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# **The Influence of Carbon Additives in Microwave Assisted Pyrolysis and Cost of Energy Regeneration**

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## Preface

This thesis is the product of a collaboration between Scanship ASA and NMBU (Norwegian University of Life Science). The author has been working with product developers in Scanship to gain a better understanding of how different waste compositions affect the overall performance of Scanship's MAP technology (Microwave Assisted Pyrolysis) through literary review and theoretical estimations.

The collaboration came about through an outreach to Scanship in form of a proposition that could benefit both parts. Scanship's MAP technology has, as of the time of writing, not been commercialized yet. This opens up interesting challenges and several problems that require more in-depth analysis, perfect for a master thesis. The proposition was that the student would work with analysing and reviewing literature and in return, Scanship would share their knowledge and provide necessary data for the student's work. More broadly, Scanship will have the possibility to strengthen their already existing relationship with the university and its research departments. As a company experiencing strong growth, exposure to students might also help in future recruitment processes. On the other side of this relationship, the university can continue its work in building bridges between students, academia, and the industry.

As a student of process engineering with focus on renewable energy, Scanship was a natural partner to reach out to with their marked leading position in waste management. This might also make way for future student who want to write their thesis for an industry actor.

Toward the end of the collaboration, it is expected that Scanship will have received helpful insight that will be helpful in bringing the MAP technology to market. The student will in return have gained valuable experience from working in the industry, and mentoring in regards to his master thesis.

As of today, Scanship is working with Sintef Trondheim to further develop their technology. In the future, it is desirable that also researchers from NMBU can get involved in this project to both strengthen the academic departments and better the use of public research grants.



## Preface (in Norwegian)

Denne oppgaven er produktet av et samarbeid mellom Scanship ASA og NMBU (Norges Miljø- og Biovitenskaplige Universitet). Forfatteren har jobbet med produktutviklere i Scanship for å utvikle en bedre forståelse for hvordan forskjellige avfallssammensetninger påvirker produksjonen på Scanships MAP teknologi (Mikrobølge Assistert Pyrolyse) gjennom litteraturstudie og teoretiske beregninger.

Samarbeidet oppsto gjennom et forslag ovenfor Scanship som kunne gagne begge parter. Scanships MAP teknologi har, på det tidspunktet dette skrives, ikke enda blitt kommersialisert. Dette åpner opp for interessante utfordringer og flere problemstillinger som krever grundigere analyse. Forslaget var at studenten skulle jobbe med analyse og gjennomgang av litteratur, og til gjengjeld ville Scanship dele deres kunnskaper og tilgjengelig gjøre nødvendig data for studentens arbeid. Mer generelt vil Scanship også få muligheten til å styrke sitt allerede eksisterende forhold til universitetet og dets relevante forskningsavdelinger. Som et selskap i sterk vekst, kan eksponering mot studenter også være en fordel i fremtidige rekrutteringsprosesser. På den andre siden av dette forholdet vil universitetet få en god mulighet til å fortsette brobyggingen mellom studenter, akademia, og industrien.

Som en prosess ingeniør med fokus på fornybar energi, var Scanship en naturlig partner å henvende seg til med deres ledende posisjon innen avfallshåndtering. Dette kan også bane vei for fremtidige studenter som vil skrive sine hovedoppgaver i samarbeid med aktører fra industrien.

Mot slutten av samarbeidet er det forventet at Scanship vil ha fått verdifull innsikt som vil være til hjelp med å få MAP teknologien ut på markedet. Studenten vil til gjengjeld ha opparbeidet seg verdifull erfaring fra industrien og hjelp med fremdriften i oppgaven.

Per i dag jobber Scanship med Sintef i Trondheim for å utvikle teknologien videre. I fremtiden er det ønskelig at også NMBU kan være involvert både for å styrke sine akademiske miljøer, og for å få en mer effektiv utnyttelse av offentlige forskningsmidler.



## Abstract

Microwave pyrolysis has seen a surge in attention since the mid 90's. Pyrolysis is the process of heating in the absence of oxygen. Conventional pyrolysis heats a cavity filled with waste, often with electrical or gas heating, while microwave pyrolysis utilizes microwaves as the source of energy, resulting in less heat loss and a more efficient heating, applying heat directly in to the waste, as opposed to heating from the outside and relying on conduction heating throughout the cavity. The products from pyrolysis are syngas, bio-oil, and bio-char. Organic waste is generally viewed as a poor microwave absorbent, so additives are commonly used to increase the absorption properties of the waste. Adding a small portion of the bio-char back to the waste is a simple and cheap solution, as carbon is considered a good microwave absorbent. The effects of adding bio-char has been evaluated based on current research and estimations have been done in order to determine how additives affect the mass balance of a microwave pyrolysis process involving a waste mixture of equally weighted wood, plastic, and dry sewage sludge. As well as evaluating the additives, an economic assessment highlights the cost and potential savings related to microwave pyrolysis. It was found that 5-10 wt% bio-char additive significantly increases the microwave absorption properties, without decreasing the amount of syngas a lot. When considering the alternative cost of waste management, the potential value of bio-char, and the energy regeneration, a microwave pyrolysis system might have an internal rate of return of as much as 17.5%. The potential for commercialization, however, is still uncertain as the current literature is based on small scale testing and more and better large scale tests are needed.

## Abbreviations

MAP	-	Microwave assisted pyrolysis
CP	-	Conventional pyrolysis
Wt%	-	Weight percentage
Vol%	-	Volumetric percentage
MW	-	Microwave
MC	-	Moisture content
GHG	-	Greenhouse gas
CCS	-	Carbon capture and storage
MSW	-	Municipal Solid Waste
NOK	-	Norwegian Kroner
Eq.	-	Equation
MC	-	Moisture content
IRR	-	Internal rate of return
NPV	-	Net present value
HP	-	Horse power



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## 1. Introduction

The concentration of carbon in the earth's atmosphere is now higher than it has ever been in at least 800 000 years [1] . There is no reasonable doubt that human caused greenhouse gas emissions (GGE) are impacting the global climate and major habitats in an unprecedented way [1]. At the current rate, this may lead to huge socio economic problems for the world community, with already an average of 27.5 million climate refugees a year between 2008 and 2013 [2], caused by increases in flooding, drought, sea level rise etc. In addition to this, the per capita consumption of non-renewable resources in the world is also increasing [3]. This has triggered several initiatives, both local and international, to reduce GGE.

