scope of the present study and have not been investigated, but some estimations can still be done.

Given the positive net in all the thermal treatment methods, a maximal investment space, I, can be calculated as

$$I = M(R - C)/a,$$

where M is the annual mass flow of digestate (recalculated and given as raw digestate with 5 % dry solid) and a is the annuity factor. Table 12 shows the maximal investment space in the different cases with an annuity factor of 0.07 assuming an interest rate of 5 %/year and a depreciation time of 25 years. For indicating the impact of a varying interest rate and depreciation time, calculations have also been made for an annuity factor of 0,12 assuming 8 % in interest rate and 15 years in depreciation time. This analysis shows that there is a substantial maximal investment space in all cases considered. However, it should be noted that operational costs also should be covered and consequently the real investment space is smaller.

Table 12. Estimations of the maximal investment space for the different study cases 1-4. M is the annual mass flow of digestate (5 wt% dry matter), *R* the revenue, *C* the cost of the digestate, and *I* the estimated maximal investment space assuming an annuity factor of 0,07 and 0,12, respectively.

	Thermal method	*M* (Mt/year)	*M*(*R*-*C*) (MSEK/year)	*I* (MSEK) – a=0,07	*I* (MSEK) – a=0,12
Case 1	HTL/G	0,15	17	245	148
Case 1	Pyrolysis	0,15	23	330	201
Case 2	Pyrolysis	0,35	52	740	447
Case 3	Pyrolysis	0,55	70	994	600
Case 4 Middle Sweden	Gasification	2,2	303	4330	2610
Case 4, Malmö	Gasification	2,2	263	3750	2260

It can be concluded that the estimated investment space for case 4 seems to in the same range as the given investment in the GoBiGas project, i.e. ~ 2000 MSEK, using the given investments of 1495 MSEK for the 20 $MW_{biomethane}$ plant and a scaling factor of 0.6.

For case 1-3, it is difficult to find any equivalent investment data to compare with. The latter is of course related to the fact that the availability of pyrolysis and HTL/G for biofuel production is significantly lower than for gasification. Another reason is a matter of scale. Recently, the investments in pyrolysis and HTL plants a 100 times larger than in the present case have been examined [82], but the large difference in scale makes a comparison difficult.

9.6 BIOFUEL PRODUCTION POTENTIALS

The total biofuel consumption by land vehicles in Sweden in year 2016 was approximately 12 Mt. The production of biofuels from sewage sludge is highest in case 4 (Table 10) but is still only 0,069 Mt/year which corresponds to some 0,6 % of the total. This figure probably does not vary a lot between regions since the total distances of transportation and the amount of sludge is directly dependent on the population. The corresponding biofuel potential of the region of Scania is 0,017 Mt/year, which is considered in case 3 (Table 10). 0,6 % may appear as a rather small fraction, but sewage sludge has this in common with many other biofuel sources. If electric vehicles become numerous the biofuel may be used for air and heavy land transportation. In that case, the use of fossil fuels for these purposes will decrease, and consequently, the fraction of biofuels will increase. In such a perspective, sewage sludge can be one of many sources that are combined and pyrolysed or gasified.

9.7 APPLICATION OF THE FINDINGS

The present findings show that thermal treatment of sewage sludge to produce biofuels may be economically plausible. Further analysis is needed to determine whether that is actually the case. The analysis points at knowledge gaps, such as the immaturity of some techniques and markets. The focus on sewage sludge was not given in advance but was rather an outcome of the analysis. However, determining factors may change, and make other sludge or other wet waste streams more interesting. A generic approach, in which an arbitrary waste stream is subject to analysis resulting in a suggested treatment method would be desirable. This could be in the form of a tool box, the schematic of which is given in Appendix E. The idea here is that the input is the properties of the waste stream in question, and that a chosen treatment method results in the tool box presenting a technical and economic result.

