Application of micro-wave cracking technology in conversion of wastewater sludge to circular biofuels

A preliminary test-based study

July 2021

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Sammenfatning

Spildevandsslam kan effektivt omdannes til bio-olie, biogas og biokul igennem mikrobølge-cracking

Organic Fuel Technology A/S (OFT) har sammen med Aarhus Vand, AffaldVarme Aarhus, Aalborg Forsyning og Aarhus Universitet med støtte fra Aarhus Kommune gennemført en forundersøgelse af mulighederne for at anvende OFT-udviklet og -patenteret teknologi til at omdanne spildevandsslam til olie, gas og kul.

Stort potentiale i OFTs mikrobølge-teknologi til bearbejdning af organisk materiale

OFT-teknologien er en patenteret anvendelse af mikrobølger til at ”cracke”, dvs. nedbryde, lange organiske molekyler, som fx træmasse (lignin), cellulose, gummi (latex) og fedt (lipider) til mindre organiske molekyler som i olie, gas og kul.

OFTs teknologi er unik, fordi den i modsætning til andre teknologier ikke anvender varme eller tryk som den primære kraft til at omdanne lange organiske molekyler til kortere. I stedet skaber OFTs mikrobølge-reaktor et meget stærkt og hurtigt vekslende elektromagnetisk felt, som rykker molekylerne fra hinanden i kraft af at molekylerne er polære, dvs. har en negativ og en positiv pol.

Fra unyttigt affald til nyttige cirkulære bio-brændstoffer

Teknologien kan således anvendes til at omdanne mindre nyttige eller helt unyttige organiske materialer, fx affaldsprodukter, til mere nyttige og derved mere værdifulde materialer. Samtidig kan processen bidrage væsentligt til grøn omstilling, da processen fortrænger fossile brændstoffer og erstatter dem med CO2-neutrale biobrændstoffer, og forhindrer CH_4 og N_2O- udledning, hvilket ville blive genereret, hvis slammet på anden måde blev opbevaret og direkte anvendt på landbrugsjord.

Derudover har teknologien teoretisk flere fordele i forhold til andre, sammenlignelige teknologier: Der anvendes mindre energi til processen og den foregår ved lavere temperaturer. Slutprodukterne af processen kan derved forventes at have en højere kvalitet, da det organiske materiale er blevet udsat for en mere ”målrettet” og mindre energikrævende bearbejdning.

Teknologien kan anvendes til bearbejdning af slam

Forsøgene på OFTs pilotanlæg i Ødum har vist, at mikrobølgerne kunne bearbejde det tørrede slam fra Aalborg Forsyning både effektivt og sikkert. Det lykkedes at identificere gode indstillinger af anlægget, der kunne styre processen godt, og der blev gennemført 2 kørsler af 10 timers varighed. Ved den første kørsel (nr. 110), blev der gradvist skiftet fra at processere rester fra dæk til at køre med slam, for på den måde at omstille anlægget til at køre med slam. Ved den anden kørsel (nr. 111) blev der kørt med tørret slam (17,3% vand) fra start til stop for at teste kontinuert drift med slam, samt finde optimale procesparametre. Begge kørsler var meget stabile og derved blev det eftervist, at kontinuert drift for processen er mulig med spildevandsslam.

Ved kørslerne blev der foretaget automatisk dataopsamling med 1 sekunds interval fra en række målepunkter, og der blev foretaget omhyggelig afvejning af materialer. Der er også foretaget en række analyser af den dannede olie og gas og det dannede restprodukt fra kørsel 111 på Aarhus Universitet. Resultaterne ser særdeles lovende ud, men de bør suppleres med yderligere tests, dels for at få et bedre statistisk grundlag og dels for af optimere yderligere både på procesparametre, men også den efterfølgende håndtering af produkterne. Forsøgene var så vellykkede, at det kan konkluderes, at det med OFTs teknologi er muligt at bearbejde slam.

Særdeles god energiomdannelse

Forsøgsresultaterne har eftervist, at teknologien kan fremvise en særdeles god masse- og energibalance. Den beregnede massebalance viser, at 27% af tørstoffet i slammet blev omdannet til olie med højt energiindhold, mens 22% blev til gas. Analysen af energibalancen tyder på, at energiindholdet i tørret, udrådnet slam formentlig hidtil har været undervurderet. I projektets analyse af energibalance har det således vist sig nødvendigt at antage et energiindhold i slammet på 18,02 MJ/kg for at analysen ikke skulle resultere i en energieffektivitet på over 100% (hvilket ville være en evighedsmaskine!), jf. afsnit 5.2. Dette er et klart højere energiindhold end blot brændværdien af slammet, som af Aalborg Forsyning måles til 11,7 MJ/kg.

Samlet set indikerer resultaterne, at mikrobølge-cracking er en særdeles effektiv teknologi til at udvinde energi af tørret slam, og at slam i fremtiden kan blive en vigtig kilde til klimavenligt brændstof.

Energibalance for testkørsler 110 og 111 på pilotanlægget samt energibalance for drift af pilotanlæg og kommende fuldskalaanlæg under antaget optimerede betingelser.

	PILOTANLÆG TEST 110 15% VAND		**PILOTANLÆG TEST 111 17,3% VAND**		**PILOTANLÆG OPTIMEREDE BETINGELSER: 5% VAND**		**NYT ANLÆG OPTIMEREDE BETINGELSER: 5% VAND**	
PROCESKAPACITET [KG/TIME]	23,67		19,67		40,00		400,00	
ENERGI TIL PROCES 1 TON [GJ]	**4,87**		**5,86**		**2,88**		**1,80**	
INVESTERING	kW	%	kW	%	kW	%	KW	%
ELECTRICITET MIKROBØLGE	16	11%	16	13%	16	7%	120	6%
ELECTRICITET ANDEN PROCES	16	11%	16	13%	16	7%	80	4%
SLAM, ZEOLIT OG NITROGEN	113	78%	94	75%	191	86%	1908	91%
ENERGI IND TOTAL	**145**	**100%**	**126**	**100%**	**223**	**100%**	**2108**	**100%**
GEVINST	kW	%	kW	%	kW	%	KW	%
OLIE (27,07% OG 37MJ/KG)	66	45%	55	43%	111	50%	1113	53%
GAS (22,14% OG 9,41MJ/KG)	12	9%	10	8%	21	9%	209	10%
KUL (50,79% OG 10,4MJ/KG)	35	24%	29	23%	59	26%	587	28%
ENERGI UD TOTAL	**114**	**78%**	**95**	**75%**	**197**	**86%**	**1931**	**91%**

Beregningerne her er baseret på cracking af tørret og udrådnet slam fra Aalborg Forsyning (anaerobt udrådnet slam har været igennem bearbejdning og afgasning i biogasanlæg). Det er ikke usandsynligt, at der kan opnås endnu bedre resultater med ikke-udrådnet slam.

Der skal anvendes energi til tørring af slammet, men selv hvis der tages højde for dette, viser energiberegninger, at anlæggets samlede effektivitet på energibalancen kun vil falde med 8 procentpoint.

- og langt bedre end i andre teknologier

Analyserne peger samlet på, at OFTs mikrobølgeteknologi er overlegen på flere parametre i forhold til en alternativ teknologi til behandling af slam, pyrolyse, jf. Appendix A. Pyrolyse anvender således mere energi per processeret ton materiale end OFTs teknologi, og - ud fra tilgængelige oplysninger - frembringer pyrolyse klart mindre energi i processen end OFTs teknologi. Dette kommer til udtryk i driften af pyrolyseanlæg, hvor alt produceret olie/gas bliver anvendt til at drive processen, hvorefter der produceres kul. I OFTs anlæg vil alt kul og gas kunne bruges til at drive tørring, hvorefter produktet bliver olie, hvilket er en mere energitæt type brændstof. Ovenstående konklusion er dog for indeværende forbundet med mange usikkerheder, da meget få oplysninger fra pyrolysebearbejdning af slam er offentligt tilgængelige.

Olie og gas er af brugbar kvalitet og kan oparbejdes

Olien, som produceres i mikrobølge-crackingen, kan klassificeres som bio-cirkulær olie med en målt brændværdi på mellem 31,2MJ-32,3MJ per kg. Hvis vandet fjernes i olien, vil man opnå cirka 37 MJ/kg HHV på tørbasis svarende til andre bioolie. Olien indeholder vand og en smule aske, der sænker kvaliteten, men det forventes, at den kan anvendes med stor værdi for kraftvarmeværker eller til iblanding i bunkerolie. Der er gode muligheder for, at olien på lidt længere sigt kan opgraderes til gældende bioolie-standarder. Gassen har en nedre brændværdi på 7,4GJ/kg og kan sælges som biogas eller anvendes som procesenergi til nærliggende processer.

Bio-kul med god brændværdi og godt potentiale

Beregningerne ud fra test-kørslerne viser, at der vil genereres godt 500 kg kulholdigt restprodukt i bearbejdningen af 1 ton tørret slam. Det forventes, at dette restprodukt i første omgang vil blive brugt som biobrændsel, da det brænder ligesom koks (dog med lavere brændværdi på HHV 10,4 MJ/kg.

På sigt kan restproduktet dog formentlig finde anvendelse som bio-kul. Det betyder, at det kan spredes på marker og derigennem recirkulere næringsstoffer og binde kulstof til jorden (carbon capture). Der er et stort udviklingspotentiale i anvendelsen af bio-kul, men undersøgelsens analyser af økonomi og miljøeffekter er ikke baseret på dette potentiale.

Tilbagebetalingstid på mellem 3 og 7 år med forsigtige antagelser

Det forventes, at Organic Fuel Technology kan levere det kommende OFT8 anlæg for en pris på 12 mio. kroner. Afhængigt af, om det enkelte rensningsanlæg allerede har etableret processer til tørring af slam, kan der desuden være behov for at etablere et tørringsanlæg, hvorved den samlede investering kan estimeres til ca. 20 mio. kroner. Der vil dog både med og uden tørringsanlæg være en tilbagebetaling på mellem 3 og 7 år.

Med de givne antagelser (vigtigst en oliepris på mellem 5 og 9 kroner per kg [1] og en betaling for behandlingen af slam på mellem 300 og 400 kr. per ton) vil det samlede anlæg generere mellem godt 3 og godt 10 mio. kroner i driftsoverskud om året. Dette betyder, at investeringen i det samlede anlæg er betalt tilbage på 3-7 år, og at det har en negativ cost of ownership over 15 år på mellem 27 og 130 millioner kroner. Dette indeholder generelle driftsudgifter, vedligehold og lønninger.

Analysens usikkerhed knytter sig blandt andet til den endelige proceskapacitet af et kommende fuldskala OFT8 anlæg. Analysen ud fra forsøgene i nærværende projekt resulterede i et meget konservativt estimat

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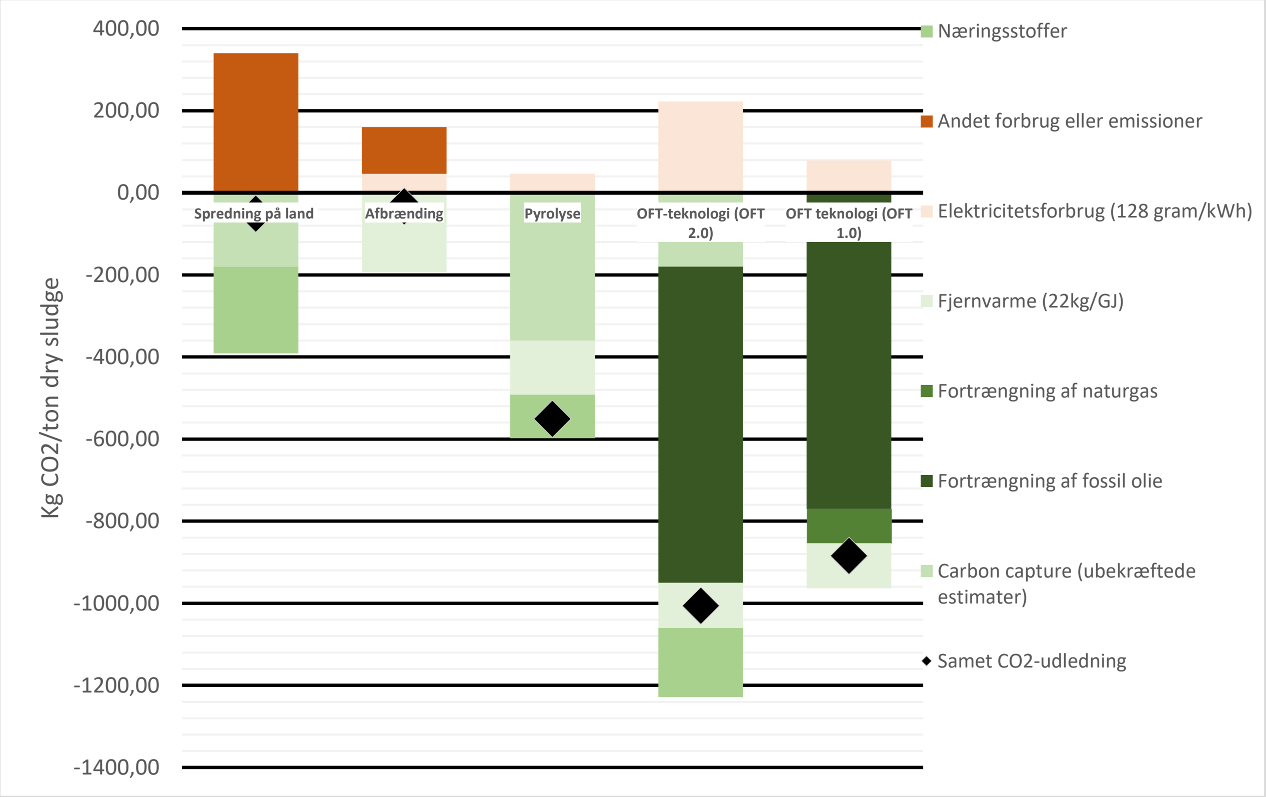
for årlig behandlingskapacitet på 2.080 ton tørret slam per år, men også mere realistiske bud på 2.500 og 3.000 ton om året, alt efter hvilke antagelser om vandindholdet i det tørrede slam, der opereres med. Selv i det meget konservative estimat er de økonomiske fordele ved OFT-teknologien betydelige.

Store CO2-besparelser til gavn for klimaet

Analysen af miljøeffekter ud fra test-kørslerne indikerer store CO2-besparelser ved at gøre bruge af OFTs mikrobølgeteknologi sammenlignet med nuværende løsninger og konkurrerende teknologier.

I den første og tidligste version af fuldskalaprocessen (kaldet OFT 1.0) bruges det skabte kulholdige restprodukt til at drive tørringen igennem afbrænding, mens der i næste generation af fuldskalaanlægget (kaldet OFT 2.0) anvendes overskydende el fra vind og sol til at drive tørreprocessen. Dette frigiver kul, som dermed (forudsat at oparbejdning og regulering er på plads) kan anvendes som gødning med iboende carbon capture.

I begge tilfælde er der markante CO2-besparelser at hente, jf. figuren nedenfor, primært fordi OFT-teknologien anvendt på spildevandsslam frembringer cirkulær bio-olie og bio-gas, som kan fortrænge afbrændingen af ikke-cirkulære fossile brændstoffer ved anvendelse i fx transportsektoren.



Sammenlignende CO2-analyse af forskellige løsninger og teknologier til slamhåndtering og -bearbejdning.

Summary

Wastewater sludge can efficiently be converted into bio-oil, biogas, and biochar through microwave-cracking

Together with Aarhus Vand, AffaldVarme Aarhus, Aalborg Forsyning and Aarhus University, Organic Fuel Technology A/S has carried out a preliminary study of the conversion of wastewater treatment sludge to oil, gas and coal with the OFT-developed and OFT-patented technology.

Significant potential in OFT's microwave technology for treatment of organic material
The OFT technology is a patented application of microwaves to "crack", i.e. break down, long organic molecules, such as tree (lignin), cellulose, rubber (latex) and fat (lipids) to smaller organic molecules such as oil, gas, char or coal.

OFT's technology is unique, as it - opposed to other technologies – neither applies heat nor pressure as the primary driver to convert long organic molecules to shorter molecules. Instead, the OFT's microwave reactor creates a very strong and rapidly changing electromagnetic field which pulls the molecules apart as an effect of their polarity.

From useless waste to useful circular bio-fuels
Thus, the technology can be applied to convert less useful or completely useless organic material, eg. waste products, to more useful and thus more valuable materials. At the same the process can contribute significantly to green conversion, as the produced bio-fuels displace fossil fuels and replace them with CO_2-neutral bio-fuels, while preventing CH_4- and N_2O-emissions, which would be generated if the material is otherwise stored and directly applied to land.

In addition, the technology has several other advantages seen in relation to other, comparable technologies: Less energy is consumed in the process and it takes place at lower temperatures. It is therefore to be expected that the end products of the process will be of a higher quality, as the organic material has been subject to a more "targeted" and less energy consuming treatment.