Alongside the ever increasing warnings from academia, the public also looks towards green initiatives in business. Implementing green solutions parallel to existing energy infrastructure is also perceived as a good part of the solution, using for example energy saving technology.

International bodies, like the UN, EU, IMF, IEA and IMO, have all stated that combating climate change should be a priority in the century to come [4] [5] [1] [6] [7]. This, combined with an increased focus on sustainability from consumers, has triggered an even larger interest in energy savings and -efficiency from both businesses and consumers around the world.

In addition to the threat of climate change, the need for new energy sources is also found in the uncertainty of future oil availability. Peak oil is a term that is often used, referring to the point in time where oil extraction is at its maximum [8]. Even though the exact point in time is heavily debated, there is reason to believe that oil will have to be replaced by other energy sources regardless of whether or not climate is the main concern. Even though there might not one single source that will replace oil and natural gas, hydrogen (H<sub>2</sub>) might be one replacement [3] and therefore be of greater importance in the future due to its versatile usage. In that case, syngas from MAP might experience higher demand due to its H<sub>2</sub> contents. In addition to this, the world's production of biosolids is increasing [3]. With increasing access to biosolids and a need for more efficient use of resources, the

future market for waste-to-energy solutions should be bright, with the potential only from China amounting to 160 000 GWh/year from food waste alone [9].

Some waste is recovered in the world today, but a lot is also burned. Burning waste without utilizing the generated heat is certainly an inefficient way to reduce the need for fossil fuel. In addition to burning, a lot of waste, especially contaminated waste, is stored at landfill facilities [10]. This poses several risk factors, like soil contamination in both short and long term and damage to public health.

## **1.1. Introduction to MAP**

Microwave assisted pyrolysis is a quite new process, first developed by Tech-En Ltd. in Hainault, UK in 1994 [11].

Microwave assisted pyrolysis is a way of converting biosolids in to biogas (syngas), biochar, and bio-oil. The pyrolyzation process occurs when a material is heated in the absence of oxygen inside a cavity. There are several ways to heat up biosolids for pyrolyzation, for instance indirect heating or electric heating. Using microwaves as the source of energy has its advantages and disadvantages. Microwave heating will result in a more efficient heating of biosolids, but it will depend on the composition of said biosolids. The efficiency of the heating comes from the rapid heating, or heating rate, that provides less heat loss than other technologies [10]. Some materials are more receptive to microwaves, while microwaves will travel practically straight through others. Plastic, for instance tend to be very transparent for microwave radiation, while carbon and water are considered great absorbents [12]. This means that in order to have an efficient pyrolyzation process, there will have to be absorbent materials, such as carbon, in the biosolid mixture. The non-absorbent materials in the mixture will then be heated indirectly by the other the more absorbent materials.

Regarding pyrolysis, there is a classification difference between conventional pyrolysis (CP) and microwave pyrolysis (MWP), often referred to as microwave assisted pyrolysis (MAP). The difference is in what way the pyrolyzing material is heated. CP applies heat from the outside, most often electric heating. This makes the material heat from the edge



and gradually towards the centre of the mass through conduction heating. MAP will heat the given substance in a more uniform matter, by penetrating deeper, not only depending on conduction heat. Figure 1 illustrates how MW heating penetrates the heating material, while CP heats from the outside inwards [13].

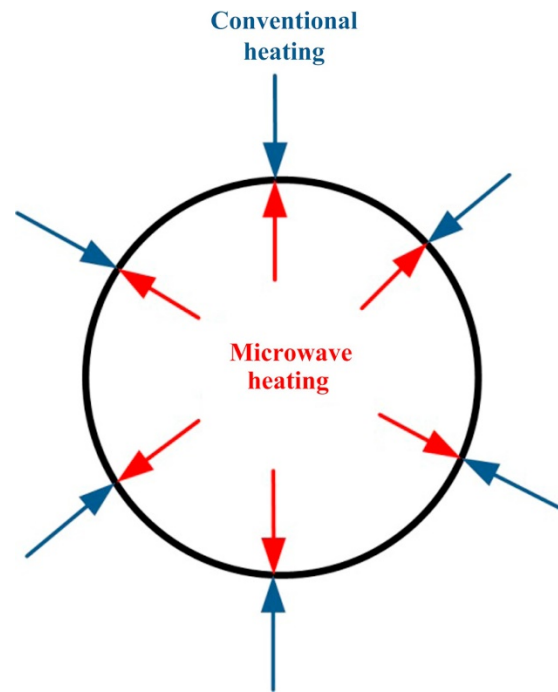


FIGURE 1: HEATING PATHS OF CP AND MAP [13]

The differences in heating profile is not the main differences regarding CP and MAP. Studies show that CP and MAP will yield different compositions of products. CP pyrolysis tends to yield more bio-oil, while MAP tends to produce more bio-char, though the total weight loss is higher with MAP, especially under 300°C [14] [15] [16].

Despite being a well-known process, MAP has yet to fully make it from research and development in to the realm of business and industry.