10 CONCLUSIONS

This project has investigated the techno-economic potential of thermochemically converting digestate from biogas plants for the production of biofuels and biochemicals. In the analysis, pyrolysis, gasification and hydrothermal treatment (HT) have been considered. The focus has been on digestate from WWTPs since this value chain can contribute to increased biofuel production at the same time as waste issues including handling of toxic heavy metals, hormones etc. are being solved. The main conclusions of the analysis are highlighted in the following:

- The economic analysis of variable costs and revenues shows that there is a significant room for investments for all three investigated thermochemical techniques (pyrolysis, gasification and HTL/G). This is true even when transportation cost for collecting digestate from regions such as Scania or the whole of Götaland and Svealand is taken into account.
- In the case of pyrolysis, the major contributions to the revenue are char and sludge reception (i.e. an avoided cost vs. the reference case), whereas the costs are dominated by the thermal drying.
- In case of gasification, more than 70 % of the revenues origins from CH_4 (in this case assumed to be the targeted biofuel product) and the rest from avoided sludge reception, whereas the composition of the costs is the same as for pyrolysis.
- In case of HTL/G, the revenue consists of about equal parts of bio-oil and sludge reception. The cost originates only from the heating, which is almost 4 times higher than is needed for pyrolysis and gasification because of 5 times more water. A substantial part of this heat could however most probably be recovered and could thereby reduce the cost for the heat net accordingly.
- The sensitivity analysis shows that when one variable at the time is varied, the largest impact is in the range of 20-30 % on the economic result. Even if the sensitivity of the parameter value is large, it does not seem to have any determining effect on the economic result and the given conclusions.
- From the perspective of the suggested value chains, biogas plants located nearby energy intensive industries such as pulp and paper or chemical industry holds a big advantage since the necessary with time non-variable low cost heat is at these locations generally available.
- Available in demonstration scale, gasification (including fuel upgrading to biofuel quality) is probably the fastest way forward to produce biofuels from digestate. Pyrolysis upgrading is still of pilot scale, whereas the equivalent for HTL/G is still in laboratory scale and which cost and performance data on larger scale are therefore still unknown.
- For gasification plants for biofuel production, sludge from very large areas needs to be collected in order to reach economic scale (1,2 Mt/yr equivalent to ~85 $MW_{biomethane}$). The sludge available in the most populated area of Sweden might therefore not be sufficient (0,4 Mt/yr). However, the estimation of economic scale is in this case given for wood-

based feedstock, so there may still be a positive net in the case of sludge gasification. Another alternative for reaching profitability is to consider co-gasification with woody biomass feedstock.

- Sewage sludge will not be the major substrate in the production of fossil-free biofuel but it may constitute an important contribution.
- The literature shows that pyrolysis of sewage sludge could be a technique for separating cadmium from phosphorus, which can then be recycled via bio-fertilization to agriculture. Ammonia nitrogen, however, is in this case to the largest extent dissolved in the water fraction that is removed upstream of the process and its nutrient value would therefore be lost by the suggested value chain.
- In case of gasification, the phosphorous ends up in char or bottom ash and it might therefore be possible to separate and recycle as nutrient to the agriculture. In the same way as in pyrolysis, the nutrient value of ammonia nitrogen is through the thermal drying process lost.
- There are indications in the literature that HTL/G of digestate from WWTPs might be a process for recovering both nutrients ammonia nitrogen and phosphorous to the farmland.

11 FURTHER WORK

Suggestions for further work are:

- A more detailed techno-economic study on gasification of digestate from WWTPs including investment costs.
- More R&D on pyrolysis upgrading and HTL/G for speeding up the development of the technologies to achieve techno-economic data on larger scale and later on reach commercial scale for biofuel and /or biochemical purpose.
- Further investigations on the environmental effects of the value chains considered in this project with focus on the nutrients in the digestate.

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APPENDIX A. DIGESTATE FROM CO-DIGESTION

The references in the appendices are given in footnotes.

Today, almost all digestate produced at co-digestion plants in Sweden is spread on farmland and utilized as a fertilizer. With few exceptions, the digestate is handled as a slurry with equipment otherwise used for liquid manure. The economic value depends e.g. on current market price for mineral fertilizers, the amount and composition of nutrients in the digestate and if it is approved as an ecologic fertilizer or not. Thus, it is difficult to give a general value. For conventional fertilizers, the market price used is 9 SEK/kg N, 20 SEK/kg P and 8 SEK/kg K, respectively.[1] For the digestates presented in Table 2 (report) and Table A1, the nutrient value as such would, with these prices, be 56 and 48 SEK/t digestate, respectively.