The technology is applicable to the treatment of sludge
The test runs at OFT's pilot plant in Ødum has demonstrated that microwaves can treat the dried sludge delivered from Aalborg Forsyning both efficiently and safely. Good process parameters for the plant, that could control the process well, were identified, and 2 test runs of 10 hours duration were carried out. During the first test run (no. 110) a gradual shift was carried out from running granular rubber waste to running sludge. This was done to adjust the plant to processing sludge. In the second test run (no. 111) sludge was processed throughout the test. Both test runs were very stable thus providing evidence that continuous processing is possible also with wastewater sludge.

During the test runs data were automatically collected with 1 second intervals from a range of measuring points, and material were weighted thoroughly. In addition, a number of analyses of the produced oil, gas and char from test 111 was carried out at the University of Aarhus. The results look very promising, but they should be supplemented with additional tests, both to improve the statistical foundations of the study and to optimize the process further to better handle the output products afterwards. The test runs were so successful that it is safe to conclude that it is practically feasible to carry out sludge treatment with the OFT technology.

Very good energy conversion

The test runs have demonstrated that the technology displays very good energy- and mass-balances. The calculated mass balance shows that 27% of the dry matter in the sludge was converted to oil with a high energy content, while 22% were converted to gas. The analysis of the energy balance suggests that most likely the energy content of dried, digested sludge has until now been underestimated. Thus, in the project's analysis of the energy balance it was necessary to assume an energy content in the sludge of 18,02 MJ/kg to avoid that the analysis resulted in an energy efficiency of above 100% (which would be a "perpetuum mobile"!), cf. section 5.2. This is a significantly higher energy content than solely the calorific burning value of dried sludge, which by Aalborg Forsyning is measured to an average of 11,7 KJ/kg.

In total, the analysis of energy- and mass-balance suggest that in the future, sludge may become an important source of climate friendly bio-fuels.

Energy balance for test 110 and 111. The data form these tests where extrapolated to optimized conditions, i.e. water content of 5%, for both pilot plan and the future full-scale plant.

	PILOT PLANT TEST 110 15% WATER		**PILOT PLANT TEST 111 17.3% WATER**		**PILOT PLANT OPTIMISED CONDITION: 5% WATER**		**NEW PLANT OPTIMISED CONDITION: 5% WATER**	
PROCESSING POWER [KG/HOUR]	23.67		19.67		40		400	
ENERGY, PROCESS [GJ/TON]	4.87		5.86		2.88		1.80	
INVESTMENT	KW	%	KW	%	KW	%	KW	%
ELECTRICITY MICROWAVE	16	11%	16	13%	16	7%	120	6%
ELECTRICITY OTHER PROCES	16	11%	16	13%	16	7%	80	4%
INPUT MATERIAL 17.17 MJ/KG	113	78%	94	75%	191	86%	1908	91%
ENERGY IN TOTAL	**145**	**100%**	**126**	**100%**	**223**	**100%**	**2108**	**100%**
OUT TO RETURN	kW	%	kW	%	kW	%	KW	%
OIL (27.07% AND 37MJ/KG)	66	45%	55	43%	111	50%	1113	53%
GAS (22.14% AND 8.51MJ/KG)	12	9%	10	8%	21	9%	209	10%
CHAR (50.79% AND 10.4KJ/KG)	35	24%	29	23%	59	26%	587	28%
ENERGY OUT TOTAL	**114**	**78%**	**95**	**75%**	**197**	**86%**	**1931**	**91%**

These results are based on the treatment of dried digested sludge from Aalborg Forsyning (digested sludge has been through treatment and digestion in bio-gas plants). It is not unlikely that even better results can be achieved by processing non-digested sludge.

The energy balance was made for dried sludge and the water removal process to obtain a water content of 5% or lower does consume a significant amount of energy. An energy analysis for the drying process was conducted and is found in section 6.4. This analysis shows that the gas and char generated by microwave cracking can provide the energy needed for drying process while converting the energy used to more than 80% district heating. This will decrease the overall efficiency of the OFT microwave cracking process with about 8 percentage points.

- and far better than in other technologies

The analyses indicate that in relation to several parameters, OFT's microwave technology is superior compared to an alternative technology for sludge treatment: pyrolysis, as seen in appendix A. Pyrolysis thus applies more energy per ton of processed material than is the case for OFT's technology. Based on available information – pyrolysis generates less energy in the process as is the case with the OFT technology. This is reflected in the fact that pyrolysis plants use all produced gas and oil in the process, and produce char, whereas OFT are able to use all char and gas to produce oil, which is a more dens type of energy. The above conclusion is, however, surrounded by significant uncertainties, as publicly available information on the process and results of pyrolysis treatment of sludge is rather limited.

Oil and gas of a useful quality

The generated oil can be classified as bio-circular oil with a calorific value of 31.2-32.3MJ/kg. If the water is removed, the calorific value would increase to 37MJ/kg. The oil contains water and some ash, which lowers its quality, but it is expected that it can be utilized with considerable value in heat-power plants or as an addition to bunker oil. In the longer term, there a good opportunities that the oil can be upgraded to applicable bio-oil standards. The gas has a low-end calorific value of 7.4MJ/kg and can be sold as biogas or used as processing energy at nearby facilities.

Bio-coal with good fuel values and a good potential

The test runs indicate that a little more than 500kg of coal-containing char product will be generated in the processing of 1 ton of dried sludge. In the short term, it is expected that this material will be used as biofuel, as burns in ways similar to coke (however with a lower calorific value of 10.4MJ/kg HHV).

In the longer term, the char can probably be utilized as bio-coal. This means that it can be applied to land and in this way re-circulate nutrients and tie carbon to earth (carbon capture). There is a considerable development potential in the utilization of bio-coal, but the analyses of economy and environmental effects in the present report are not based on these potentials.

Pay-back time of 3 to 7 years based on conservative assumptions

It is expected that Organic Fuel Technology can make the future OFT8-plant available for a price of mDKK 12. Depending on whether the specific wastewater treatment plant has already established procedures for water removal from sludge, there will be a need for an additional investment in water-removal equipment. If this is the case, the total required investment will amount to approximately mDKK 20. Both with and without the drying facility, the return of investment will be in 3 and 7 years.

With the given assumptions (most importantly an oil price of between 5 and 9 DKK/kg [1] and a payment for sludge treatment of between 300 and 400 DKK/ton), the total plant will generate between mDKK 3 and mDKK 10 in yearly operating profits. This means that the investment in the total plant including drying will be paid back in 3 to 7 years, and that there is a significant negative cost of ownership over a 15 period of between mDKK 27 and mDKK 130. This includes daily operation expenses, maintenance and salaries.

The uncertainties of the analyses are primarily related to the final processing capacity of the coming OFT8-plant. The results from the test runs resulted in a very conservative estimate of a yearly processing capacity

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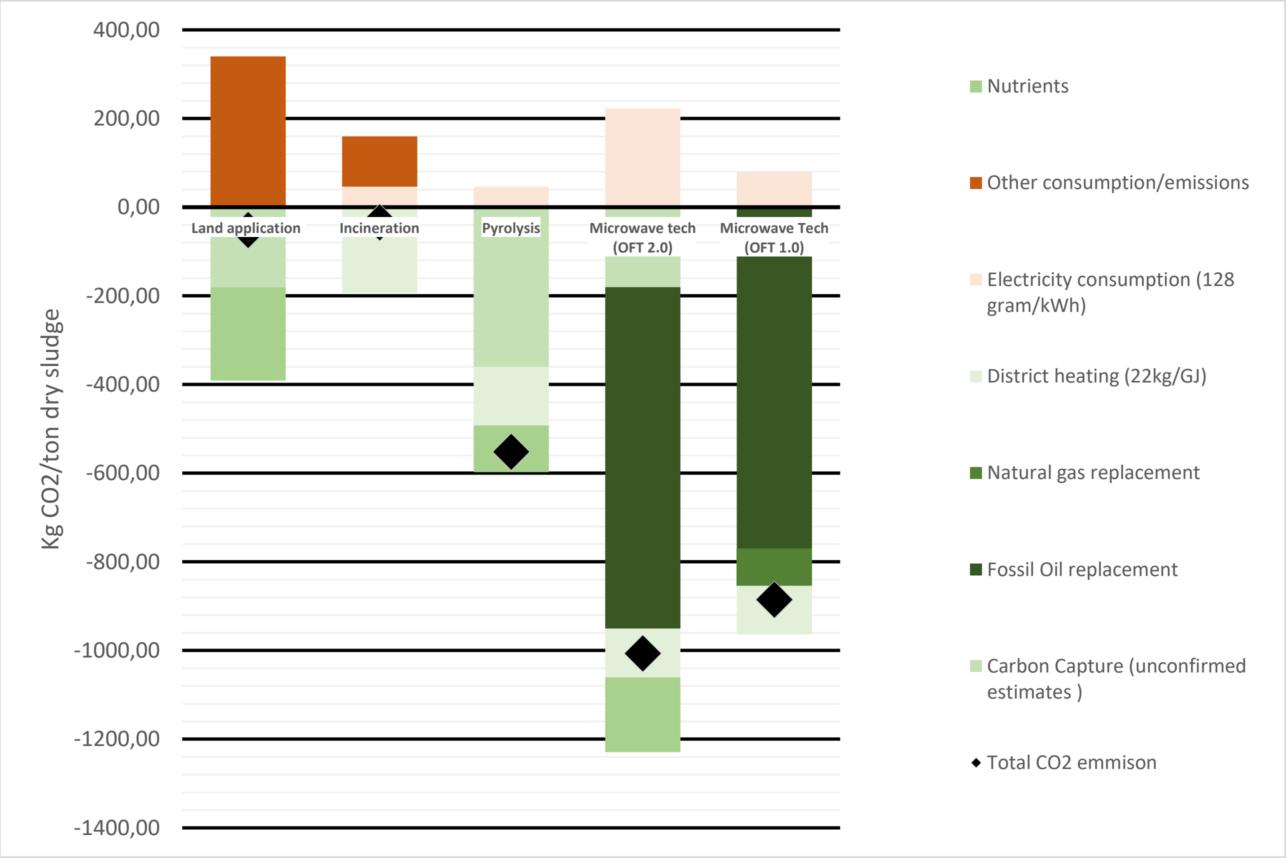
of 2,080 tons of dried sludge per year, but also in more realistic estimates of 2,500 and 3,000 tons per year, depending on the assumptions that are applied regarding the water contents of dried sludge. Even if the most conservative estimate for processing capacity is applied, there significant economic benefits ensue from utilizing the OFT technology.

Significant reductions in CO_2-emissions mitigating climate change

Based on the test runs the analysis of environmental impacts indicates that there are significant CO_2-savings to be made by applying OFT's microwave technology compared to existing solutions and competing technologies.

In the first phase of the full-scale application of the technology (named OFT 1.0), the coal-containing char-product is assumed to be utilized to drive the water removal process through incineration. In the next generation of the full-scale technology (named OFT 2.0) surplus wind and solar power as assumed to drive the water removal process. Assuming that refinement processes and the necessary regulation are in place, this makes it possible to apply the coal- and nutrient-containing material as fertilizer with carbon capture in land application.

In both cases, significant reductions in CO_2-emissions can be achieved, cf. the figure below. This is so primarily because when applied to sludge, the OFT-technology generates circular bio-oil and biogas, which displaces non-circular fossil fuels, for instance when applied in the transportation sector.



1. Background

For many years the primary goal for municipal wastewater treatment plants has been the handling and cleaning of wastewater from cities and agriculture. This ensured healthy cities with minimal sickness and thus enabled cities to grow larger without polluting the local environment in hazardous ways.

Now, the world is looking for new technologies that can enable our wastewater treatment plants to take a giant leap forward from being a major energy consumer to a green energy supplier and a producer of valuable nutrients and raw materials.

Aarhus Vand is trying to move forward on both the cleaning and useability of wastewater to produce the most efficient wastewater treatment solutions of the future [2]. The utility is aware that new innovative technologies are needed to achieve this goal and is therefore a major partner in the new Water Valley initiative in Aarhus where wastewater technologies will be developed for new wastewater treatment plants around the world.

Organic Fuel Technology A/S has developed a technology that could prove efficient and groundbreaking in turning sludge into valuable resources in the form of oil, gas and sterilized nutrient-rich biochar. The technology is already developed and tested on various feedstocks. Therefore, this project is solely carried out to test the developed technology in sludge to bioproduct conversion.

Important technology parameters must be found including, but not limited to; (i) Mass and energy balance, (ii) process capacity, (iii), bioproduct quality, (iv) economic feasibility, (v) environmental benefits and impacts, and (vi) comparison with other solutions.

The project is a collaboration between Aarhus Vand, Aarhus AffaldVarme, Aarhus University, and Organic Fuel Technology. The project is funded with 250,000DKK by Aarhus Municipalities “Den grønne investeringspulje” (Green Investment Fund). Aalborg Forsyning is an external project partner and provided dried sludge and dried sludge analysis for the project.

Aarhus Vand’s role in the project is a sparring partner. They have throughout the project provided valuable end-user feedback, sludge data, information about current sludge handling, and knowledge about local and global environmental conditions.

2. OFT’s microwave technology

The energy technology that will be used and analyzed in this project is the advanced microwave pyrolysis technology that has been developed and patented by Organic Fuel Technology A/S.

Organic Fuel Technology A/S has finished the development of its patented microwave pyrolysis reactor. This reactor can efficiently and at low temperatures, convert polar materials to oil, gas, and char. The process has been developed to convert rubber from used tires or artificial turf but has recently shown great promise in biomass conversion. Especially by converting lignin, cellulose and fat to oil, gas, and char as seen in Figure 1.

Figure 1 – Basic principle of the OFT process

The technology uses microwaves to generate a high field strength in the reactor that heats and cracks polar materials into long nonpolar carbon chains also known as oil. Microwave heating offers a number of advantages over conventional heating such as: (i) non-contact heating; (ii) energy transfer rather than heat transfer; (iii) higher heating rate; (iv) material selective heating; (v) volumetric heating; (vi) quick start-up and stopping; and (vii) heating from the interior of the material body [3]. This in turn gives the material a higher heating rate that in turn favors oil production [4]. In addition to heating rate, the microwaves appear to also influence product quality and catalyze conversion, with preliminary data on OFT products, indicating reactions proceed at 350 ºC which would otherwise proceed at far higher temperatures (650 ºC). Furthermore, the properties of microwave pyrolysis oil were slightly different from conventional pyrolysis oil, with higher carbon content, lower oxygen contents and higher heating values reported [5].

The technology works in two ways. Firstly, the pre-heated material is further heated to optimal processing temperature, using a refined dipole heating method, like that used in a household microwave. This provides an efficient and quick way of heating materials and therefore provides fast processing times. See Figure 2.

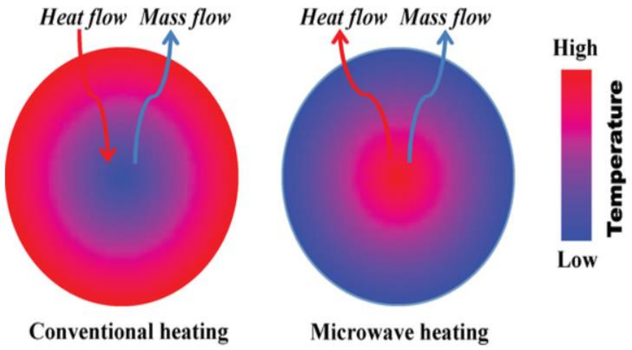


Figure 2 – The basic principle of microwave heating. Zhang, Y.; et al; Microwave-assisted pyrolysis of biomass for bio-oil production. In Pyrolysis Intech Open: London, UK, 2017; pp. 129–166

Traditional microwaves randomly and uncontrollably spread out the waves inside the oven. This is where the OFT technology differs. OFT has developed a reactor, that besides heating, sends the microwaves in a single mode into the reactor and thereby creates a constantly changing electromagnetic field. The reactor design is amplifying this field to provide the highest field strength and electromagnetic power possible. This is why the OFT technology can process lignin, cellulose, and fat at 350°C and not 650°C used in competing technologies. See Figure 3.

Since the microwaves generate a high field strength the technology relies on the polarity of the molecules to ensure the microwave power will process the material.