Microwave pyrolysis heats a substance in three different forms of dielectric heating. One is what is called dipole polarization, where the motion of the molecules generates heat. The way this happens is that the poles of polar molecules try to align with the microwave field. Heat is released from what is called intermolecular resistance to the motion, leading to increasing molecular vibration and energy within the molecules [3]. The other way substances are heated is from what is known as the Maxwell-Wagner depolarization. This happens between two materials with different dielectric properties or if the heated

material contains free electrons that can move freely. Carbon is one such material, and is therefore considered ideal for microwave heating [17]. The dielectric properties are fundamental for understanding the MAP process and will be elaborated upon in chapter 2.1 and 2.2. The third is conduction heating, meaning heat is transferred from a hot particle to a cooler particle [10]. For example, coal heated by microwave radiation, will heat up surrounding plastic, even though plastic is a poor microwave absorbent. Figure 2 shows one possible future use of MAP, where plastic waste has been converted into bio-oil.



FIGURE 2: PICTURE SHOWING PLASTIC BEFORE AND AFTER BEING PYROLYZED INTO BIO-OIL [18]

## 1.2. MAP Flow Diagram

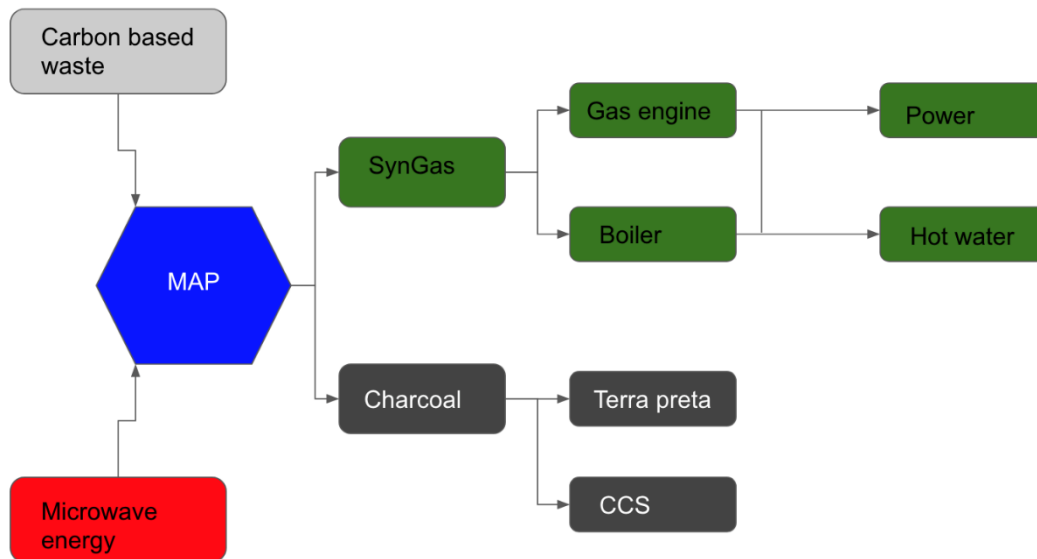


FIGURE 3: FLOW DIAGRAM WITH CONVERSION OPPORTUNITIES

Figure 3 shows a flow diagram based on the Scanship ASA MAP process, but is similar to any given MAP process. What is not included in this flow diagram are the liquid bio-oil products. The current setup consists of the microwave energy and carbon based waste entering the MAP cavity, where it is pyrolyzed at 450-550°C. From the cavity, syngas and charcoal is collected. Added on the flow diagram is also possible opportunities for utilization of charcoal and syngas. The energy from burning syngas may be used as fuel for a gas engine or hot water boiler, among other things. The potential for generating electric energy from a steam powered engine is quite easy to calculate using the Rankine cycle [19]. The charcoal may be used for terra preta, a soil improvement by adding carbon, or directly stored through other ways of CCS. The condensate is not included in this sketch, but does represent a potentially valuable source of energy that may be used, for example, to produce biodiesel.

### 1.3. MAP Process Description

Before the waste enters the MAP cavity, where the flow diagram in figure 3 begins, the waste goes through several stages. Biosolids will often have to be dried before entering any waste to energy process because extensive amounts of water will decrease the energy efficiency of the system and lead to lesser quality products.

For biosolids from sewage sludge, the sludge will go through a dewatering process in the form of centrifugation. The centrifugation process will separate the solids from the water. The amount of water that is extracted from the sludge will depend on centrifugation type, centrifugation time, and effect.

After centrifugation, the waste will proceed in to a dryer. At this stage, the biosolids from sludge will be mixed with other waste before entering the dryer, where the amount of water extracted will depend on both heat, dryer type, and residence time.

After the drying process, the waste is mixed with dry waste, like plastic, cardboard and wood. When All of the waste is dry and mixed, it will be fed into a shredder. The shredder breaks down the waste into smaller pieces and passes it through a sieve, before a conveyor belt transports the waste into a pellet press.

The pellet press transforms the waste from a loose mass to packed pellets. There are several different options in regards to pellet diameter, the ideal diameter depending on several factors regarding the process design. In the Scanship MAP process, the pellets are 12 mm in diameter. This is because bigger pellets have been shown to potentially clog the system by getting stuck, most commonly stuck in sensors along the way. Smaller pellets also pose a risk of clogging by getting stuck in cracks and crannies along the pipes through the system.

From the press, the pellets are transported to a feeding silo, located above the cavity. A feeding screw will transport the pellets to the cavity when level measurements signal low. The feeding stops when a separate level measures high. This makes it a semi-continuous process with a steady flow of small batches. The pyrolyzed pellets are transported out of the cavity through a transport screw that is located at the bottom of the cavity. The discharge rate is decided by the feeding rate of the transport screw.

The gaseous products are extracted from the cavity using a fan. Out of the cavity, the gas goes through four separate condensers where bio-oil and water is removed using pumps. The syngas is transported further on through the fan. In its current set-up, the syngas is burned, but it could be stored or be used for power generation.

## **1.4. Competing Technologies**

The MAP process is versatile in its use, because of its potential for compact design and the differences in waste it can handle. This makes incineration and anaerobic digestion perhaps the biggest competitors in the waste-to-energy segment. Incineration can be performed in a compact manner, while anaerobic digestion may be performed in a cost-effective way given the time and space.