Table A1: Digestate composition at two of the larger co-digestion plants in Sweden.

	Helsingborg	**Kristianstad**
DM (%)	3,5	3.6
VS (% of DM)	62	69.4
NH4-N (kg/t)	3.8	3.1
N-tot (kg/t)	5.4	4.7
P (kg/t)	0.5	0.4
K (kg/t)	1.5	1.5
Pb (g/kg)	0.07	0.08
Ca (g/kg)	0.01	0.01
Hg (mg/kg)	1.1	0.9

If the digestate is to be used as feedstock in a thermochemical process, it is assumed that it is dewatered and that the solid fraction is transported to thermochemical conversion plant. For the co-digestion plant, this means that there will be an additional cost for dewatering and that some of the nutrients are removed with the solid fraction. Thus, the co-digestion plant should be compensated for the dewatering cost and the lost nutrient value.

Based on an estimation provided by Purac[2], the cost for dewatering is set to 12 SEK/ton wet weight. The assumed distribution of nutrients and dry matter are based on separation of manure and summarized in Table A2. For some parameters, the mass balance does not add up which according to LandbrugsInfo[3] is due to various uncertainties in collection and analysis of samples. For NH_4-N and P it is assumed that 90 % and 34 % respectively stays in the liquid fraction. Given this distribution of nutrients and the original digestate composition presented in Table A1, the value of the nutrients in the solid fraction is calculated to 120 and 100 SEK/t, respectively.

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[2] Cost estimations from Purac, 2017-02-01

[3] LandbrugsInfo (2017) Massbalance calculations for separation of manure, https://www.landbrugsinfo.dk/Tvaerfaglige-emner/Gylleseparering/Sider/Program_til_at_beregne_massebalancer_ved.aspx, visited 2017-11-27

However, given the fact that the volume of liquid digestate is reduced, the cost for spreading of the liquid digestate is also reduced. The cost for spreading is set to 20 SEK/t.[4] Here, it is assumed that the cost for the solid fraction could be reduced with the same amount.

Table. A2. Typical distribution of nutrients and dry matter in separated manure.

	Volume	Dry matter	NH_4-N	P	K
Liquid fraction	91 %	52 %	91 %	23 %	91 %
Solid fraction	9 %	48 %	10 %	66 %	9 %

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[4] Lantz, M., Kreuger, E. Björnsson, L. (2017) An economic comparison of dedicated crops vs agricultural residues as feedstock for biogas of vehicle fuel quality, AIMS Energy, 5(5): 838-863.

APPENDIX B. DIGESTATE TRANSPORT

Anaerobic digestion generates a digestate that in most cases needs to be transported away from the biogas plant. In general, the digestate is transported by trucks but there are also some examples where the digestate is pumped to sattelite storages. In this study, the digestate is transported by trucks.

TRANSPORT OF DEWATERED DIGESTATE

In this study, it is assumed that dewatered digestate has a DM content of 25 %. Thus, the digestate can be piled and handled as a more or less solid material. Trucks transporting dewatered digestate are assumed to be loaded with a loader. For unloading, the digestate is simply tipped of. Background data used to calculate the transportation cost is given in Table B1.

Table B1: Costs for transportation of dewatered digestate.[5]

	High	Low
Capacity	40 t	40 t
Loading and unloading		
- Time	0.5 h	1.0 h
- Loader	10 SEK/t	20 SEK/t
Hourly rate	1 000 SEK/h	1 000 SEK/h
Average speed	60 km/h	60 km/h

TRANSPORT OF LIQUID DIGESTATE

When liquid digestate is transported, it is assumed that it can be pumped and transported in a tank truck. Here, loading capacity is set to 35 ton and the time to load and unload is set to 20 minutes [4]. The hourly rate and the average speed is set to 1 000 SEK and 60 km/h respectively[5]. In the case of digestate transport only, no time for cleaning of the vehicle has been included. Assuming a one-way transport distance of 10 km would thus give a transportation cost of aproximately 20 SEK/t digestate.