Organic Fuel Technology A/S has already developed the microwave technology from a laboratory scale to a pilot plant capable of

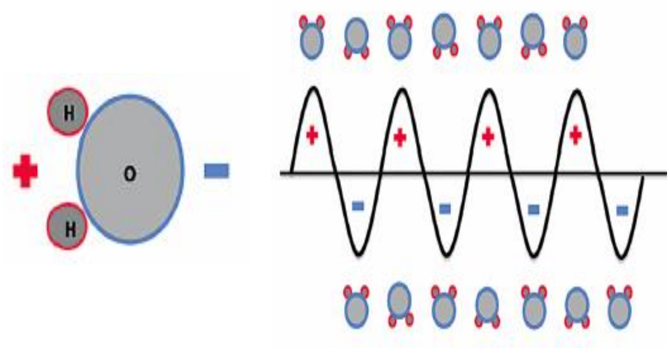


Figure 3 – A changing electromagnetic field can rotating a water molecule

continuously converting 50kg of feedstock per hour. Originally developed to depolymerize rubber in car tires and artificial turf OFT has now adapted the process for biomass conversion to produce renewable liquid fuels and biochar for carbon sequestration. A particular renewable source of interest is sludge from wastewater treatment plants. This sludge is at present of very limited value but contains important nutrients including potassium, calcium, and phosphorus, which, in the interests of a circular economy, require reuse.

Direct application of sludge to land may under certain circumstances be problematic due to active bacteria, virus, pharmaceutical products, persistent organic pollutants, and microplastics present within the sludge. The OFT microwave pyrolysis may offer a solution, destroying such pollutants while creating a renewable liquid fuel and nutrient-rich biochar free of these pollutants and not creating further pollutants in the process.

Biochar intended for soil application must fulfill certain properties and compositions, to prevent harm to the ecosystem [6]. These properties induce the degree of graphitization and threshold values for contaminants (including polycyclic aromatic hydrocarbons (PAH), heavy metals and dioxin) and contaminant analyses is an important part of certification. Dioxin and PAH formation are temperature dependent and often produced at 550 ºC pyrolysis temperatures [7]. The lower processing temperatures, around 350 ºC, brought about via OFT microwave technology should minimize PAH and dioxin formation, although it remains unclear to what extent.

Heavy metals would most likely stay in the char, due to the lower temperature in the reactor. From studies it is found that most of the heavy metals (Cr, Ni, Cu, Zn, Pb) are non-volatile in temperatures under 705°C, and thereby won't enter a gaseous state in either OFTs technology or pyrolysis. It is stated that, it is an advantage not to get heavy metals evaporated, thus it is difficult to remove them in a gaseous state. Cd will be non-volatile at temperatures under 600°C, and Hg under 350°C. There is a possibility, that Hg undergoes evaporation at lower temperatures, and it could maybe be an advantage to remove it earlier in the process, before the sewage sludge enters the microwave reactor [8] Another experiment has also been conducted, where the heavy metals is removed from the char at 800°C [9].

2.1. The OFT pilot plant

The pilot plant consists of one patented 10kW continuous microwave reactor system, a semi-continuous feeding system, two condensers for continuous oil extraction, one gas burner, and one batch container for char collecting.

Work on the pilot plant commenced in 2013 based on research and small lab-scale experiments. From the outset, requirements for a subsequent scale-up to an industrial scale plant were taken into account.


Figure 4 – Pilot plant, located in Ødum, Denmark.

Pilot plant development and optimalization was completed several years ago and since then a large number of experiments and test runs have been conducted to build up knowledge and establish the best possible platform for subsequent design and construction of an industrial-scale plant.

Pilot plant design concept

The reactor design is based on over 200 microwave simulations to optimize the electromagnetic field strength in the reactor and thereby its processing capability. The simulations and laboratory experiments pointed to an optimal reactor design module and one of these modules is today installed in the pilot plant.

The innovative microwave infeed system of the pilot plant is also highly optimized. It is airtight which ensures that all materials including gas and particles remain inside the reactor while allowing, with minimal losses, that single mode microwaves enter the reactor.


Figure 5 – Oil sampling from condenser 1

The material input and output are, from a reactor and process point of view, continuous.

To limit required development work in later stages the team went from batch-based laboratory tests to continuous operation in the pilot plant.

Continuous operation offers several advantages over batch-based technologies including a better energy balance, increased efficiency and lower operational costs. The continuous operation is secured by adding batches feeding into continuous infeed system. The resulting oil and gas are cooled and extracted from the plant, while for safety reasons the char is cooled in a batch-based container. The pilot plant’s container size limits the plant to 10 hours of operation, this being the only pilot plant parameter that limits duration of each test run.

The pilot plant operation has been proven on various rubber and biomass-materials. It is fully equipped with sensors and data logging to ensure not only correct processing, but also to gain processing knowledge.

Oil extraction and oil sampling is done at five different locations. Besides the four locations seen in Figure 6, oil can also be extracted at the filter unit.

However, more than 100 test runs have only shown small differences in the oil from the five sampling points and for the present project, the plant will only have one extraction point.

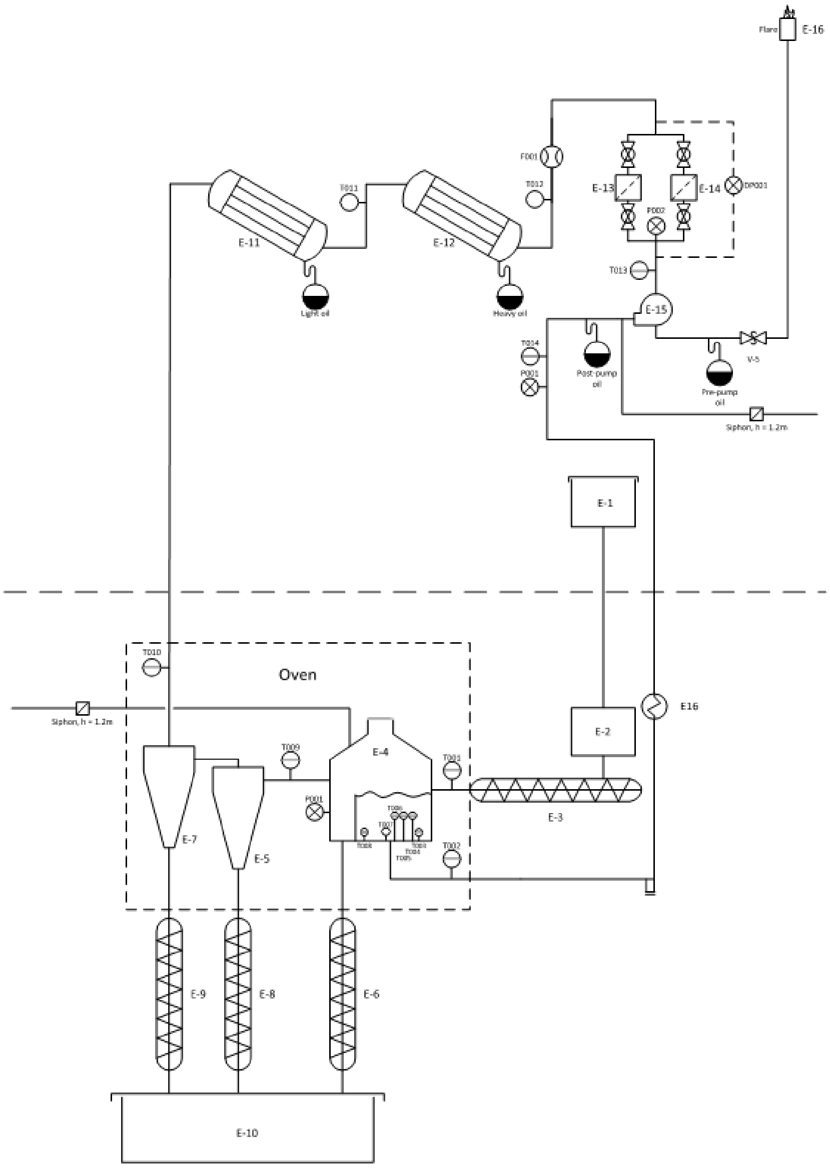


Figure 6 – PI diagram of the pilot plant.

2.2. OFT8 – a design for a full-scale plant

Based on extensive pilot plant development work, Organic Fuel Technology A/S has designed a full-scale waste processing plant (OFT8). The design work has been assisted by the fact that since an optimal reactor design is contained in the pilot plant, a scale-up can be done by doubling the power density in each module and by adding more modules. The test results, knowledge, design, and experiences from the pilot plant reactor have thus be used directly in the design of a full-scale commercial plant.

The new plant, illustrated in Figure 7, is based on an 8-reactor module system that is made ready for easy production and is easily scalable. The cooling and char extraction unit is designed to enable continuous operation for 25 to 28 days at the time.

The plant consists of:

- 8 reactor modules that have been further optimized. Each is fitted with one microwave infeed system.
- Continuous infeed system
- Continuous oil cooling and extraction
- Continues gas cooling and extraction
- Continuous char cooling and extraction
- Filtration systems for increased oil quality
- Energy from cooling is used to heat input material to increase process capability
- Sensor and data collection system to optimize control parameters.

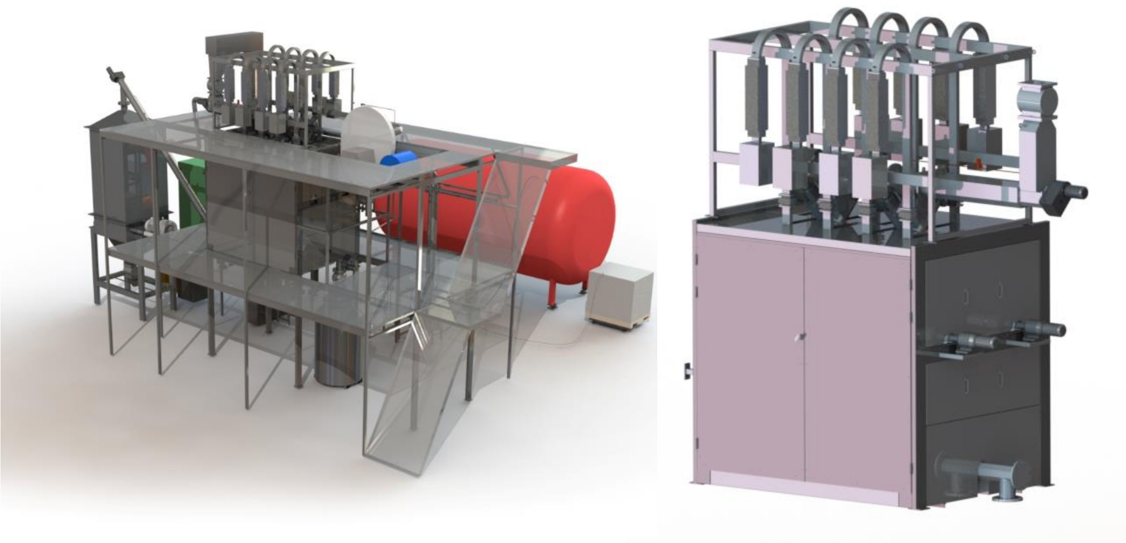


Figure 7 – Showing the design of OFT's first commercial plant. On the right side, the OFT8 module, which can be mass produced, is shown. Its dimensions in meters are 4.1 (H) 2.45 (L) and 1.95 (W). On the left side, the OFT8 module is seen embedded with all the required proximity systems.

3. Experiments and tests with sludge

To test the described theory and technology with sludge, two tests were conducted at Organic Fuel Technology's microwave pilot plant. The first to determine if sludge can be processed in the microwave reactor, and the second to observe long term processing of sludge, while optimizing the process conditions.

3.1. Test 110: adaptation to sludge processing

When a new material is introduced into the OFT system a run-in test is conducted. Even though the reactor and operational systems don't change with material feedstock, the system's behavior and processing parameters do change. Therefore, care must be taken before adding new material to the reactor.

Goal

The goal of this test was to optimize set-up of the plan gradually to change from a known material to sludge and in addition to obtain a broad overview of sludge processing with the OFT technology. The main research question was to determine whether sludge can be processed with OFT's microwave technology and to identify the processing parameters. In addition, it was an objective to familiarize OFT personal with the processing of sludge. If possible, representative oil, gas, and char samples should also be sampled from the test run for analysis.

Setup

The experiment was conducted in 6 parts that slowly incorporated more sludge into the system. These steps were familiar to OFT a large number of test runs in processing rubber. By slowly incorporating dried sludge into a rubber mass, sufficient time was provided to adjust processing parameters while gaining experience with the processing of sludge. The processing plan proceeded according to Table 1.

Table 1 – Test 110 feeding schedule and the slow movement toward 100% dried sludge

Feeding order	Rubber	Sludge	Zeolite
Part 1 - 1	40 kg	0	1%
Part 2 - 1	22.5kg	7.5kg	1%
Part 2 - 2	22.5kg	7.5kg	1%
Part 3 - 1	15kg	15kg	1%
Part 3 - 2	15kg	15kg	1%
Part 4 - 1	7.5kg	22.5kg	1%
Part 4 - 2	7.5kg	22.5kg	1%
Part 5 – 1	0	30kg	1%
Part 6 - 1	0	30kg	1%
Part 6 - 2	0	30kg	1%

Part 5 was for "cleaning up" of the system to ensure minimal rubber leftovers and thus allow for the use of part 6 for samples and measurements for energy and mass balance.

Data and observations

After successful run-up, pressure test, heating of plant, and microwave leak test, rubber was added, and the process was commenced. After about 1 hour, part 2 was initiated adding sludge. During part 2 and part 3, the temperature slowly decreased. The process parameters were therefore changed in parts 3, 4, and 5 to reach an equilibrium at the desired temperatures and it was furthermore observed that the optimum temperature in the reactor should be increased from 320 to 350°C to obtain maximum processing flow.

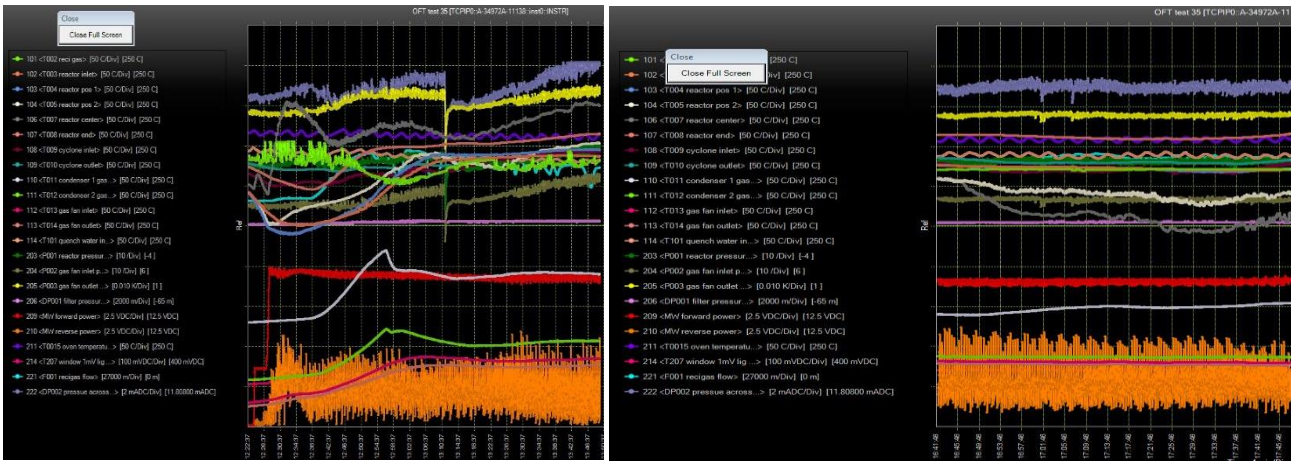


Figure 8 – Left picture shows data is from process start. Right picture shows data is from process with 75% sludge. Red is microwave power and averages about 8.5kW, Yellow and blue are pressure average about 20mBar. Gray and white are process temperatures. It can be seen how the temperatures decreased when sludge was added.

Indications, comparing to previous tests with organic material, was also that the water content of the sludge was higher than the 7-9 % indicated by the sludge supplier – in the order of 15 %. This is likely to be caused by sheltered, but outdoor storage of the material prior to the test. Weather had been wet with high moisture level in the atmosphere during the storage period.

Figure 8 shows the processing start and data for an increase in sludge percentage.

While adding more sludge the optimal parameters for processing of sludge was found and steady processing was achieved. Figure 9 shows the data from the processing of part 6 proving that steady temperatures and pressures was achieved throughout the processing of 100% sludge.