### **1.4.1. Incineration**

One of the main technologies competing with MAP, is incineration. During a incineration process, waste is enclosed in a furnace and burned. To perform the combustion, liquid fuel such as for instance diesel is added to the furnace. This results in a well performing process for mass reduction and heat recovery. The problem with incineration is that there are a lot of toxic particles released during the process [10]. These toxic particles, particularly polycyclic aromatic hydrocarbons (PAHs) and chlorinated hydrocarbons (CHCs) pose a risk to public health [20].

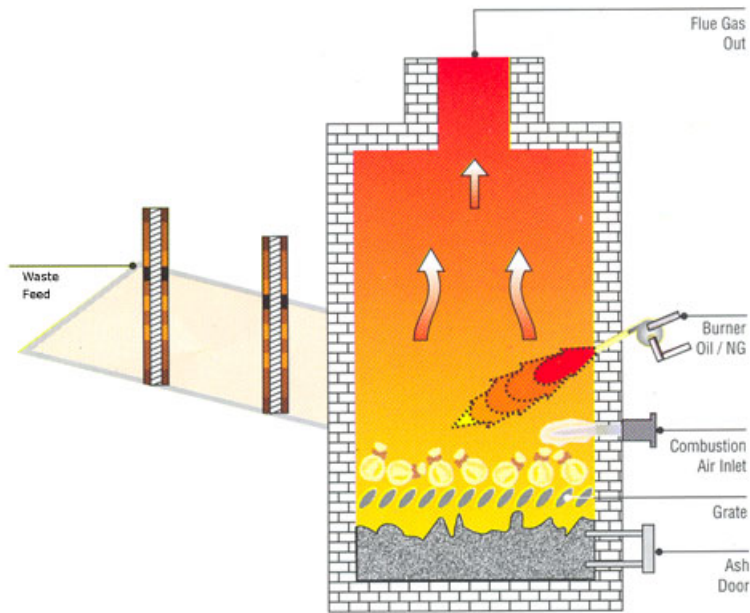


FIGURE 4: SKETCH OF THE INCINERATION PROCESS [21]

Cleaning the gases before releasing into the air is not hard, however, but it is a fairly costly process [10]. Figure 4 shows a sketch of the incineration process. Waste is fed in to the furnace alongside air and burner oil/ gas. The ash is left on the bottom, while the gaseous products are extracted at the top. The sketch does not include a heat recovery apparatus, a common supplement to the incineration process.

#### 1.4.2. Anaerobic decomposition

While incineration is a relatively compact process, anaerobic decomposition is more space consuming. The process is a decomposition of organic material or waste in an environment free of oxygen. In the case of waste to energy, this process is used for extracting biogas in the form of methane and carbon dioxide. The ratio between  $\text{CH}_4$  and  $\text{CO}_2$  in biogas is 55-70%  $\text{CH}_4$  and 30-45%  $\text{CO}_2$  in addition to other trace elements [22].

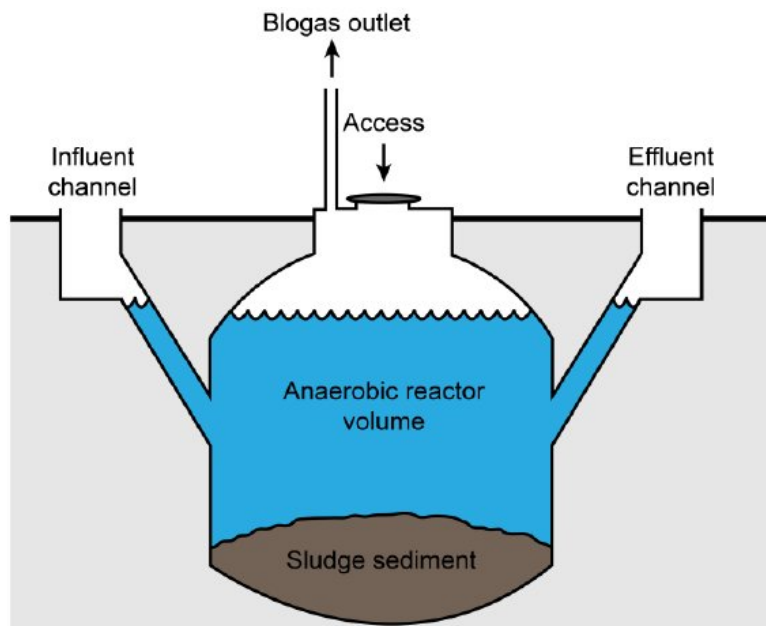


FIGURE 5: SKETCH OF ANAEROBIC DECOMPOSITION [23].

Figure 5 is a sketch of anaerobic decomposition. The process is relatively simple, because the waste only needs time and absence of oxygen. This also makes it potentially cheap [23], but time consuming.

## 1.5. Problem formulation

The problem formulation for this thesis is as follows:

*In what way will varying carbon contents of the waste affect the mass balance of the MAP system and what are the operational costs associated with running the MAP on a daily basis?*

## 1.6. Purpose

Before MAP is fully commercialized, there are still gaps to be filled in regards to the efficiency of the system. One of these gaps is how the microwaves are absorbed in different substances. More specifically, the theory states that a higher carbon content will increase the energy absorption in the pelletized waste and thus increase heating efficiency. This is due to the dielectric properties of different substances, described in

chapter 2.1-2.2. In turn, this implies that adding carbon to the in-feed will increase energy absorption from the microwaves. However, it is uncertain at what level of carbon add-in the overall efficiency of the system will start to decrease.

In the process of increasing efficiency, there is also a need to look at other parameters that are related to the dielectric properties or the composition of the pyrolyzed products. This would be:

- the heating rate of a given waste composition
- the required energy input
- the penetration depth of the MWs

To gain a better understanding of how these factors are related, existing literature will be presented along with calculations and estimations for how they are connected. Hopefully, this will contribute as a theoretical basis for how added MW receptors along with varying product compositions will change the output of gas, oil, and char.