TRANSPORT DISTANCE AND COST IN CASES 2 – 4

In this study, four different cases are presented where different amounts of digestate are converted in a thermochemical process. In cases 2 – 4, digestate is transported to the production plant from a number of different WWTP and some co-digestion plants. In cases 2 and 3, the production plant is located at Sjölunda in Malmö and the transportation distance is calculated by measuring the linear distance to each plant and multiply this distance with a tortuosity factor of 1.3 (see footnote 4). In case 4, the production plant is assumed to be located in Malmö and the distance was instead measured from the central station in each town. This approach was chooses of practical reasons but is deemed to have a minor impact on the result. The transportation cost is calculated based on the data given in Table B1.

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[5] Blad, M. (2017) Responsible for AGRO and the southern district at RagnSells, personal communication spring 2017.

Table B3: Calculated transportation distance and cost in Case 2.

Municipality	**Digestate (t)**	**Distance (km)**	**Transport cost (SEK/t)**	
			High	Low
Malmö (Sjölunda)	27 800	0		
Helsingborg	11 400	65	77	99
Lund	11 300	14	34	56
Eslöv	6 000	35	52	74
Landskrona	4 200	37	54	76
Malmö (Klagshamn)	3 900	19	39	61
Kävlinge	2 900	23	42	64
Average		**21**	**31**	**44**

Table B4: Calculated transportation distance and cost in Case 3 (Malmö).

Kommun	**Digestate (t)**	**Distance (km)**	**Transport cost (SEK/t)**	
			High	Low
Malmö (Sjölunda)	27 800	0		
Helsingborg	11 400	65	77	99
Lund	11 300	14	34	56
Eslöv	6 000	35	52	74
Landskrona	4 200	37	54	76
Malmö (Klagshamn)	3 900	19	39	61
Kävlinge	2 900	23	42	64
Co-digestion plants				
- Helsingborg	25 200	67	79	101
- Kristianstad	20 400	104	109	132
Average		**46**	**56**	**72**

Table B5: Calculated transportation distance and cost in Case 3 (Helsingborg).

Municipality	**Digestate (t)**	**Distance (km)**	**Transport cost (SEK/t)**	
			High	Low
Malmö (Sjölunda)	27 800	65	77	99
Helsingborg	11 400	0		
Lund	11 300	62	75	97
Eslöv	6 000	58	71	94
Landskrona	4 200	28	46	68
Malmö (Klagshamn)	3 900	76	86	108
Kävlinge	2 900	49	63	86
Co-digestion plants				
- Helsingborg	25 200	7	28	51
- Kristianstad	20 400	113	117	140
Average		**52**	**64**	**84**

Table B6: Calculated transportation distance and cost in Case 4 (location Malmö).

Municipality	**Digestate (t)**	**Distance (km)**	**Transport cost (SEK/t)**	
			High	Low
Stockholm	132 950	667	578	601
Göteborg	57 809	315	285	307
Hässleholm	32 142	101	106	129
Malmö	31 731	0	23	45
Västervik	22 211	425	377	399
Norrköping	12 755	500	439	461
Borås	12 119	306	277	300
Västerås	12 004	641	557	579
Uppsala	11 690	712	616	638
Helsingborg	11 402	68	79	101
Linköping	11 400	456	402	425
Örebro	11 313	558	488	510
Lund	11 300	21	40	62
Eskiltuna	9 439	609	530	552
Kristianstad	8 470	112	116	138
Halmstad	7 788	154	151	173
Växjö	6 689	235	219	241
Trollhättan	6 395	392	349	371
Eslöv	5 979	41	57	79
Kalmar	5 835	311	282	304
Jönköping	5 825	328	296	318
Karlstad	5 723	547	478	501
Skövde	5 507	408	363	385
Varberg	5 026	225	210	233
Average		**407**	**360**	**382**

APPENDIX C. LIST OF VARIABLES, DENOTATIONS AND UNITS

Table C1. List of variables, denotations and units, used in Chapters 6-8 in this report.