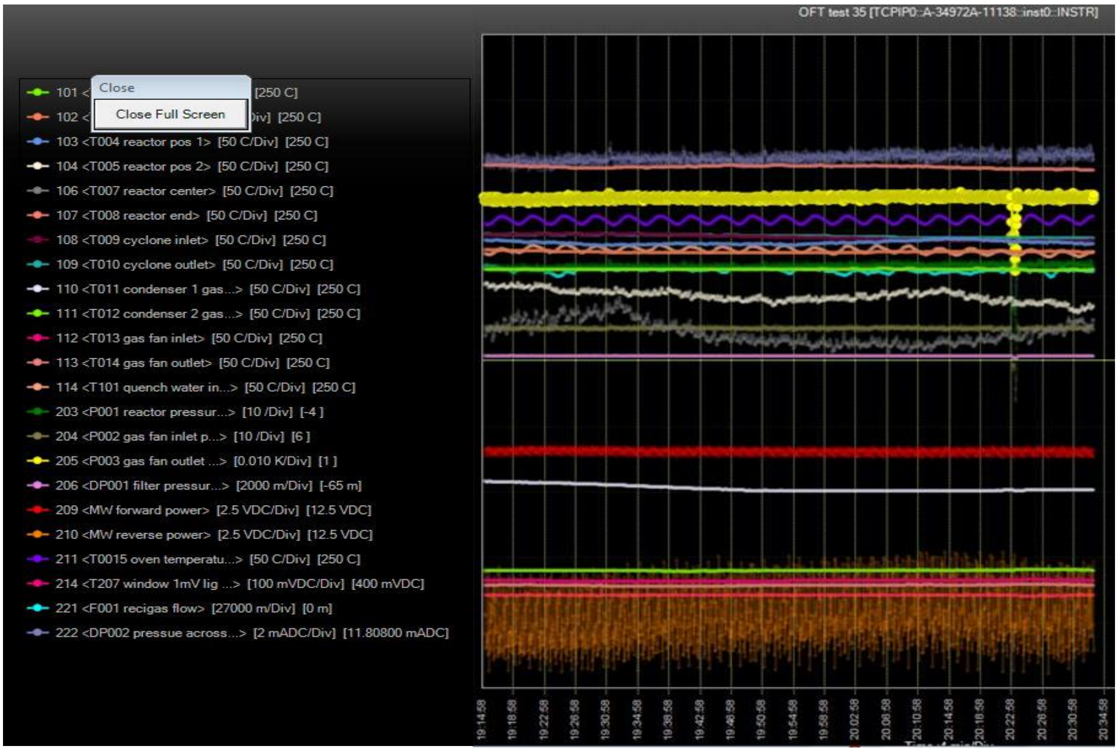


Figure 9 – Data from the processing of 100% sludge on OFT pilot plant, test 110, part 6. The infeed speed was decreased to accommodate for the material change.
At 20:23 material was added incorrectly and therefore a pressure drop.

Table 2 – Processing times throughout test 110.

Part:	Event	Kg	minutes to process	kg/hour
Part1, 0% sludge	Refill	40	47	
	Part 1 total	**40**	**47**	**51.1**
Part2, 25% sludge	Refill	30	44	
	Refill	30	48	
	Part 2 total	**60**	**92**	**39.1**
Part3, 50% sludge	Refill	30	57	
	Refill	30	47	
	Part 3 total	**60**	**104**	**34.6**
Part4, 75% sludge	Refill	30	51	
	Refill	30	56	
	Part 4 total	**60**	**107**	**33.6**
Part5, 100% sludge	Refill	30	72	
	Part 5 total	**30**	**72**	**25.0**
Part6, 100% sludge	Refill	30	66	
	Refill	30	68	
	Part 6 total	**60**	**134**	**26.9**

During part 6, the gas-burning properties were observed showing good properties and high energy flow. Upon shut down and cooling of the system the char was observed as very well-processed char (dry and uniform). The oil production from part 1-5 and part 6 is seen in Table 3.

Table 3 – Oil Production test 110 in kg

Part/place	Condenser 1	Condenser 2	Filter	Before fan	After Fan
Part 1-5	10.6	25.96	15.99	19.65	25,4
Part 6	2.7	4.55	3.62	5.44	6.42

Conclusions

It was possible to process sludge and identify good processing parameters. Compared to rubber processing's temperature of 320°C, a slightly higher temperature of 350°C was needed to process the material optimally. It also took more energy to process the material than has been the case for rubber. This reduced the infeed quantity from 50 kg/hour to 26.7kg/hour. The additional energy usage was most likely due to high water content and the corresponding energy usage from heating and evaporating water.

Oil and gas samples were acquired from part 6 but were not to be analyzed unless failure of the full-scale test in test 111. Char samples were taken, but it was difficult to ensure that the samples were not mixed with tire char and no use was therefore made of these samples.

3.2. Test 111 - sludge

With a successful test 110, it was possible to do a long test run obtaining more statics.

Goal:

The goal for test 111was to find longer-term behavior (over 6 hours) to see if the material is fully processed or non-processed material slowly will clog the system. It will also test how the system behaves when the process is started on 100% sludge and not rubber. This test should also produce more material for analyses and data from the test to lay the foundation for the energy and mass balance calculations.

Observations

After successful start-up including pressure test, heating of plant, and microwave leak test, 100% digested, dried sludge (82.7% DM) was added. Processing proceeded as expected including slightly lower temperature gradient compared to an operational start-up with rubber. Figure 11 shows data from the start-up of test 111.

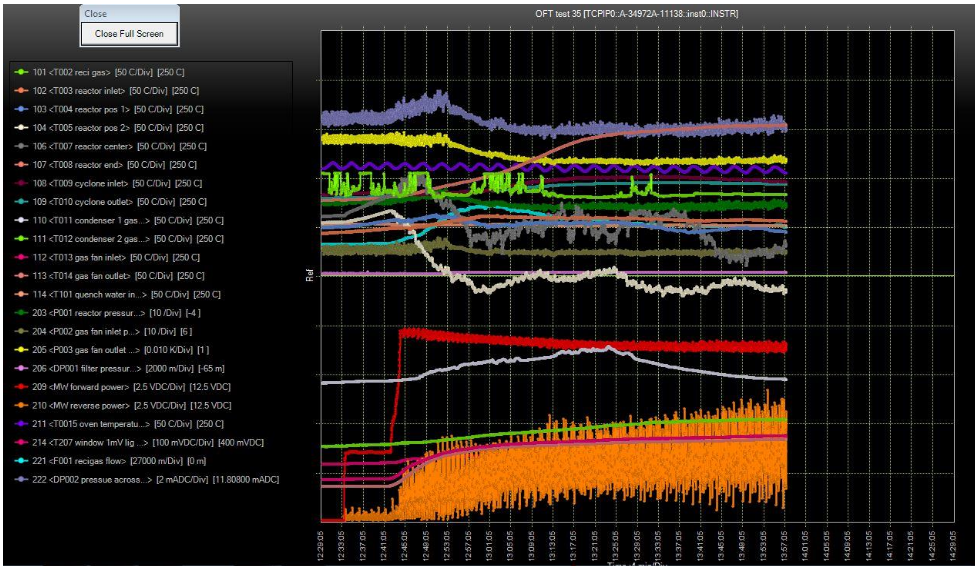


Figure 11 – Process start-up with 100% sludge. Shows normal behavior for starting up the process. Proving that the process can be started using sludge mixed with zeolite.

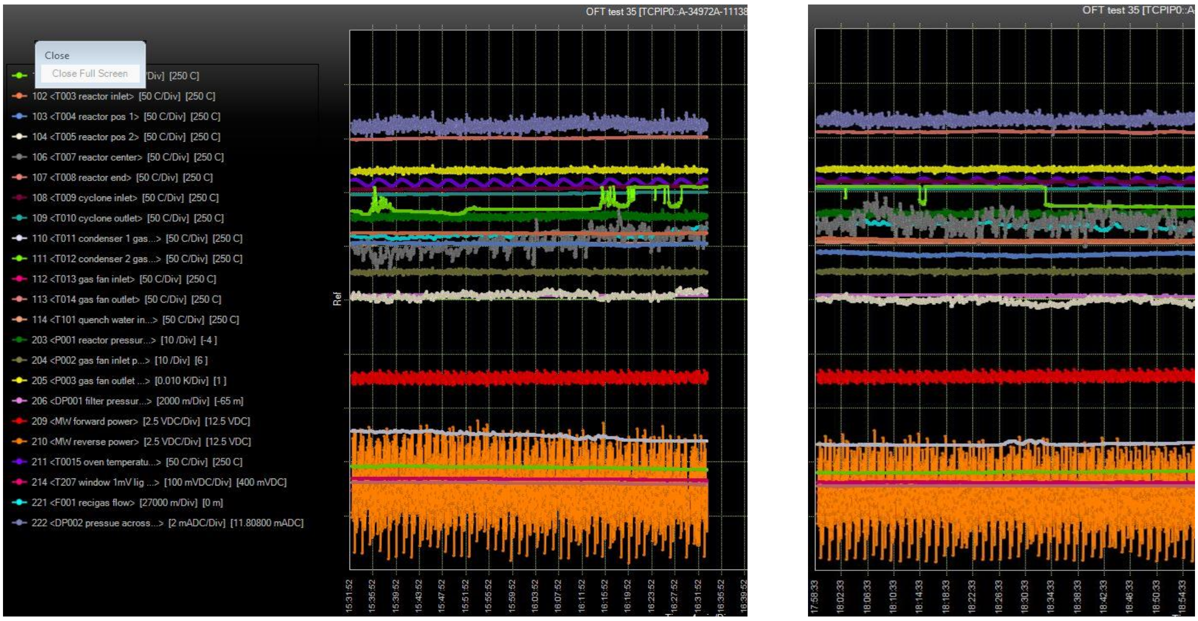


Figure 10 – Showing two samples of data from test 111, showing stable and smooth processing.

After fine-tuning of parameters, achieving equilibrium, the process ran smoothly without any interruptions or fluctuations. Figure 10 and Figure 12 displays data from the test run and the shutdown.

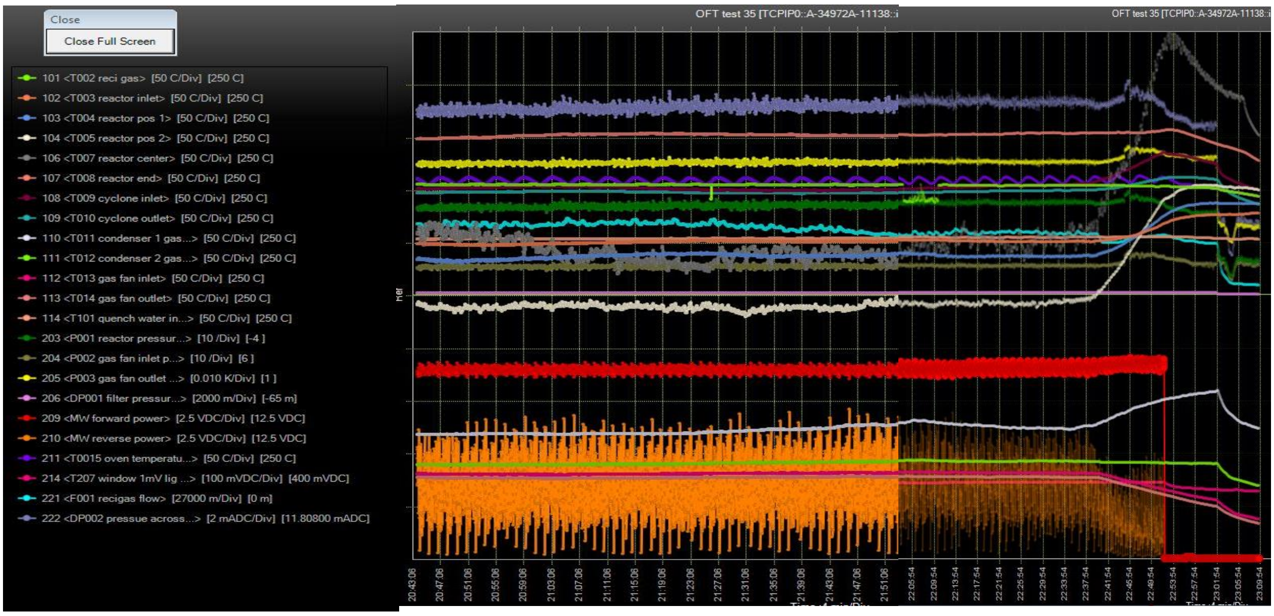


Figure 12 – the final hour of test 111 and smooth shut down.

Throughout the test, the gas burned constantly high energy. All char was very well processed, completely dry and uniform. Oil and char were weighed after the test and the amount of gas produced was estimated from the mass balance. The oil production is seen in Table 4.

Table 4 –oil production throughout test 111. After the initial start-up, the production was very stable.

Datapoint samples for every 45kg processed after 90kg.	Condenser 1	Condenser 2	Filter	Before fan	After Fan
90kg	1.95	3.03	3.80	9.50	9.59
135kg	1.94	1.525	2.045	5.83	4.735
180kg	2	1.865	2.285	4.23	5.645
225kg	1.905	1.965	2.45	4.24	4.82
End (residual after shut-down)	0.94	0.88	0.67	1.42	1.01
Total	**8.735**	**9.265**	**11.225**	**25.22**	**25.8**

The oil and char fraction were afterwards measured by weight, and the water percentage of oil was later analyzed. The gas yield was calculated with simple mass balance as why the gas is mentioned in kg, and the leftover water were estimated to be in the gas as the char were dry. The fractions of gas, oil and char is seen in Table 5.

Table 5 – Distribution of masses from test 111

Output after processing of 225kg sludge and 2.25 kg zeolite and 6.98 kg nitrogen.		
Oil and water	80.2	34.3%
Char	99.2	42.3%
Gas and water vapor	54.8	23.4%
Total	**234.2kg**	**100%**

Conclusions

It is possible to start up the process with sludge mixed with zeolite which makes the process initiation relatively simple. The process ran smoothly without issues for about 10 hours, where it was decided to shut down. Throughout the test, oil was sampled to see any variations in the process outputs. Table 4 shows steady oil production, further validating the observation of a stable and smooth operation.

3.3. Test 110 and 111: conclusions

It can be concluded that the OFT process based on microwave technology, smoothly and with ease processes sludge without any short-term issues. After 10+10 hours of operation, the process still ran smoothly, offering a promising indication of long-term stability.

The processing speed was a lower than expected and therefore a water content analysis of the dried sludge was conducted. After test 111 this showed 17.3% water content in the sludge and not the 7-9% Aalborg Forsyning initially estimated. Based on experience from the processing of other materials, the water content of the sludge during test 110 is estimated to 15%.

Due to the Covid-19 pandemic the dried sludge was stored for a longer period of time than expected before being used for the test runs. Dried sludge was obtained in November 2020. However, tests were not conducted until February 2021 and the sludge's increased moisture content is most likely due to storage issues. Higher moisture content has implications for process throughput and efficiency. Energy required to heat the water and water vapor to 350 ^{o}C, with the 17.3% water content consume 45% of the processing power.

4. Data processing

All data from test 110 and 111 has been analyzed and relevant parameters/numbers have been calculated, with the focus mains focus being on data from the longer duration test 111. Relevant tests and analyses were conducted at Aarhus University.

4.1. Dried sludge characterization

General sludge composition on a dry matter basis appears in Table 6. The information is based on a literature review.

A thorough analysis of the processed sludge is out of scope for the current project and since the composition of sludge is seen to vary greatly, the composition indicated in Table 6 should only be used as a reference indication. The data in Table 6 indicates a level of contamination with a high amount of medicine, heavy metals, and various other environmentally damaging substances.

Studies also suggest that 622 ton of microplastics ends up in the sludge every year in Denmark [10]. This mostly originates from rubber abraded off tires, cosmetics and fabric fibers. The risk factors associated between human health and microplastics is unknown, but they do pose a risk to animals within the environment, undergo limited degradation and accumulate in the environment so discharge to the environment is best mitigated.

In Table 6, there is a section of pollutants and heavy metals found in sludge and are continually monitored in wastewater as their presence can limit their potential application to land. LAS is one of the main components in detergents and affects the normal growth and development of marine organisms in near-shore areas. Additionally, Triclosan is found in various products like deodorants and toothpaste due to its ability to kill bacteria. The Danish Environmental Protection Agency recommends avoiding triclosan, as it is linked to increasing microbial resistant genes in bacteria and a known endocrine disruptor. The current legislation on pollutants on agriculture is stated in appendix B.

Other than the pollutants, the sludge contains nutrients like N, P, and K. The dry matter content is calculated to 25.4 %. The energy content of sludge varies greatly and not just between digested and non-digested sludge.

Table 6 Overview of sludge composition from various articles [11], [12] and analysis from Aalborg Forsyning.

Energy content (MJ/kg)	**9.3-14**
Overall composition	
Volatile solids (% of TS)	40
Grease and fats (% of TS)	18
Cellulose/Carbohydrate (% of TS)	10
Protein (% of TS)	18
Nutrients	
N (kg/ton)	49.85
P (kg/ton)	28.85
K (kg/ton)	4.5
S (kg/ton)	11.38
Heavy metals	
Pb (mg/kg TS)	30
Zn (mg/kg TS)	960
Cu (mg/kg TS)	246
Hg (mg/kg TS)	1
Other pollutants	
LAS (mg/kg TS)	136.5
PAH (mg/kg TS)	1.06
Ibuprofen (mg/kg TS)	5,100
Triclosan (mg/kg TS)	2,100

4.2. Oil characterization, test 111

The oil from test 111 was analyzed by Aarhus University and is presented here. In Table 7 the component analysis is shown. It shows that the oil is mostly ash-free while the distillation curve shows that the oil is volatile and that a large fraction is in the diesel segment. The distillation curves are shown by Figure 13.