Given how a substantial part of the pyrolysis literature is based on single tests performed on one given substance, this thesis might serve as a basis for further testing that might be needed to verify/discard the conclusions given.

Rebuilding a test facility is expensive and time consuming. It is therefore worth studying these issues more in depth before building a new set-up solution to any existing MAP system. The absorption properties of different types of biomass at different conditions may provide satisfying answers. This includes looking into dielectric properties, penetration of microwaves, heating rate, and pyrolyzation time. By varying the carbon contents of the waste compositions, hopefully significant changes in mass balance is achieved to draw solid conclusions.

Besides carbon, there are several other great microwave absorbers. This includes iron and aluminium, among others. The reason for using carbon as an absorbent add-in is the cost and availability. While some absorbents are costly and not easily accessible, carbon can be collected from the products of the MAP. It is also assumed that using carbon simplifies the process as other absorbents might have to be removed from the end products after the pyrolyzation process is completed.



If the results from literature and simulation are conclusive enough, adding a feedback loop to a MAP process system should be considered. This feedback loop will transport a given amount of carbon from the discharge and add it to the shredder to increase the carbon content of the pellets.

In regards to the economic aspect of the MAP system, this is necessary to assess before commercialization. In order for future customers to be satisfied, they must be provided with reliable data for future cost and savings.

## **1.7. Limitations**

To answer the problem formulation in an satisfactory manner, it would be ideal to perform tests specifically designed to answer this. When formulating the problem, this was also the plan, but limitations on test facilities and equipment forced the project in another direction, focusing on existing literature and drawing conclusions from that. The limitations on performing tests at the Scanship MAP test facilities included problems with homogenizing the waste composition, delays because of improvements being made and the unforeseen need for more urgent tests that appeared. The next step was to look at the possibility of small scale testing, which required another set of equipment and access to a laboratory facility. Neither of this was possible, so a literary weighted study was left as the only viable option. When possible and relevant, however, older test data from Scanship has been used.

In order to pelletize the waste before entering the MAP, the waste must be dried to prevent too high pressure in the cavity and too long residence time that may potentially reduce the efficiency of the system. In a commercial set-up, there would be a drying process for wet waste before entering the MAP cavity. The cost evaluation in this thesis is, however, primarily focused on the pyrolysis process. It is not given that estimating drying costs would be of great value either, given that different industries deals with different types of waste and consequently different needs for drying.

## 1.8. Pyrolysis Reactors

In the pyrolysis literature, cavity and reactor are often used interchangeably, and there are many different types of pyrolysis reactors. In choosing a reactor for pyrolyzation, the process parameters and desired product outcome should be factored in. In order to seal the reactor and minimize the oxygen levels inside, inert gas is often encapsulated around the reactor, most commonly nitrogen [24]. Some of the most common reactors are [25]:

### 1.8.1. Rotating Cone Reactor

In the rotating cone reactor, biomass and hot sand is fed into the bottom of the reactor. The rotation of the cone exhibits a centrifugal force on the biomass, pushing the heavier particles to the side of the cone. The cone-shape makes the particles move upward and exit the reactor from the edges on the top. The gas is transferred from the reactor over to condensers for separation of bio-oil and syngas, while parts of the bio-char and sand is reheated for further use [26].

### 1.8.2. Fluid Bed Reactor

In a fluid bed reactor, there is a bed of fluid-solid mixture heating up the pyrolyzing waste. The fluid is pressurized through the solids, resulting in rapid thermal transport. This method is therefore ideal for fast pyrolysis [25] [26]. A fluid bed reactor is depicted in figure 6.