Variable	Denotation	Unit
Mass flow	$\dot{m}$	kg/s
Yield	y	-
Water content	w	-
Temperature	T	°C
Annual mass flow of digestate	M	kg/year
Cost	c	SEK/kg
Price	p	SEK/kg or J
Heat of vaporisation of water at 100 °C	H	J/kg
Heat capacity of water at 60 °C	C_p	J/kgK
Sum of costs	C	SEK/kg
Revenue	R	SEK/kg
Sensitivity	S	-
sensitivity factor	f	-
Investment space	I	SEK
Annuity factor	a	%/year
Indices		
Absolute	A	
Air	a	
Ash	ash	
Carbon monoxide	co	
Char	c	
Dewatered, Dewatering	dw	
Digestate	d	
From the system	out	
Gas	g	
Heat	$heat$	
Hydrogen	$h2$	
Methane	$ch4$	
Normalised	N	
Oil	o	
Relative	R	
Steam	s	
To the system	in	
Water	w	
Water treatment	wt	

APPENDIX D. LIST OF INPUT PARAMETERS FOR ECONOMIC ANALYSIS

Table D1. List of input parameters, and theirs sources, used for economic analysis described in Chapter 7 in this report.

Parameter	Value	Used value	Unit	Reference
c_{dw}	0,0124	0,0124	SEK/kg	Estimation by Purac
c_{wt}	0,00221	0,00221	SEK/kg	Average for WWTP with >10 000 person equivalents, [based on Svenskt Vatten's statistics]
p_{heat}	6,9444e-8	6,9444e-8	SEK/J	Calculated from 250 SEK/MWh, [Lantz, M., Kreuger, E. Björnsson, L. (2017), AIMS Energy, 5(5): 838-863.]
p_c	3,5		SEK/kg	The price of biochar certified for soil enhancement, [http://biokolsverige.se/]
	8,1		SEK/kg	Calculated from 1000 $/ton, [http://www.biofuelsdigest.com/bdigest/2017/06/08/biomass-pyrolysis-comes-of-age]
	11,6667		SEK/kg	Calculated from 1400-2000 SEK/m^3 and a density of 120 kg/m^3, [personal communication, Susanne Paulrud, RISE]
		3,5	SEK/kg	-
p_{ch4}	5,1388	5,1388	SEK/kg	Calculated from 0,20 SEK/kWh natural gas, [https://apportgas.se/pris/]
p_o	1,722		SEK/kg	Pyrolysis oil: calculated from estimated production cost, [https://www.energimyndigheten.se/contentassets/35c97a28c647407a853949188f3734dd/bjorn-kjellstrom-150506.pdf]
	1,63215		SEK/kg	Pyrolysis oil: calculated from 13$/GJ, [http://www.biofuelsdigest.com/bdigest/2017/06/08/biomass-pyrolysis-comes-of-age/]
	5,1516		SEK/kg	Pyrolysis oil: calculated from 0,53-1,45 $/l, [Anex et al. Fuel 89, 29-35, 2010]
	0,71325		SEK/kg	Pyrolysis oil: calculated from production costs, [http://www.eubia.org/cms/wiki-biomass/pyrolysis-and-gasification/pyrolysis/]
	0,50		SEK/kg	Pyrolysis oil, calculated from 690-900 €/15 ton, [personal communication Susanne Paulrud, RISE]
		1	SEK/kg	
	3,399		SEK/kg	Bio-oil: calculated from 10 £/GJ, [Rogers and Brammer, Biomass and bioenergy 36, 208-217, 2012]
	4,1		SEK/kg	Bio-oil: calculated from 80$/barrel.[http://breakingenergy.com/2011/08/26/biocrude-still-a-drop-in-the-barrel/]
	14,094		SEK/kg	Bio-oil: calculated from 0,53-1,45 $/l, [Anex et al. Fuel 89, 29-35, 2010]
		4	SEK/kg	-
p_s	0,3	0,3	SEK/kg [a]	Gruvberger, C. (2017) Department manager at VA SYD, personal communication summer 2017

APPENDIX E. TOOLBOX FOR A SUBSTRATE HANDBOOK

Among the 43 words added to the official Swedish dictionary at the end of year 2016 was – 'cirkulär ekonomi' or in English 'circular economy'. Circular economy is a concept where an attention is given to develop ways to minimize the waste at industrial level by employing one of the nine proposed strategies[6]. Through remanufacturing or repurposing, the waste could be transformed into the same or new products. Thus, yesteryears waste streams or low-value residual streams are today's feedstocks. To assist development for valorization of such residual streams a user-friendly handbook can be very handy. It can help 'a user' to assess the most applicable technology/process for a particular residual stream through technical, economical and perhaps even geographical perspective. 'A user' can be an independent entrepreneur, developer, researcher or an industry.