Table 7 – Component analysis of oil. Mostly ash-free besides K1. Most of the oxygen content is assumed to be water.
K: condenser, EB: after fan and FB: before fan

Name	N [%]	C [%]	H [%]	S [%]	Ash	O [%]	MJ/kg HHV	Water fraction
K1.1	5.9	50.5	9.9	0.7	1.5	31.6	23.7	0.116
K2.1	6.2	65.8	10.9	1.1	0.0	16.1	32.3	0.147
EB 1	4.2	62.9	11.5	0.8	0.0	20.6	31.2	0.41
FB 2	4.3	64.7	11.4	0.8	0.0	18.8	32.1	0.5
Filter	4.6	63.8	10.9	1.1	0.0	19.6	31.2	0.162

The oil analysis was undertaken using simulated distillation, elemental analysis, thermogravimetric analysis and Karl Fischer titration. The simulated distillation is performed to get an idea of the different oil fractions, and to determine if the samples shows similar properties. Diesel evaporates from 150-350 °C, where petrol is from 50-150 °C [13]. Samples had been obtained as relatively large batches using the sampling methodology and therefore posed some challenges as immiscible water droplets in the oil became miscible with time, appearing most notable in the EB and FB samples with the oil properties changing over time and appearing to become more aqueous.

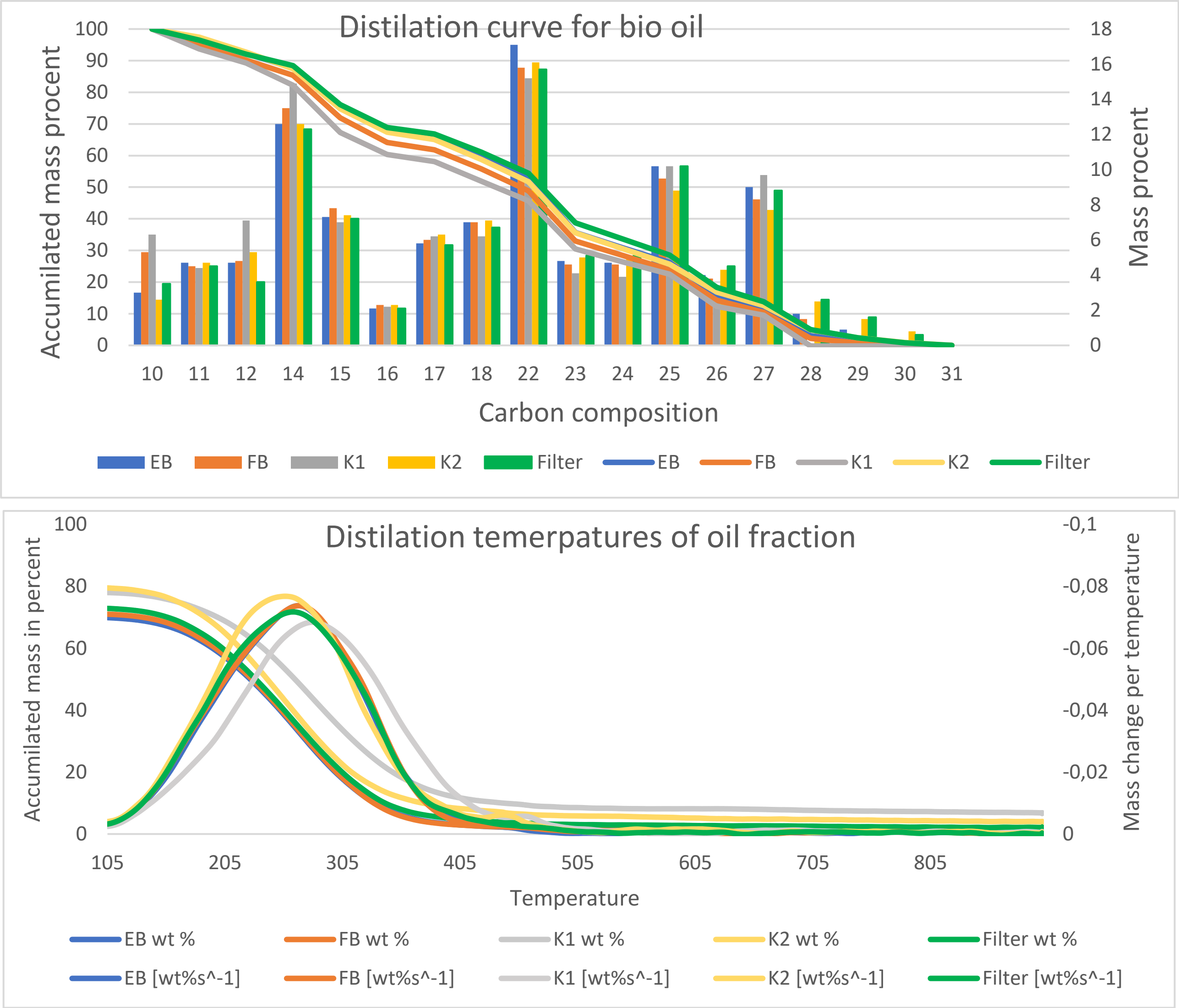


Figure 13 – Distillation curves of oil. Large part is diesel fraction.

Delays due to Karl Fischer reagent deterioration over lockdown unfortunately delayed the moisture analysis which has brought some disconnect between the water and other oil analyses, leading to some mismatches. Multiple smaller sample volumes with full dissolution in tetrahydrafuran prior to water analysis, would be recommended in the future to close the mass balances more accurately. The measured water content in Table 8 has uncertainties evaluated mainly to be in regards to heating value and oil properties and not mass balance. The water content of oil is therefore used to estimate the amount of water in the liquid fraction and what is be left is evaluated to be water vapor in the gas fraction.

Table 8 – Showing water content analysis, test 111

	K1	K2	FILTER	BEFORE BLOWER	AFTER BLOWER	TOTAL
CONDENSED [KG]	8.735	9.265	11.225	25.22	25.8	**80.2**
WATER PERCENTAGE	11.6	14.7	16.2	50	41	**34.12**
WATER IN OIL [KG]	1.01	1.36	1.82	12.61	10.58	**27.38**
OIL [KG]	7.72	7.90	9.41	12.61	15.22	**52.9**

The distillation curves and general oil analysis shows that the oil types and samples are quite similar from sample point to sample point and will therefore be treated as one. The only sample that diverges is K1 due to its ash content and it is assumed that the oil fraction without ash will be like that form the other sample points. Future plants will have improved ash removal capabilities and an ash free oil before. The fractional average HHV of the oil samples is 31.66 MJ/kg as shown in Table 7. This heating value is measured with water content, and since for mass, energy, and commercial analysis, the HHV for dry oil is needed - this is accounted for and calculated. The distillation curve shows that between 20 and 30% of the oil fraction is below 105°C. The content of this area will be alkanes with low C content and water. The oil HHV-DB value can then range between 31.66 and 45.23MJ/kg. It is here assumed the water content is 15% which corresponds with the water content analysis. The remaining 5-15% is assumed without value. The oil energy value is finally calculated to 37.25MJ/kg HHV DB. For the rest of the analyses, a conservative 37MJ/kg HHV DB is used.

4.3. Gas characterization

A gas sample from the long representative test run was made to analyzed by Aarhus University. The analysis can be seen in Table 9.

Table 9 – Component analyses of a gas sample from test 111. The last 12.8 % of the gas is assumed water or without calorific value.

Gas	Volume (%mol v)	HHV	LHV	Mol Mass	g /l	KJ/L (HHV)	KJ/L (LHV)
Hydrogen (H_2)	17.1	142	120	2.016	0.01536	2.18	1.84
carbon monoxide	7.4	10.1	10.1	28.011	0.092098	0.93	0.93
Nitrogen (N_2)	25.0	0	0	28.0134	0.312486	0.00	0.00
Methane	9.7	55.6	50	16.043	0.069388	3.86	3.47
carbon dioxide	24.7	0	0	44.01	0.484818	0.00	0.00
ethylene	0.6	50.3	47.2	28.054	0.007824	0.39	0.37
ethane	1.3	51.9	47.5	28.05	0.016475	0.86	0.78
acetylene	0.7	50	48.2	26.038	0.007674	0.38	0.37
propane	0.6	50.4	46.4	44.097	0.011154	0.56	0.52
propylene	0.3	49	45.8	42.081	0.00508	0.25	0.23
Total	87.2					9.41	8.51

Within the gas sample, the above gases should account for 87.2% of the gas volume. There was a large water peak present within the gas sample which will account for some of the remaining gas volume, but the instrument is not setup to quantify this. From experience, OFT has seen some amounts of C4, C5, and even C6 gasses in previous samples, based on other biomaterials, but it was not possible at this time to quantify these gasses. The oil analysis showed that a large part of the water ends up in the gas and therefore the 12.8% that is not quantified in the gas is assumed water or without value. The density is assumed the same as biogas at 1.15kg/m^3 and the HHV and LHB is evaluated to 8.51GJ/ton and 7.40GJ/ton. There are some uncertainties to the gas quality and this analysis is only used to provide indications of the useability of the gas. Further analysis and tests are needed to fully quantify the gas quality. Other components, H_2S and siloxanes should be further analyzed and quantified to ensure proper handling of the flue gas.

4.4. Char characterization

The char was analyzed by Aarhus University and can be seen in Table 10.

Table 10 – Analysis of char sample from test 111. It should be noted that the char probably got too low an oxygen. Ash made from biomass will oxidize chlorides, sulfides etc., thus underestimating the oxygen. Some caution is needed here.

NAME	N [%]	C [%]	H [%]	S [%]	ASH	O [%]	MJ/KG (HHV)
CHAR	2.5	26.7	0.8	0.8	65.3	3.8	10.4

The char can be used in various ways and the exact use case is dependent on the ash chemistry, environmentally harmful substances, and the stability of the carbon. The easiest use case is to burn it as fuel to power the sludge drier as it is going to burn almost like coke and an appropriately setup coal-fired furnace could efficiently convert the char to energy.

The char may also be used in biomass combustion as the ash appears largely alumina silicate-based and in which case enable it as an additive in biomass fuel combustion to mitigate potassium chloride issues as an alternative to kaolin as it will contain energy and be cheaper. Furthermore, the Sulphur content is favorable if combusted with biomass in large combustion plant operating electrostatic precipitators as biomass is typically low in Sulphur and therefore Sulphur is added in order to increase precipitator efficiency reducing fly-Ash / particulate emissions.

Perhaps the most topical use of the char is as a soil additive, biofertilizer and carbon sequestration agent in the form of a biochar. To be classed as a biochar and biofertilizer, the product should be free of pathogens, organic contaminants and the heavy metal content should be below limiting for mineral fertilizers according to the Fertilizing Products Regulation in Europe [14]) and European Biochar Certificate. Due to the currently (arguably artificially) low carbon price, the potential to certify a biochar as an EC marked biofertilizer is attracting commercial interest in slurries such as sewage sludge rich in phosphorus.

Technical difficulties do however exist within the technical proposals for selected new fertilizing materials under the Fertilizing Products Regulation [14] set out in [15], which currently excludes sewage sludge derived biochar's. The authors argument being that there is no clear evidence that biochar processes eliminates pharmaceuticals and other contaminants combined with opposition in some EU member states against the disposal of sewage sludge to land. Changes to this position are however likely based on rebuttal evidence and the fact that in a number of EU member states application of sewage sludge to land is already commonplace. Nonetheless when specifically focusing on biochar as a phosphorus fertilizer the quality of the biochar product will be strongly influenced by the sewage treatment process, with systems which use iron salts in phosphorus recovery likely to yield biochar's with low plant phosphorus availability. The phosphorus would, over a period of time, be available but it is not known when and can therefore not be used as commercial fertilizer.

In addition to Fertilizing Products Regulation, accreditation via a biochar accreditation agency such as the European Biochar Certificate is required when CE marketing biochar. At present certification requires a minimum organic carbon content in char of 50 %, with the digested sludge yielding 26.7 %, therefore requiring a higher potion of organic carbon, see Table 10. Carbon content is likely higher in non-digested sludge and reductions in ash content might be possible by excluding the Zeolite catalyst, otherwise supplementary biomass, like sawdust or other low value biomass, maybe required in order to achieve accredited biochar. This should be further researched, but zeolite mostly consists of Aluminium silicat, and the sludge contains a large part of aluminium silicate. Therefor it could be possible to process the sludge without the zeolite. This will be a long-term goal to reach this, but for this analysis, the char is used to power the drier.

A thorough analysis of the char was out of scope for this project at therefore the commercial and environmental aspects will be based on simple heating value and burning properties. There is a large potential in researching this is more and get a better characterization of the char.

4.5. Reactor throughput calculation

It was originally assumed that the water content of the sludge would be 7% and that the reactor throughput for a new demonstration plant would be very similar to the reactor throughput of tests of the present project. The dried sludge did however prove to have a much higher water content – 17.3% measured by Aarhus Vand and 17.5 % measured by Aarhus University. Therefore, the reactor throughput must be calibrated for lower water content when assessing true potential throughput.

The hourly throughput in the long representative test was 22.61 kg/hour + zeolite and nitrogen. Of this 17.3% was water thus equaling 3.9kg/hour water. To heat 3.9 kg water from 10°C to 350°C, there is needed 12.103 kJ equivalent to 3.36 kW. The OFT pilot plant is estimated to deliver 7.5 kW into the material and, therefore, water heating takes up 45% of total microwave processing power.

The future OFT8 full scale plant has a slightly better microwave efficiency and 8 kW will be delivered into the material. It will also be possible to heat the feedstock to 80°C before it is added to the reactor. Based on linear energy considerations where the throughput is linearly proportional with the energy applied to process the chemical bindings, the full-scale plant's throughput was calculated for different water contents. A comparison table with the current throughput and energy usage and for a new plant with can be seen in Table 11.

Table 11 – Throughput calculation for various amounts of sludge. Throughput is without 1% zeolite and nitrogen.

Description	*15% at 5°C (Test 110)*	*17.3% at 5°C (Test 111)*	*5% at 80°C*	*2% at 80°C*	*1% at 80°C*
Throughput [kg/hour/reactor]	26.7	22.61	38	42	44
Energy to material [kW]	7.5	7.5	8	8	8
Water [kg/hour]	4.0	3.9	1.9	0.8	0.4
Energy to remove water [kW] (%)	3.34 (46%)	3.38 (45%)	1.47 (18%)	0.66 (8%)	0.34 (4%)
Energy to heat material [kW] (%)	2.27 (30%)	1.88 (25%)	2.78 (35%)	3.18(38%)	3.34(40%)
Energy to process [kW] (%)	1.89 (24%)	2.33 (30%)	3.74 (47%)	4.16(52%)	4.32 (54%)
Throughput per process energy [kg/hour/kW]	15.03	10.1	10.1	10.1	10.1

The linearity projection is used due to its simplicity, but will likely underestimate the throughput and is, therefore, a conservative estimation. From experience, OFT knows that higher field strength does not result in an exponential like increase in throughput. Since processing power and field strength are closely linked the same principle would likely apply here. This is also the most likely reason that part 6 of test 110 had a better throughput per energy than test 111.

OFT's pilot plant reactor can normally process above 50kg/hour completely dry material, however, for prediction of results with drier sludge, a throughput of 5% H_2O at 80°C is linearly projected from test 111 results, and used as the conservative estimation for one microwave reactor throughput.

5. Energy and mass analyses

Test data from test 111 was used to calculate a mass balance for the system. Since the de-watered sludge was not fully characterized before processing, a proper energy balance cannot sensibly be calculated. Therefore, the energy content of the sludge does bring some uncertainty to the produced energy balance. To overcome this an energy analysis was also conducted that focused on the ratio between electricity inputs to drive the process and storable energy outputs.

The test did not involve water removal from the sludge, but a technology review, mass and energy calculations taking water removal into consideration, and issues concerning implementation with water removal from sludge is part of the commercial analysis in Section 6 below.

5.1. Mass balance

To calculate the mass balance the oil/water and char masses were measured after test completion. Since the test duration was 10 hours there is a relatively low level of uncertainty as to the accuracy of these weight measurements. Water content was, however, estimated from the water added to the reactor through sludge. From the oil's water content analysis, the amount for water that ends up in the oil/liquid fraction can be evaluated and from a total mass of water the amount of water left in the gas can be deduced. It is possible that during the process some of the oxygen was transformed into water. This is, however, assumed to be neglectable.

The gas mass was estimated in two ways, from nitrogen content (N_2) in gas and secondly from a mass balance. Based on the assumption that there is no production of nitrogen in the process and an appropriate mixing of gas within the reactor, it is possible to calculate the mass flow of gas from the nitrogen content in the gas sample, as N_2 is used as an inert gas in the process. The reactor carrier gas is nitrogen (N_2) with a flow of 10L/min. The nitrogen content at the flare is 25% of the gas by volume, thus the reactor is yielding 30 L/min or 1.8 m^3 gas per hour. The density of the gas is calculated by the composition and is about 1.15kg/m^3 and therefore the gas sample can be compared to the mass balance.