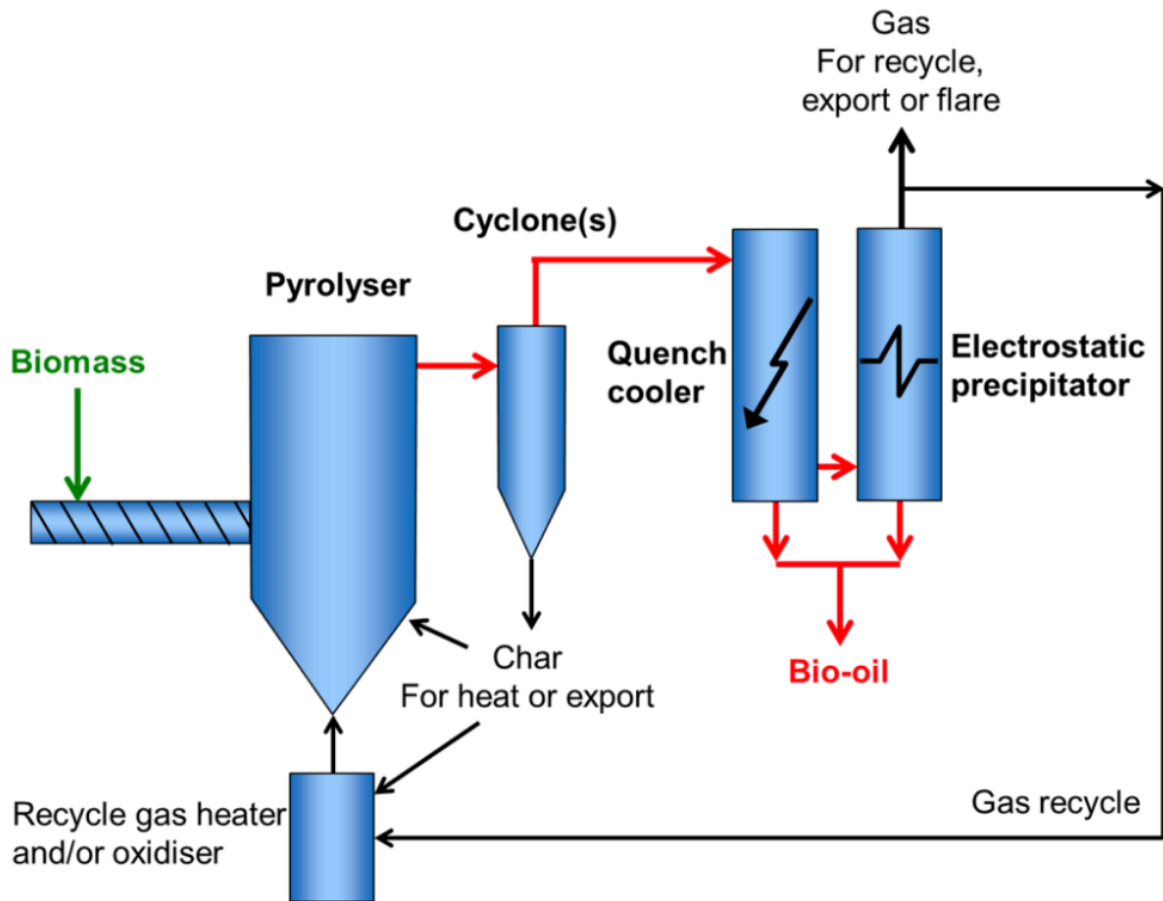


FIGURE 6: FLUID BED REACTOR [25]

### 1.8.3. Circulating Fluid Bed Reactor

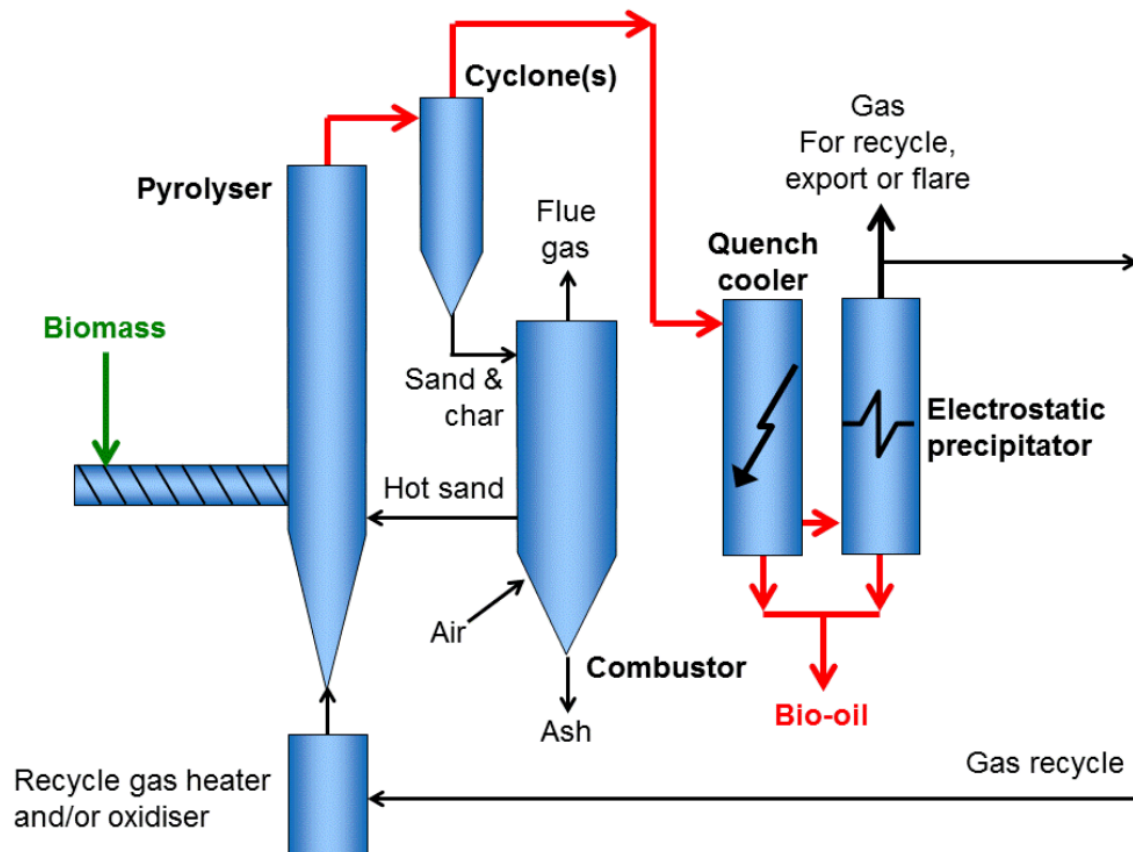


FIGURE 7: CIRCULATING FLUID BED REACTOR [25]

The circulating fluid bed reactor in figure 7 shares a lot of similarities with the fluid bed reactor, but the residence time for gas, liquid, and char is almost the same. This reactor is commonly used in the petrochemical industry, due to its large capacity. The heat in this system comes in large part from heated sand [25].

### 1.8.4. Screw Reactor

In a screw reactor, the solids are transported through the reactor with a transportation screw. Heat is applied from the outside, so the material is pyrolyzed while moving, as figure 8 shows. The in-feed and out-feed is located in opposite ends of the screw, while vapour is transported from the top and further into condensers where syngas and bio-oil is separated [25].