With the increasing attention to minimizing waste at domestic, municipal or industrial level, a number of interesting research and developmental projects are being undertaken under the umbrella of 'Circular Economy'. All such projects, currently ongoing or completed in recent past, will provide the data for the handbook. In its current iteration, the handbook is organized on three main levels (Figure E1). At first level, all the feedstocks are arranged by name. When a particular feedstock is chosen, the user will be presented with a short description about the feedstock, its composition, availability, current use, and alternative processes that can potentially valorize the feedstock. The user can there select any of the alternative processes and thus enter the second level with information about the application of that process to feedstock selected at the 1st level. Thus, at the 2nd level, the user will find a short summary of the process, its important process parameters, its current technology readiness level (TRL), and the main products. Here again, the user can select any product of interest and enter the 3rd level to find more information about a product.

In this project, digestate from anaerobic digestion was investigated. Techno-economic estimations were performed for its thermochemical conversion using combustion, gasification, pyrolysis or hydrothermal conversion to produce variety of products (Figure E1).

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[6] Kirchherr, J., Reike, D., & Hekkert, M. (2017). Conceptualizing the circular economy: An analysis of 114 definitions. *Resources, Conservation and Recycling*, *127*, 221-232.

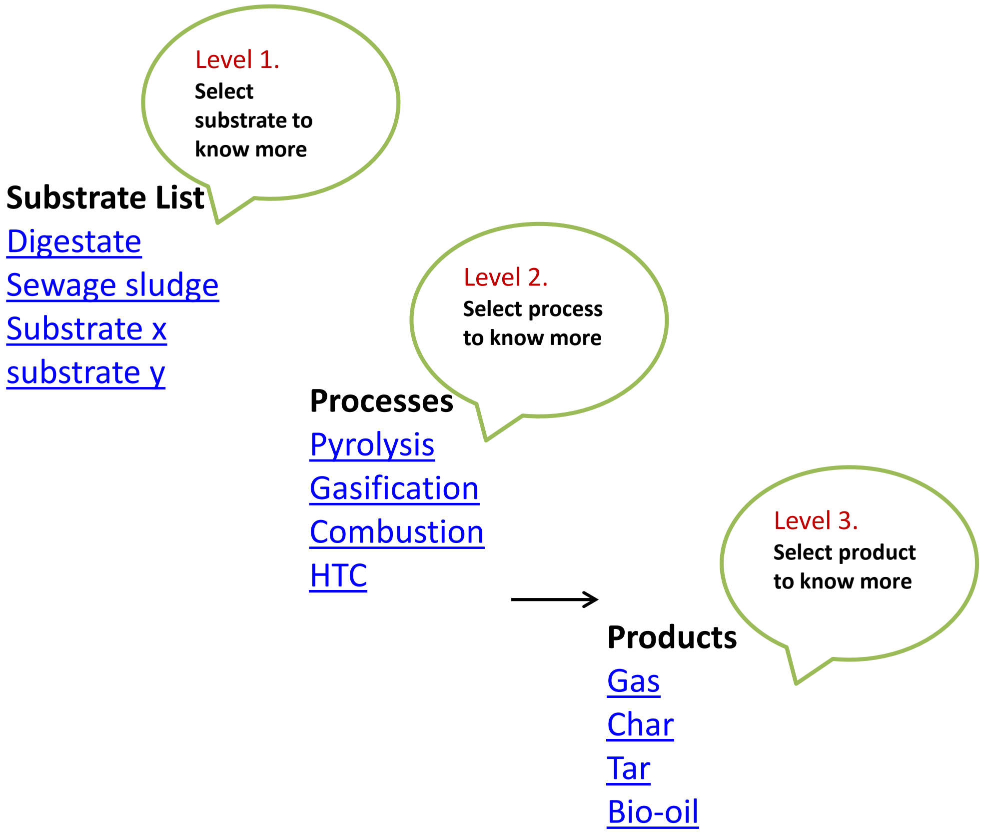

Figure E1. Schematic illustration of a structure for a new substrate handbook under development at RISE.

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