The mass balance calculated an estimated a production of 5.51kg gas/hour or 4.79m^3. Therefore, either nitrogen gas was produced during the process or, more likely, the sample was not representative. However, if there are other Nitrogen compounds (NO_x) in the gas that are not measured in table 9, this could change the calculation. Looking at the sludge composition in Table 6, chances are, other gaseous Nitrogen and Sulphur compounds will be produces.

Due to this uncertainty, the mass flow of gas is calculated from the mass balance and not from the nitrogen content. The resulting mass balance for test 111 is given by Table 12.

Table 12 Total mass balance from test 111.

	FROM TEST		WITHOUT WATER		WITHOUT WATER, NITROGEN AND ZEOLITE	
	Mass [kg]	Percentage [%]	Mass	Percentage	Mass	Percentage
MASS INPUT	234.23	100.00	195.31	100	186.08	100
WATER (17,3%)	38.93	16.62	0	0	0	0
DRY MATTER	186.08	79.44	186.08	95.27	186.08	100.00
NITROGEN (N_2)	6.98	2.98	6.98	3.58	0	0
ZEOLITE	2.25	0.96	2.25	1.15	0	0
MASS OUTPUT	234.23	100	195.31	100	186.08	100
WATER IN OIL	27.38	11.69	0	0	0	0
WATER IN GAS	11.54	4.93	0	0	0	0
OIL	52.86	22.57	52.86	27.07	52.86	28.41
GAS	43.24	18.46	43.24	22.14	36.26	19.48
CHAR & ASH	99.21	42.35	99.21	50.79	96.96	52.1

5.2. Energy balance

To conduct an energy balance analysis, data on the energy content of dried sludge was needed. Aalborg Forsyning carries out a yearly measurement of calorific burning value of their dried sludge. In these measurements, the calorific value averages 11.7MJ/kg.

From the literature review the energy content of dried sludge is estimated to 9-14MJ/kg. A component analysis on the received sludge carried out by Aarhus University estimated an HHV of 17.4MJ/kg. Due to high ash content this result does have some uncertainties, and as being mentioned belove, the energy must be at least 4% higher than measured at Aarhus University.

However, the produced biofuels from microwave cracking indicate that the received batch of dried sludge had an even higher energy content than this and thereby possibly also that previous analyses underestimate the actual energy content of dried sludge. In the microwave cracking process, every kg of processed material, including Zeolite and Nitrogen, was measured to produce 17 MJ of energy. Since sludge is 95% of this mass, and Zeolite and Nitrogen does not contain energy, the received sludge total energy content should therefore be at least 18.02MJ/kg. If a value below this is used as sludge input energy, the energy balance will produce efficiencies above 100%.

Therefore, for the calculation of energy balance, an energy content in the processed dried sludge of 17.17MJ/kg input material is used, corresponding to 18.02MJ/kg energy in the received sludge on dry basis.

The energy balance calculation was carried out for both test 110 and 111 and then compared to an estimated energy analysis of the pilot plant during optimal conditions, i.e. with a water content of 5%. Finally, the results were extrapolated to an energy analysis for the future full-scale OFT8 plant, also with a water content of 5% in the sludge. The results of the analysis are given in Table 13.

Table 13 Energy balance for test 110 and 111. The data form these tests where extrapolated to optimized conditions for both pilot plan and a new plant. There are uncertainties re. the energy content of the sludge. In the analysis it is assumed to have the same energy content as the output.

	PILOT PLANT TEST 110 15% WATER		**PILOT PLANT TEST 111 17,3% WATER**		**PILOT PLANT OPTIMISED CONDITION 5% WATER**		**NEW PLANT OPTIMISED CONDITION 5% WATER**	
PROCESSING POWER [KG/HOUR]	23.67		19.67		40		400	
INVESTMENT	KW	%	KW	%	KW	%	KW	%
ELECTRICITY MICROWAVE	16	11%	16	13%	16	7%	120	6%
ELECTRICITY OTHER PROCES	16	11%	16	13%	16	7%	80	4%
INPUT MATERIAL 17.17 MJ/KG	113	78%	94	75%	191	86%	1908	91%
ENERGY IN TOTAL	**145**	**100%**	**126**	**100%**	**223**	**100%**	**2108**	**100%**
OUT TO RETURN	kW	%	kW	%	kW	%	KW	%
OIL (27.07% AND 37MJ/KG)	66	45%	55	43%	111	50%	1113	53%
GAS (22.14% AND 8.51MJ/KG)	12	9%	10	8%	21	9%	209	10%
CHAR (50.79% AND 104MJ/KG)	35	24%	29	23%	59	26%	587	28%
ENERGY OUT TOTAL	**114**	**78%**	**95**	**75%**	**197**	**86%**	**1931**	**91%**

The energy balance shows an efficiency of 86% for the pilot test if the water contents of sludge are 5%. With similarly dry sludge, it is calculated that this efficiency can be increased to 91% in the future OFT8 full scale plant. These calculations do not include possibilities for energy recovery which, if implemented, can increase efficiency further.

The energy balance was made for dried sludge and the water removal process to obtain a water content of 5% or lower does consume a significant amount of energy. An energy analysis for the drying process was conducted and is found in section 6.4. This analysis shows that the gas and char generated by microwave cracking can provide the energy needed for drying process while converting the energy used to more than 80% district heating. This will decrease the overall efficiency of the OFT microwave cracking process with about 8 percentage points.

5.3. “Power-to-X” energy analysis

An energy analysis was conducted to see how a plant could be used as a “power-to-X” solution. This analysis removes the uncertainties about the sludge energy content by assuming it without value. The energy analysis for the conducted test was carried out based on the mass balance and the oil, gas, and char analysis. This analysis was made for both test 110 and 111 and then compared to an estimated energy analysis of the pilot plant during optimal conditions. Finally, the results were extrapolated to an energy analysis for the future full-scale OFT8 plant. The results of the analysis are given in Table 14.

The results in Table 14 indicate that under optimized conditions, the pilot plant produces 3.48 units of energy in the form of oil per energy unit of electricity added to the process. While doing so the plant also produces 2.5 units of other energy sources. The results also suggest that a future OFT8-plant with the use of 1 energy unit of power inputs to process and convert dried sludge and can produce 5.56 energy units of oil, and while doing, it will also produce 4 energy units of other energy sources (gas and char).

Table 14 - Energy analysis for the pilot plant and for the pilot plant and the new full-scale plant under assumed optimized conditions. The energy in the oil output is up to 5.6 times larger than the electricity input and the total energy (oil, gas and char) output will be op to 9,6 times higher than the electricity input. The mass balance without water content is used for this calculation.

	PILOT PLANT TEST 110 15% WATER		PILOT PLANT TEST 111 17.3% WATER		PILOT PLANT OPTIMISED CONDITION		NEW PLANT OPTIMISED CONDITION	
PROCESSING POWER [KG/HOUR]	23.67		19.67		40.00		400.00	
ENERGY FLOW PER KG [KW/KG/HOUR]	1.35		1.63		0.80		0.50	
ENERGY TO PROCESS 1 TON [GJ]	**4.87**		**5.86**		**2.88**		**1.80**	
INVESTMENT	kW	%	kW	%	kW	%	KW	%
ELECTRICITY MICROWAVE	66	206%	55	171%	111	348%	1113	556%
ELECTRICITY OTHER PROCES	12	39%	10	32%	21	65%	209	105%
ENERGY IN TOTAL	35	109%	29	90%	59	183%	587	293%
OUT TO RETURN	**114**	**353%**	**95**	**293%**	**197**	**597%**	**1931**	**955%**
OIL (27.07% AND 37MJ/KG)	66	206%	55	171%	111	348%	1113	556%
GAS (22.14% AND 8.51MJ/KG)	12	39%	10	32%	21	65%	209	105%
CHAR (50.79% AND 10.4MJ/KG)	35	109%	29	90%	59	183%	587	293%
ENERGY OUT TOTAL	**114**	**353%**	**95**	**293%**	**197**	**597%**	**1931**	**955%**

If gas and char is used to power the drying unit, the conversion will be reduced to 7.59. For further analysis of the plant with drying unit see section Mass and energy balance and analysis with implementation of de-watering.

6. Commercial analysis

To evaluate the business case for OFT's microwave technology, a commercial analysis was carried out. The analysis aimed to quantify the commercial value of the outputs of the technology based on available data. Since it is new technology and the produced products have not yet reached the market, most of the analysis is based on assumptions and indications from the public market sources.

6.1. Commercial use of oil

The main source of income from the OFT process is oil and therefore it is important to classify the OFT oil correctly and to obtain price data from the correct market. Bio-oil prices vary but indications of OFT oil value can be made from Fame, SME, and rapeseed oil which is currently (25/05-2021) valued at 9.7kr/kg, as seen in Figure 14.

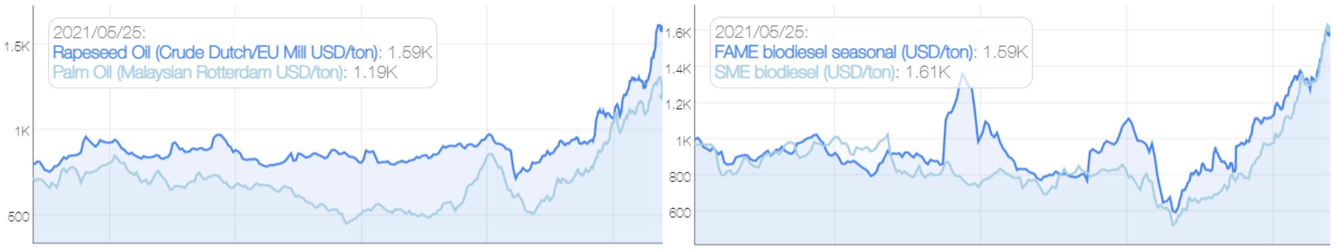


Figure 14 – Biofuel price data from [1]

It is currently not known which process will be needed to upgrade OFT's oil to fit standards for Fame, SME, or virgin bio-oils in general. These processes must be identified and evaluated in the longer term. The initial market for the produced OFT oil will thus be on a low-quality oil market, where OFT-oil will either be mixed with regular fossil fuel or used as start-up heating at combined heat and power plants. It is estimated that the price point of oil to this market will be 80% of the upgraded bio-oil price and that it will be traded on a MJ basis. The calorific value of bio-diesel is found to be between 35-40MJ/kg where as the calorific value of OFT's bio-oil is calculated to 37MJ/kg.

In the future, it should be possible to characterize the OFT oil more adequately and to upgrade its classification to fit the FAME properties. As a consequence, the price (and the recognized positive environmental impacts) of OFT's oil will increase. However, in the remainder of the commercial analysis, the price for OFT oil will be assumed to be 7.0kr/kg.

6.2. Commercial use of gas and char as biofuel

The gas and char analysis did not indicate with certainty that there is a market for these products apart from as biofuels. As the OFT process needs dry sludge to run efficiently and water removal requires a relatively large amount of energy, it can be assumed that in the first phase of the commercial roll-out of the OFT8-technology, OFT gas and char will be utilized for combustion to power water removal from sludge. Furthermore, it can be assumed that the surplus energy from this process can be converted to district heating (for instance, a drying system from Swedish Exergy promises to convert 80-95% of the energy to district heating).

To simplify the case and to limit income uncertainties, it is assumed that the energy from both gas and char will be used to dry the wet sludge. District heating is set at 75kr/GJ and it is assumed that 80% of the energy is converted to district heating. This is believed to be quite conservative assumptions concerning possible income from gas and char.

A possible easy upgraded and potentially future proof use case for the char is as an additive in biomass fuel combustion to mitigate potassium chloride issues as an alternative to kaolin as it will contain energy and be cheaper. This market is currently unknown but should be kept in mind and be researched further in the future.

6.3. Commercial use of char as fertilizer

It is preferable that in the longer term, the use of char as biofuel is avoided. The environmental value of the product is potentially higher if used as fertilizer with carbon capture. However, a number of things need to be assessed, tested, and quantified before application of char as fertilizer can happen and some upgrades may be needed before the product can commercially compete with industrial fertilizer. Some of the things that need to further in future research are:

1. PAH and Dioxin content before and after the OFT process. The relatively low processing temperature should limit the formation of these toxic substances, but it is presently not known to which extent.
2. A carbon content of 26% is not high enough to allow the char to be classified as biochar, within the European Biochar Certification (EBC), and therefore the ash should be removed if biochar certification is to be obtained.

3. Measures for heavy metal removal should be identified. It is assumed that heavy metals end up in the char and the must be removed prior to or after the OFT process before the char can be used as fertilizer.
4. It should be quantified how much microplastic the OFT process can remove from sludge.
5. The quantity of nutrients in the char and how they can replace commercial fertilizer should be analyzed.
6. The amount of Carbon Capture should be calculated.
7. Growth experiments with nutrients (N and P) and their availability in soil.

OFT has already applied for research grants and proposed research plans to answer the above questions. There may be a need for field testing before use of char as fertilizer can be approved, meaning that the process of reaching a commercial product may take a considerable amount of time. Besides this, the current regulatory infrastructure is not yet in place biochar to be used as a green fertilizer with carbon capture. The subject has however caught political attention, and changes are underway.

Until the necessary research has been carried out and the regulatory infrastructure is in place, OFT recommends making use of the char is biofuel.

Right now, there are a few agencies, that offer certification of biochar, the most updated being EBC [16], who updated their guidelines in 2021. Otherwise one of the most known is International Biochar Initiative (IBI) [17], who offers different grades of biochar. Their lowest grade needs a minimum of 10 % organic carbon. Sludge is not yet acknowledged as a feedstock to produce biochar in EBC, but IBI acknowledge all feedstocks, as long as the output properties are within the guidelines.

6.4. Implementation of a commercial plant

For OFT's technology to process sludge efficiently, the sludge must be dried. Thus, with a lower water content, processing power will not be used to superheat water, but instead used for its main purpose of processing lignin, cellulose, and fat. Further research, calculations, and experiments are necessary to identify the optimal water content, but for the present analysis, an assumption of 5% water content in sludge is used. The wet sludge is assumed to be received after mechanical separation and with a water content somewhere between 70% and 75%.

OFT does not possess specialist competences nor operational experience in sludge de-watering systems and the technical analysis of these technologies with mass and energy balance is based on public available data and conversations with companies within this sector.

De-watering technologies

Two drying options are presented here: firstly, a superheated steam dryer, and secondly a traditional relative humidity drier. The first option uses superheated steam to transfer energy to the material. The heat evaporates water to steam while the superheated steam is cooled to 100°C. Afterwards, the steam can be condensed and cooled to 80°C and thereby return most of the energy as district heating.

The second process uses warm dry air to remove water from the sludge. The relative humidity will dry the material. This solution does however significantly influence the amount of surplus energy from the process that can be converted to district heating. The technologies are summarized in Table 15.

Table 15 – Showing two methods for drying sludge. Data from https://www.swedishexergy.com/

PER TON WATER REMOVED	ELECTRICITY (GJ)	ENERGY (GJ)	RECOVERY (GJ)	EFFICIENCY (%)
TRADITIONAL	0.18	1.62	0.65	36
SUPER HEATED STEAM	0.18	2.74	2.19	75

For this analysis, the super-heated steam drier is used for analytical purposes, but the reader should be aware that other options exist. However, since it is likely that in the future wastewater treatment plants will be expected to generate energy for the surrounding city, high efficiency through district heating is believed to be a relevant solution.

Swedish Exergy were asked to estimate a price for a 30,000ton/year drying plant (1,500,000 Euro) to indicate the financial costs for a superheated drier. The company was also asked to estimate a price for a smaller machine that would fit one OFT8 plant. This was between 5-7.5 million kroner. The flow chart for the drying is shown in Figure 15.

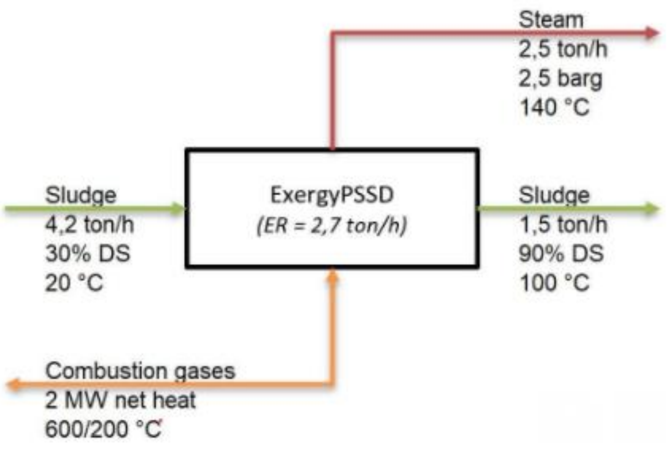


Figure 15 – Super-heated drying plant from Swedish Exergy

- The only technology that can achieve up to 95% of energy recovery.
- There is no emission or odor from drying process which makes it easy to install the dryer within the city limits (perfect for municipal sludge drying).
- Long plant lifecycle (first designed plant in 1979 is still operational).
- 10-15 seconds drying time with continuous 24/7 operation.
- Fully automated operation.
- Quick control over drying process.
- Rapid start-up and shutdown.
- No heavy rotors or belts are required (hence up to 50% reduction in footprint)
- Budget price for the EXERGYPSSD is around 1,500,000 Euro.