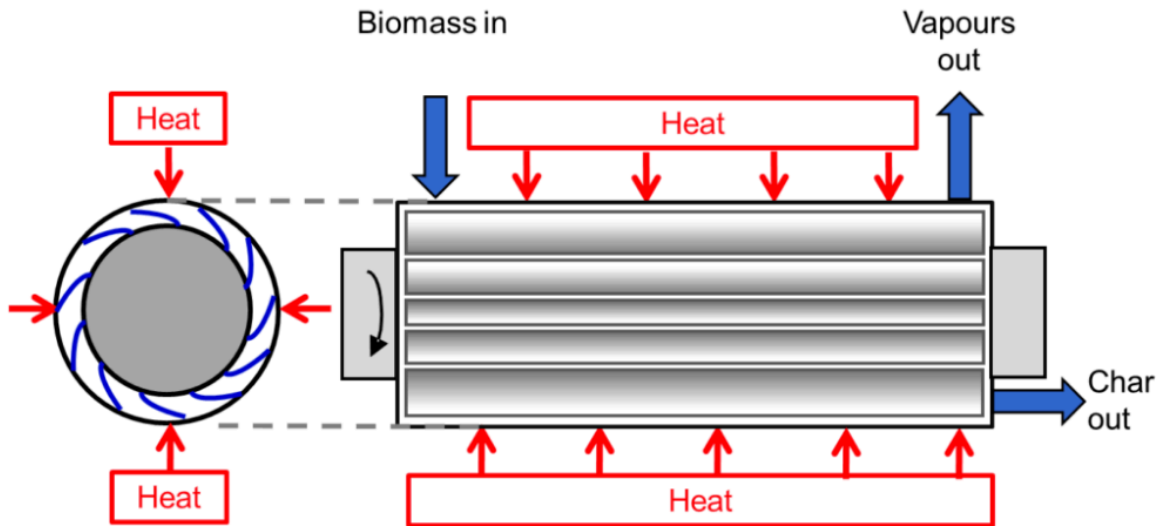


FIGURE 8: SCREW REACTOR [25]

### 1.8.5. Microwave Reactor

The microwave reactor is used when applying heat through microwaves. It consists of a hollow glass cylinder surrounded by a nitrogen filled space between the glass and the outer casing of the cavity. The specific design varies greatly from manufacturer to manufacturer, but the principle of MW transparent glass incapsulated with nitrogen is shared by most large scale MAP plants [27]. In smaller lab scale tests, there is a greater variation in the set-up depending on both budget, the main objective of the tests, among other things.

## 2. Theory

### 2.1. Microwaves

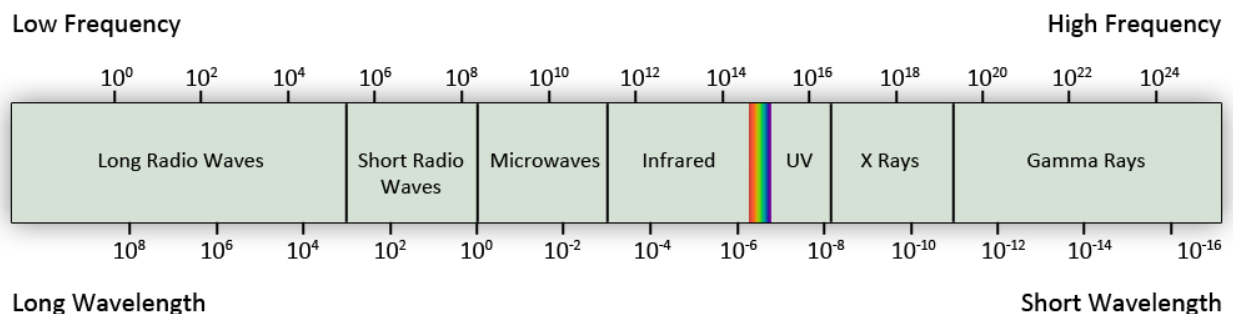


FIGURE 9: THE ELECTROMAGNETIC SPECTRUM [28]

Figure 9 Shows what is called the electromagnetic spectrum. Electromagnetic waves are waves of energy traveling at the speed of light [29]. The true nature of electromagnetic

waves still contains knowledge gaps among physicists, but the utilization and energy contents are quite well understood. MAP relies on microwaves. Microwaves are electromagnetic waves in the frequency range of 300 MHz to 300 GHz with corresponding wavelengths of 1m to 1mm, as figure 9 shows [14]. MAP is performed at a frequency of 915 MHz or 2.45 GHz with corresponding wavelengths of about 12 and 33 cm.

### 2.1.1. Microwave structure

In order to understand the MAP process, it is worth looking into microwaves and their properties. Microwaves are a type of electromagnetic radiation, just as radio waves or visible light. As the name implies, electromagnetic waves consist of both electric and magnetic fields. The electrical component is generally expressed as  $\vec{E}$  and  $\vec{B}$  for the magnetic wave.

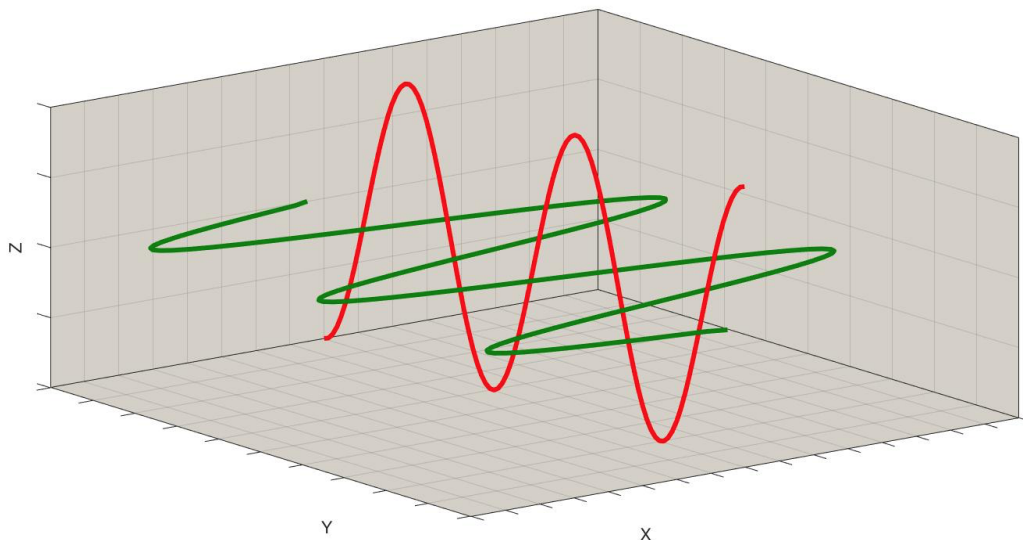


FIGURE 10: ILLUSTRATION OF AN ELECTROMAGNETIC WAVE, WITH THE ELECTRIC AND MAGNETIC COMPONENT AT AN 90 DEGREE ANGLE.