Table 16 lists the energy needed to remove water from wet sludge at different dry matter fractions to obtain 1053kg sludge at 5% water equivalent to one ton of 100% dry sludge.

Table 16 – Energy need for drying 1ton 100% dry sludge

Dry matter fraction	*0.25*	*0.28*	*0.3*
Water needed to be removed [Ton]	2.95	2.52	2.28
Electricity [GJ/ton]	0.53	0.45	0.41
Energy Steam [GJ/ton]	8.06	6.89	6.24
District heating [GJ]	6.45	5.51	4.99

Mass and energy balance and analysis with implementation of de-watering system

Since the OFT microwave technology must be integrated with a drying system, the energy usage from a water removal technology is added to the energy analysis below. In the analysis, it is assumed that water removal process (here super-heated steam drier) uses energy to produce steam and electricity for various components to power the steam generator.

There are significant synergies between the OFT microwave technology and the water removal technology as seen in Table 17 and Table 18. If gas and char is used for energy, is it possible to power the drier. This will ensure the needed energy flow and limit the need to sell the produced gas and char commodities. The only thing that would need to be sold, and where transactions and transportation must be managed, is the produced oil.

If the drier is powered by the OFT plant’s own produced gas and char, the conversion factor for energy to oil is 4.76 while producing 2.26 units of energy for district heating and 0.58 energy units for in extra gas for each unit of electricity added to the process. In comparison, it can be mentioned that hydrogen electrolysis demonstrates a comparable conversion factor of only 0.6-0.8.

The efficiency of the plant with a super-heated steam drier is between 83 and 87% depending on how the internal energy used for sludge drying is analyzed.

Table 17 - Energy balance for plant with drying system

	OFT 8 PLANT WITH WATER REMOVAL			
INPUT IS 1049.63KG DRY SLUDGE WITH ZEOLITE AND NITROGEN EQUAL TO 1000KG SLUDGE DRY MATTER	Buy energy for steam		Uses own energy	
	GJ	%	GJ	%
ENERGY 1000KG SLUDGE AT 18.02MJ/KG	18.02	68%	18.02	89%
ELECTRICITY TO PROCESS 1 TON SLUDGE DRY MATTER	1.80	7%	1.80	9%
ELECTRICITY DRIER [GJ]	0.41	2%	0.41	2%
ENERGI STEAM [GJ]	6.24	24%	0.00	0%
INPUT TOTAL	**26.47**	**100%**	**20.23**	**100%**
ENERGY OUT				
OIL (27.07% AND 37MJ/KG)	10.51	40%	10.51	52%
GAS (22.14% AND 8.51MJ/KG)	1.98	7%	1.28	6%
CHAR (50.79% AND 10.4MJ/KG)	5.54	21%	0.00	0%
RECOUVERY (DISTRICT HEATING) 80%	4.99	19%	4.99	25%
ENERGY OUT TOTAL	**23.03**	**87%**	**16.79**	**83%**

Table 18 – Energy conversion efficiency for the OFT8 and future plants. Whether or not to use own produced energy depends on the energy market especially accessibility to cheap green electricity.

	OFT 8 PLANT WITH WATER REMOVAL			
INPUT IS 1049,63KG DRY SLUDGE WITH ZEOLITE AND NITROGEN EQUAL TO 1000KG SLUDGE DRY MATTER	Buy energy for steam		Uses own energy	
	GJ	%	GJ	%
ELECTRICITY TO PROCESS 1 TON SLUDGE DRY MATTER	1.80	21%	1.80	81%
ELECTRICITY DRIER [GJ]	0.41	5%	0.41	19%
ENERGI STEAM [GJ]	6.24	74%	0.00	0%
INPUT TOTAL	**8.45**	**100%**	**2.21**	**100%**
ENERGY OUT				
OIL (27.07% AND 37MJ/KG)	10.51	124%	10.51	476%
GAS (22.14% AND 8.51MJ/KG)	1.98	23%	1.28	58%
CHAR (50.79% AND 10.4MJ/KG)	5.54	66%	0.00	0%
RECOVERY (DISTRICT HEATING) 80%	4.99	59%	4.99	226%
ENERGY OUT TOTAL	**23.03**	**272%**	**16.79**	**759%**

6.5. Assumptions on total plant expenses

The future OFT8 full scale plant can be constructed and installed for 12,000,000DKK. Since this will be the first full scale OFT plant it can be assumed that some extra costs will be incurred in construction, installation, commissioning and the start-up of operations. However, it can be assumed that OFT will take responsibility for such issues and provide the necessary engineering and microwave specialist resources to ensure the continuous operation of the plant continuously.

As analyzed above, the OFT process needs to be installed in integration with systems that remove water from sludge. Technologies for water removal in sludge are well known and used around the world. For small plants, water removal processing equipment is however relatively demanding in terms of required Capex investment. Initial price indications for a drier that can process the needed quantity of sludge for one OFT8 plant range from 5-7,500,000DKK.

A de-watering system can be set up anywhere and does not need any buildings to surround it. It does however need a silo before and after the drying process to ensure that required storage space is available for sludge ready to be dried and for storage of dried sludge. It also needs to be connected to the district heating. The price for silo and district heating connection is estimated to 1,000,000DKK.

The OFT8 plant and its control room should be situated indoors and connected to a stable power grid. This building needs to be 8 meters tall and have an area of a minimum 12*8m.

Therefore, the total required plant investment is estimated to be between 17,000,000 to 19,500,000DKK. For the purpose of calculating the business case it is cautiously assumed that a plant setup including a water removal system can be constructed for 20,000,000DKK and without a water removal system for 15,000,000DKK.

6.6. Business case calculations

To examine the full business case, a budget estimation for plant operation was developed. It is based on the commercial analysis and assumptions above and with the following additional assumptions applying:

1. Oil price between 60 and 80% of the commercial bio-oil price
2. Income from handling wet/dry sludge
3. All gas and char are used to dry wet sludge and will provide 80% district heating at 75kr/GJ. This is with the assumption that the district heating is needed all year.
4. Electricity price set at 0.8kr/kWh
5. For the conservative business case, the conservative throughput assumption is used, while in the standard and optimistic scenarios, a throughput of respectively 2,500 and 3,000 tons per year is assumed. A throughput of 2,500 tons per year is deemed realistic, cf. the section on Reactor Throughput Calculation.

The business case calculations including water removal are contained in Table 19.

Table 19 – Scenarios for OFT8 in operation with expenses for water removal included

(1000DKK)	**CONSERVATIVE**	**STANDARD**	**OPTIMISTIC**
OIL PRICE [DKK/KG]	5.00	7.00	9.00
SLUDGE HANDLING PER TON WET [DKK/TON]	0.30	0.37	0.40
TROUGHPUT PER YEAR (WET) [TON]	6,933	8,333	10,000
TROUGHPUT PER YEAR (DRY) [TON]	2,080	2,500	3,000
INCOME			
SLUDGE HANDLING	2,080	3,083	4,000
DISTRICT HEATING	900	1,082	1,298
OIL	2,954	4,970	7,668
TOTAL INCOME	**5,934**	**9,135**	**12,966**
EXPENCES			
ELECTRICITY	1,280	1,280	1,280
ADMINSTRATION	215	215	215
ZEOLITE	104	125	150
SALARIES	552	552	552
MAINTENANCE	600	600	600
TOTAL EXPENSES	**2,751**	**2,772**	**2,797**
YEARLY RESULT	**3,183**	**6,363**	**10,169**
15 YEAR OWNERSHIP WITH CAPEX 20 MILLION DKK	**27,741**	**75,449**	**132,540**

The payback-time for the entire plant is estimated to be between 3 and 7 years depending on the actual operation and will during 15-year ownership in the standard scenario earn almost five times the investment. The calculations for a plant without water removal is shown in Table 20.

Table 20 – Scenarios for OFT8 in operation with no expenses for water removal included

(1000DKK)	CONSERVATIVE	STANDARD	OPTIMISTIC
OIL PRICE [DKK/KG]	5.00	7.00	9.00
SLUDGE HANDLING PER TON 5%WET [DKK/TON]	0.37	0.43	0.47
TROUGHPUT PER YEAR (WET) [TON]	2,632	2,632	3,158
TROUGHPUT PER YEAR (DRY) [TON]	2,080	2,500	3,000
INCOME			
SLUDGE HANDLING	974	1,132	1,484
GAS AND CHAR	1,125	1,352	1,623
OIL	2,954	4,970	7,668
TOTAL INCOME	**5,053**	**7,454**	**10,775**
EXPENSES			
ELECTRICITY	1,280	1,280	1,280
ADMINSTRATION	215	215	215
ZEOLIT	104	125	150
SALARY	552	552	552
MAINTENENCE	600	600	600
TOTAL EXPENCES	**2,751**	**2,772**	**2,797**
YEARLY RESULT	**2,302**	**4,682**	**7,978**
15 YEAR OWNERSHIP WITH CAPEX 15 MILLION DKK	**19,522**	**55,230**	**104,672**

Looking at the business case in a set-up where investment for water removal is not required, the payback time is calculated to approximately between 2 and 6 years, and in the 15- year ownership scenario, the plant will earn back the investment more than 4 times.

A sensitivity analysis, shown in Table 21, for both business cases was performed to obtain a clearer picture of the impact of the various drivers for the business case. The analysis in made by changing each parameter to its conservative and optimistic extreme and compare the yearly result obtained in the extreme cases with the standard case. If the oil price turns out to be the conservative estimation and everything else is the standard case it would decrease the yearly turnover by 22.3%.

Table 21 –Sensitivity analysis for the business case. Reduction and increase in profit (yearly result) compared to the standard case in percentage for the conservative and optimistic scenario. Left is a setup with water removal and right is setup without water removal.

	MIN	MAX
OIL	-22.3%	21.5%
SLUDGE	-9.2%	3.9%
THROUGHPUT	-24.1%	28.7%

	MIN	MAX
OIL	-30.3%	27.5%
SLUDGE	-3.4%	2.2%
THROUGHPUT	-26.7%	31.8%

The analysis illustrates that the most important driver for profitability is the oil price and the throughput. The oil price uncertainty can be reduced by obtaining confirmations from oil-purchasers and by obtaining certifications for oil quality. Throughput uncertainty can be reduced with more test performances. The income from handling sludge does not affect the business case very significantly.

7. Environmental analysis

In this section, an environmental analysis is carried out to estimate the environmental impact of applying OFT microwave technology compared to other solutions and technologies in sludge handling. The approach is adapted from [12]"Livscyklusvurdering og samfundsøkonomisk analyse for anvendelse af spildevandsslam" by the Danish Ministry for the Environment (Miljøministeriet) from 2013. Some figures are updated to 2019 figures. These include CO2-emissions from electricity (updated to 35.56kg/GJ) and from district heating (updated to 22kg/GJ). Both figures are from average Danish emission data found at Energistyrelsen [18].

The comparison here is between land application of sludge, which is currently used by Aarhus Vand, sludge incineration, in Denmark mainly used on Zealand, pyrolysis technology, and the OFT microwave technology. Calculations are made for each solution/technology and compared at the end of the section.

The solutions are compared after biogas digestion of sludge where much of the sludge's energy content is converted to biogas. Biogas digestion is a well-established technology and a frequently used solution in the Danish waste treatment sector. It seems relevant therefore to assume that sludge has been biogas digested before further treatment. The CO_2 emissions are calculated for the handling of 3,334 Ton sludge with 30% dry matter equaling the CO_2 emissions for 1 ton of dry sludge.

7.1. Land application

After digestion and biogas production the wet sludge is mechanically dried to 25-30% dry matter and transported to nearby fields. This solution ensures that nutrients from the sludge are returned to the fields and some of the carbon contained in the sludge is captured for a long period of time. The drawback of this solution is significant requirements and expenses for transportation, emissions from storage of wet unstable sludge, and potential pollution from microplastics, drug remains, bacteria, virus, and heavy metals.

Sludge cannot be applied to fields all times of the year and will therefore need to be stored for long periods of time. During this storage methane and N_2O gasses are emitted. For every ton digested (on dry matter basis) 8.235kg methane and 0.574kg N_2O are emitted [12]. This is converted to CO_2 equivalents.

$$8.235 \cdot 25 + 0.574 \cdot 298 = 376.79\ CO_{2eq}$$

The transportation of sludge and the application to fields are costly, but short distances decrease the negative environmental impacts of this – at least on a CO_2 basis where it is calculated to just 15.42kg CO_2 per ton dry matter. Transportation and field application do however bring noise and particle pollution from transport and extra road expenditures and odor issues.

Table 22 – CO_2 overview for land application

	CARBON CAPTURE	OIL	GAS	DISTRICT HEATING	ELECTRICITY	OPERATION AND TRANSPORT	NUTRIENTS
LAND USE	-180	0	0	0	0	340	-211

When the sludge is spread, nutrients will be reused, and some carbon capture is achieved. Carbon capture is estimated to 180kg CO_2/ton dry matter [12] of the 391 kg CO_2 savings /ton dry matter that is used for land applications in that study. This leaves 211kg of CO_2 savings/ton dry matter by replacing commercial fertilizer. The summed-up CO_2 emission is shown Table 22.

7.2. Incineration

After digestion and biogas production wet sludge is mechanically dried to 25-30% dry matter and incinerated. When incinerated the mechanically dried sludge can generate surplus energy to run the process and provide district heating (8.8GJ/ton). The process uses electricity(1.3GJ), gas, calcium carbonate, and sodium hydroxide. Data from [12]. The CO_2 emission is seen in Table 23.

Table 23 – CO2 overview for incineration

	CARBON CAPTURE	OIL	GAS	DISTRICT HEATING	ELECTRICITY	OPERATION AND TRANSPORT	NUTRIENTS
LAND USE	0	0	0	-193.6	46.22	113.71	0

7.3. Pyrolysis

After digestion and biogas production, wet sludge is mechanically dried to 25-30% dry matter and goes through a thermal dryer and then the pyrolysis process. This process is combined and uses produced gas and oil to power both dryer and pyrolysis. The output is a carbonaceous char.

Since the process uses self-generated energy its only CO_2 emissions are from electricity consumption. This is estimated to 1.3 GJ/ton. The quality of the carbonaceous char is presently unclear. The high temperature of the pyrolysis-process most likely contaminates the char with PAH and dioxins. It also most likely renders the nutrients of the sludge non-biodegradable and therefore probably not useful as a replacement for commercial fertilizer. It does however clean the sludge from all potential pollutants except heavy metals.

For the present analysis, it is assumed that the contamination of PAH, Dioxins and heavy metals does not affect its useability as fertilizer and carbon capture. The fertilizer contents are set to 50% efficiency compared to land use. This is equivalent to 100% of the phosphor being utilized but calcium and nitrogen not being utilized.

During pyrolysis, the carbon in sludge changes to a more stable form, and therefore a higher amount of carbon will be captured for 100 years or more. Much research is however still needed to estimate the carbon capture potential of carbonaceous char accurately. Some of the carbon will be converted to gas and oil and some to non-stable carbon and thereby reducing the total amount of carbon in the char. There are presently many unknowns. For the purpose of the present analysis, it is assumed that the carbon capture potential is twice that of regular land application. It is also assumed that 6GJ/ton of district heating can be generated. The summed Carbon footprint for pyrolysis is shown in Table 24.

Table 24 – CO2 overview for pyrolysis-processing of sludge

	CARBON CAPTURE	OIL	GAS	DISTRICT HEATING	ELECTRICITY	OPERATION AND TRANSPORT	NUTRIENTS
LAND USE	-360	0	0	-132	46.22	0	-105.5

7.4. Organic Fuel Technology-microwave processing

After digestion and biogas production wet sludge is mechanically dried to 25-30% dry matter. Additional water removal is carried out. The dried matter is then subjected to the OFT microwave process. This process uses electricity for applying water removal as well as running the microwave plant (2.81 GJ/ton).

For analytical purposes, two alternative solutions for operating water removal and microwave processing using the OFT technology are compared. Below these are categorized as OFT 1.0 and OFT 2.0, shown in Table 25.

OFT 1.0 is based on the current design of the OFT technology. The goal will be energy-efficient biofuel production. Therefore, in this technology/market phase, the biochar produced from the process will be used in combustion along with some of the gas to ensure water removal from 25-30% dry matter to 95% dry matter. It is assumed that 80% of the energy used during this process will be re-used for district heating. This leaves oil and most of the gas to replace fossil-based oil (73.3 kg/GJ) and natural gas (56.1 kg/GJ).

OFT 2.0 is the longer-term goal and will produce bio-oil as well as bio-fertilizer. The bio-oil is sold and replaces fossil fuels, while the biochar is cleaned and upgraded to fertilizer with carbon capture. As the OFT technology produces a large amount of oil, relatively little carbon will be left in the char. The carbon will, however, be more stable compared to sludge that is applied on land and is therefore estimated to have the same carbon capture efficiency as land application of sludge.

The relatively low temperatures at which sludge dry matter is processed in the OFT technology is assumed to ensure that a high share of biodegradable nutrients is preserved in the bio-fertilizer (assumed 80%). For the same reason, it is also is assumed that there is no production of PAH and no dioxin formation.

There is a potential for additional CO2-savings in making use of surplus solar or wind power for water removal purposes, using OFT gas as a back-up power source. However, for the sake of simplicity these additional CO2-saving are not included in the calculations.

Table 25 – CO2 overview for OFT-processing of sludge

	CARBON CAPTURE	OIL	GAS	DISTRICT HEATING	ELECTRICITY	OPERATION AND TRANSPORT	NUTRIENTS
OFT 1.0	0	-770.38	-83.59	-109.78	78.58	0	0
OFT 2.0	-180	-770.38	0	-109.78	222.58	0	-168.8

7.5. Comparison

The analysis is summarized in Figure 16 and shows that all of the analyzed solutions contribute with negative CO_2 emissions. It is however clear from this analysis the OFT-technology will not only enable CO_2 neutral handling of sludge but can utilize sludge to power our society with CO_2-neutral fuels. Thus, replacing fossil fuels with biofuels generated from the OFT-process generates a considerably larger negative CO_2-contribution than the other solutions and technologies analyzed here.

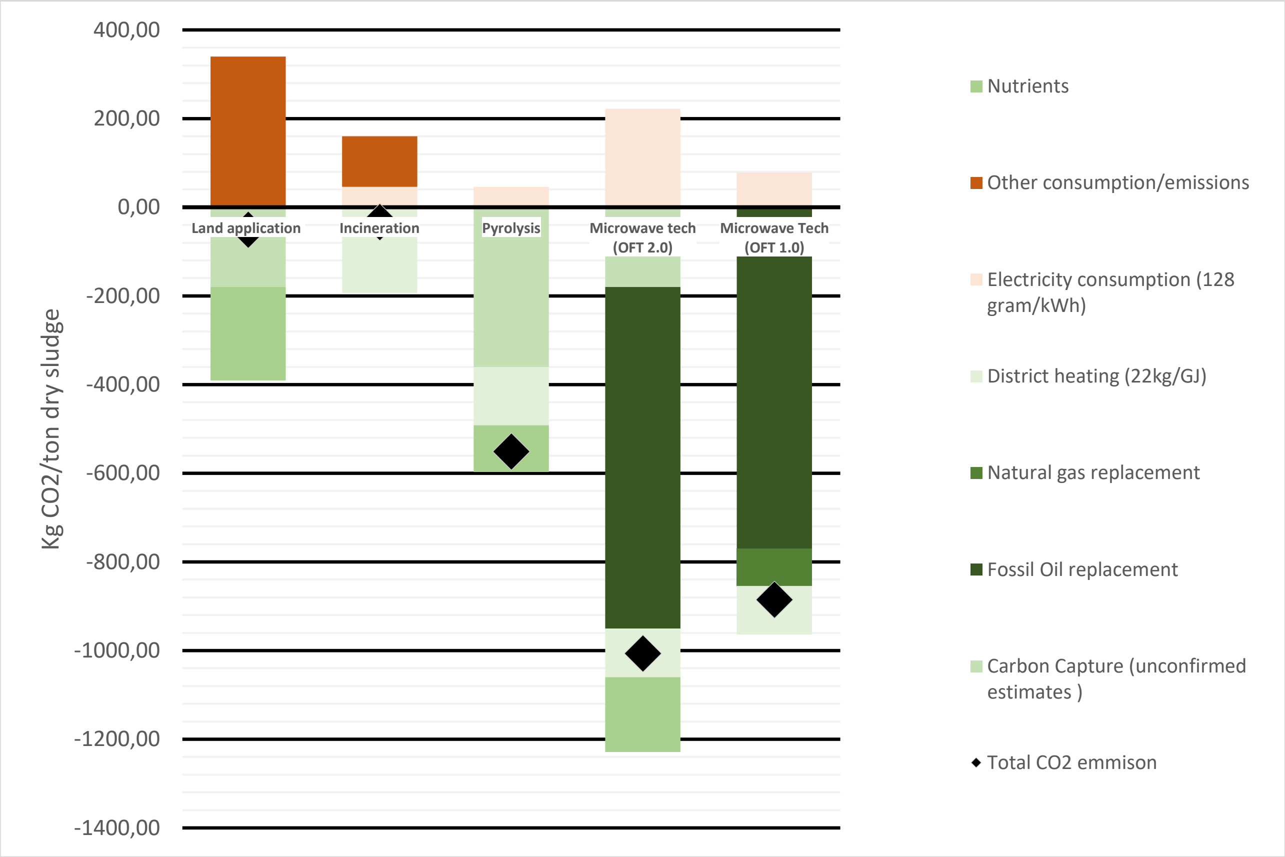


Figure 16 - Comparison chart of the CO2 analysis of different technologies and solutions to wastewater sludge.

8. Uncertainties

8.1. The energy content of dried sludge

One of the most significant uncertainties in this project concerns the energy content of dried sludge. The energy output of the process was significantly higher than the originally assumed input, which was based on the calorific burning value of the dried sludge. Based in this assumption, the resulting energy efficiency was calculated to be above 100%. As this is impossible, the energy content of the sludge must be higher than what has been assumed.

There is, however, a slight chance that the energy of the test run outputs have been over-estimated. But the most reasonable explanation seems to be that the energy content in sludge is underestimated in general if this estimation is based on calorific burning content. OFT has previously experienced similar tendencies with other materials, latest shea which is a waste stream from chocolate manufacturing. In this instance, the energy content of the material was proved significantly higher than originally expected.

As a result, we have set the energy content of sludge as the energy content of the output from OFT processing. This approach also comes with uncertainties. Aarhus University analysis showed an energy content of 17.4MJ/kg and compared to 11.7MJ/kg assumed by Aalborg Forsyning this does indicate an underestimation of the energy potential in the sludge. To overcome this an energy analysis showing electrical to biofuel conversion factors.

8.2. Carbon capture and land application of biochar

The quantified carbon capture is also an uncertainty, as it is unknown to what extend carbon is sequestered in the soil. Biomasses on soil are assumed to have a negative CO_2-emission, but the amount of carbon capture is not yet quantified. This uncertainty applies to the carbon content of wet non processed sludge but also the biochar that trough treatment has its carbon content converted to more stable forms.

Additionally, the possibility of applying both sludge and biochar on soil, are not yet certain. Especially biochar from pyrolysis have yet to prove that the produced biochar doesn't contain a high amount of PAH and dioxin and thereby enable land spreading. There has not yet been any biochar from wastewater sludge spread on land fields, as a commercial product. This constitutes to a huge part of the environmental analysis in pyrolysis. It is also uncertain, whether land application of non-processed sludge can continue due to the many environmental disadvantages related to it.

8.3. Non-digested sludge and oil price uncertainties

There is a possibility that OFT's technology will be able to process activated non-digested sludge. As the water contents of this type of sludge is higher than the water contents of digested sludge at the outset, this will include more water removal. At the same time, however, the non-digested sludge will contain a larger amount of carbon. It is therefore to be expected, that the microwave cracking process will result in more oil and gas produced, which may more than compensate for the additional energy required for water removal. If this is the case, it opens the door to the possibility that the OFT technology could substitute biogas plants, rather than process digested bio-mass waste from them.

The oil, and its price, is a significant uncertainty in relation to the business plan. The oil price has not yet been evaluated by commercial partners and until a "letter of intent" concerning the willingness to purchase

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the produced oil at a given price, the price level will remain an uncertainty. The assumed oil price levels are an estimate made from price data on comparable oils. It is assumed that the OFT oil has slightly inferior properties compared to commercially available bio-oil, and that it therefore may need some upgrading before use. The challenge in upgrading OFT's bio-oil will come down to the oxygen and water content and the general stability of the product.

8.4. Handling of waste streams

There are some waste streams in the process, that have not yet been quantified and the handling of which has not yet been determined. This includes the reject stream from the drying process, as the drying processes for the sludge was within the scope of the current project.

If the char produced from microwave cracking is used to power the drying unit, a reject stream from the kettle and ash will remain from the incineration of char. Additionally, there would be a need for filtration or cleaning of the flue gas from the kettle.

9. Conclusion

From both the initial test and the long representative test run it could be concluded that the developed technology could process and convert sludge into oil. Due to a large amount of water in the sludge, it was not possible to evaluate the throughput of the reactor system and a conservative estimation was done. This estimation has a great impact on the economic feasibility of the demonstration plant, and therefore also adds some uncertainties to the commercial analysis.

The test and analysis showed that OFT technology could produce 27% oil with a relatively high calorific value of 37MJ/kg. There are still some uncertainties with the oil analysis and evaluation, but it does look quite promising.

Since Organic Fuel Technology does not possess water removal technology, research was conducted to present relevant technologies and companies within this sector. This was used to create a full business case with conservative, standard and optimistic scenarios from the sludge-handling company's perspective.

The analysis suggests that the OFT-technology is cost-efficient in with conservative, standard and optimistic scenarios with a payback time between 3 and 7 years and a total negative ownership cost of between mDKK 27 and mDKK 132 over 15 years. A sensitivity analysis was carried out and showed that uncertainties surrounding both the oil price and the throughput quantity of a future plant were the main reasons for the big span in ownership costs.

The environmental analysis and comparison with competing technologies and sludge solutions indicated that OFT's microwave technology is an environmentally attractive choice. Due to the technology readiness, the CO_2 calculation was done for phase 1 of the OFT-technology's application (named OFT 1.0), where the generated biochar is burned for heating, and for phase 2 (named OFT 2.0) where biochar is upgraded to a point where it can be used as commercial fertilizer and the necessary regulation allowing this is in place.

Since both cases result in a significant amount of bio-oil that can replace fossil-based fuels, both phases demonstrate CO_2 savings of respectively 756 and 885 kg/CO2/kg sludge and with a potential to increase this even further.

10. Possible next steps

The project's goal was to obtain indications as to whether or not sludge could be processed by OFT's technology and from there on identify the possible next steps for this technology. The results did however go beyond indications and suggest clear possibilities for making use of OFT's microwave technology in wastewater sludge treatment with both good financial returns and significant environmental benefits.

Therefore, the next step could include planning for and setting up a full-scale OFT8 plant, but while doing so carrying out additional tests on the existing OFT pilot plant. This parallel set of activities can speed up process optimization which will benefit the business case for the first OFT8 plant.

The most significant uncertainty emerging from the analyses of this project concern the water content of the sludge. The level of water content in sludge has significant effects on processing parameters and the reactors' throughput. It would therefore be beneficial to investigate this issue further. Tests with lower water content could be carried out and used to update the throughput calculations for various water contents.

The char ash is believed to be mostly aluminosilicate and might be similar to the zeolite that is used as the process catalyst. It should be investigated whether it is possible to make use the aluminosilicate already present in the sludge, thus rendering the addition of zeolite superfluous. If this is the case, it will ease the process, save resources, and increase sludge processing throughput. It will also ensure a lower content of ash in the char thereby making it more valuable.

Flue gas analyses and combustion of coal is not a part of this study but will be further analyzed later. There is a possibility, that both some of the nitrogen and Sulphur could oxidate forming e.g., NO_x and SO_2. More than 50% of the N ends up in the gas, while 20% of the nitrogen from sludge ends up in the char. The N in the char is assumed available for soil, however it has not yet been analyzed, in what form, the N ends up as.

To validate and improve the business case, market and customers for the bio-circular oil should be analyzed further and assumptions concerning oil price should be confirmed, for instance through letters of intent from major purchasers.

The most important issue with the produced oil is its water content which may be difficult to separate. This may make it difficult to fully upgrade the oil to commercial standards. Research into the oil's use cases in bunker oil, CHP and for refineries should be investigated to identify the maximum potential for the oil.

If it is possible to obtain it, the benefits of extremely dry (99.99 per cent dry) sludge should also be investigated. This very low amount of water input could greatly benefit the oil quality and ensure a lower water content in the resulting oil.

OFT will not be a supplier of sludge de-watering systems but will continue to investigate possibilities and identify potential partners that could take responsibility for the drying units needed for the OFT8 plant. OFT is already in contact with several suppliers of such equipment within the sector, both traditional drying systems and super-heated steam drying systems. Dryer tests should be conducted, implementation, optimal dryer technology and optimal dry stuff percentage should be researched and quantified.

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Appendix A: Overview over alternative sludge handling solutions

Comparative overview over alternative technologies and solutions in sludge handling

Description	Microwave Tech biofuel focus (OFT 1.0)	Microwave Tech biochar focus (OFT 2.0)	Land application	Incineration	Pyrolysis (Estimate)	HTL
General idea:	Before or after digestion (biogas) the sludge is dried and through micro-wave cracking converted to oil, gas, and char.	Before or after digestion (biogas) the sludge is dried and through micro-wave cracking converted to oil, gas, and char.	After digestion (biogas) the sludge is transferred to fields to recirculate the nutrients.	After digestion (biogas) the sludge is incinerated to firstly handle the sludge and secondly to produce district heating	Before or after digestion (biogas) the sludge is dried and through pyrolysis converted to oil, gas, and char.	Before or after digestion (biogas) the sludge is heated (350-400) under high pressure (250 bar) and converted to oil, gas, and char.
Companies / operators	OFT	OFT	Established solution Farmers contracted by treatment facilities	Established technology Wastewater treatment plants	Aqua Green, Biogreen, LVKUN, Beston, Pyrotech and more	Bio2Oil, Licella, and others. Not close to the market. Research review here and here.*
Energy production and energy usage	Oil: 10,51GJ Gas: 1,45 GJ District heating: 4,99GJ Electricity: -2,21 GJ	Oil: 10,51GJ District heating: 4,99GJ Electricity: -6,26 GJ	**None**	District heating: 8,8GJ Electricity: -1,3 GJ Gas: -0,69 GJ	District heating: 6GJ Electricity: -1,3 GJ	Unknown – but about 20% oil efficiency
Non energy consumption and non-energy output	None	Biochar produktion	none	NaOH: -37kg CaCO3: -6,4kg	Biochar produktion	Low energy sludge
Handles: Microplastics	Yes	Yes	No	Yes	Yes	Yes
Handles: Medicine, bacteria, and virus	Yes	Yes	No	Yes	Yes	Yes
Handles heavy metals	Yes	Heavy metals must be removed before the use of biochar as fertilizer	No	Yes	Heavy metals must be removed before the use of biochar as fertilizer	Heavy metals must be removed before the use of biochar as fertilizer
Nutrients back to fields	Trough phosphorus mining	Yes	Yes	Trough Phosphorus mining	In theory no. But pyrolysis operators contest this.	In theory yes
PAH and dioxins contamination	In theory no	In theory no	N/A	No	In theory yes	In theory no
Carbon capture*	No – but CO_2 negative	To some extent	To a small extent	No	Yes	To some extent
CO_2 emissions*	-885 kg CO2/Ton	-1006 kg CO2/Ton	-51 kg CO2/Ton	-34 kg CO2/Ton	-551 kg CO2/Ton	Unknown

Appendix B: Legal limitations on agricultural use of sludge

The current legislation in Denmark for applying sludge in agriculture sets the below maximum limits for the contents in sludge of heavy metals, as seen in Table 26, and other pollutants, as seen in Table 27.

Table 26 Heavy metal limitations in sludge for applying on land fields [19]

	Mg/kg dry matter	**Mg/kg total P**
Cadmium (Cd)	0.8	100
Mercury (Hg)	0.8	200
Lead (Pb)	120	10,000
Nickel	30	2,500
Chrome (Cr)	100	
Zink (Zn)	4,000	
Copper (Cu)	1,000	

Table 27 Other pollutants limitations for applying sludge on land [19]

	Mg/kg dry matter
LAS1)	1,300
PAH2)	3
NPE3)	10
DEHP4)	50
PCB$_7$5)	0.2

1) LAS: Linear alkylbenzensulphonates

2) PAH: Polycyclic aromatic hydrocarbons

3) NPE: nonylphenol

4) DEPH: di(2-ethylhexyl)phthalat

5) PCB$_7$: PCB28, PCB52, PCB101, PCB118, PCB138, PCB153 og PCB180