Figure 10 is a representation of an electromagnetic wave. The motion of the wave is sinusoidal, with the electric and magnetic components visualized in different colours – red and green. These are traveling at a 90 degree angle relative to each other.

Microwaves, or more generally - electromagnetism in itself, was not fully understood until James Clerk Maxwell in 1865 formulated proof and later expressed the basic principles of electromagnetism through what is now called Maxwell's equations [29]. Even though not discovered by Maxwell himself, he is credited with relating them to each other and seeing the significance of them [30]:

**Gauss's law for  $\vec{E}$**

$$\oint \vec{E} \cdot d\vec{A} = \frac{Q_{encl}}{\epsilon_0} \quad (1)$$

Where  $\vec{A}$  is area

$Q_{encl}$  is total charge enclosed within the surface

$\epsilon_0$  is the permittivity of free space

What this means is that the surface integral of  $E_{\perp}$  over any closed surface equals  $\frac{1}{\epsilon_0}$  multiplied with the total charge within the surface [31].

**Gauss's law for  $\vec{B}$**

$$\oint \vec{B} \cdot d\vec{A} = 0 \quad (2)$$

Gauss's law for  $\vec{B}$  states that there are no single magnetic charges that can act as sources of a magnetic field, there has to at least one pair [30].

**Ampere's law**

$$\oint \vec{B} \cdot d\vec{l} = \mu_0 (i_c + \epsilon_0 \frac{d\Phi_E}{dt})_{encl} \quad (3)$$

Where  $d\vec{l}$  is the segment carrying a current

$\mu_0$  is the permeability of vacuum

$i_c$  is the conduction current

$\epsilon_0$  is the permittivity of vacuum

$\Phi_E$  is the electric flux

Combined,  $\epsilon_0 \frac{d\Phi_E}{dt}$  is an expression for the displacement current.

What this means is that current causes an electric field [31].

### ***Faraday's law***

$$\oint \vec{E} \cdot d\vec{l} = -\frac{d\Phi_B}{dt} \quad (4)$$

Faraday's law explains how a magnetic field induces an electric current, similar to the magnetic field [32].

#### 2.1.2. Energy in electromagnetic waves

Every single photon of light carries electromagnetic energy. The amount of energy is determined the photon's frequency and wavelength, measured in joules.

$$E = hf = \frac{hc}{\lambda} \quad (5)$$

Where E is the amount of energy in one proton [J]

h is the Planck constant: 6.626 [J·s]

f is the frequency [Hz]

c is the speed of light:  $299.7 \cdot 10^6 \left[\frac{m}{s}\right]$

$\lambda$  is the wavelength [m]

The total amount of energy will therefore be dependent on the amount of protons. In the Scanship MAP process, testing is done with an energy input at 30-70 kW. Even though understanding how a proton carries energy is important in manufacturing a microwave generator, microwave energy is most often referred to in kilowatts or watts, not in joules per proton.



### 2.1.3. Standing electromagnetic waves

Microwaves, as any electromagnetic wave, may be reflected off surfaces. In practical applications of microwave technology, this is a common issue and must in some cases be accounted for. One possible result of wave reflection is standing electromagnetic waves, or stationary waves. In short, this means that there is a point where the amplitude of the wave remains constant [29]. Standing electromagnetic waves can then produce local hot-spots where the energy is concentrated. In developing MAP systems, this may cause problems such as devitrification and inhomogeneous heating inside a cavity.

### 2.1.4. Microwave Heating

Even though microwave energy is easily calculated, the amount of energy that is absorbed by the heated mass will vary depending on the composition of the absorbing material. This is due to the dielectric properties of the material, including the dielectric loss tangent,  $\tan\delta$  [33]. When a material has a dielectric loss factor  $>0.2$ , it is considered to be an efficient absorber of microwave energy [34]. In the case of sewage sludge, the dielectric loss tangent is in the area of 0.06 [33]. This means that sewage sludge is considered a bad absorbent of microwave energy. In order to attain higher temperatures, adding material with higher absorption properties is one option. Table 1 shows the absorbent properties for different carbon based products [33]:

TABLE 1: HEAT ABSORBING VALUES FOR COMMON WASTE MATERIALS

Material	$\epsilon'$	$\epsilon''$	$\tan\delta$
Activated carbon	16.12	27.50	1.71
Charcoal	9.67	11.13	1.15
Bio-char	9.60	9.95	1.04
Bio-solids	1.39	0.06	0.04

$\epsilon''$  is the dielectric loss factor. It is a value attributed to materials to determine their efficiency in regards to converting microwave energy into thermal energy.  $\epsilon'$  it the

dielectric constant. The dielectric constant is a measurement for the ability a molecule has to be polarized [3]. The dielectric loss tangent,  $\tan\delta$ , is the ratio between  $\epsilon''$  and  $\epsilon'$ :

$$\tan\delta = \frac{\epsilon''}{\epsilon'} \quad (6)$$

It is important to remember that microwave distribution in a cavity is not as straight forward as the theory suggests. Water contents, among others, in the waste will affect the microwave distribution and the dielectric properties may decrease with decreasing water contents [3].

The  $\tan\delta$  value is dependent on several factors, such as temperature, microwave frequency, and moisture content. The variation of the dielectric constant and the dielectric loss factor in regards to MW frequency and moisture content is shown in figure 11 [3]:

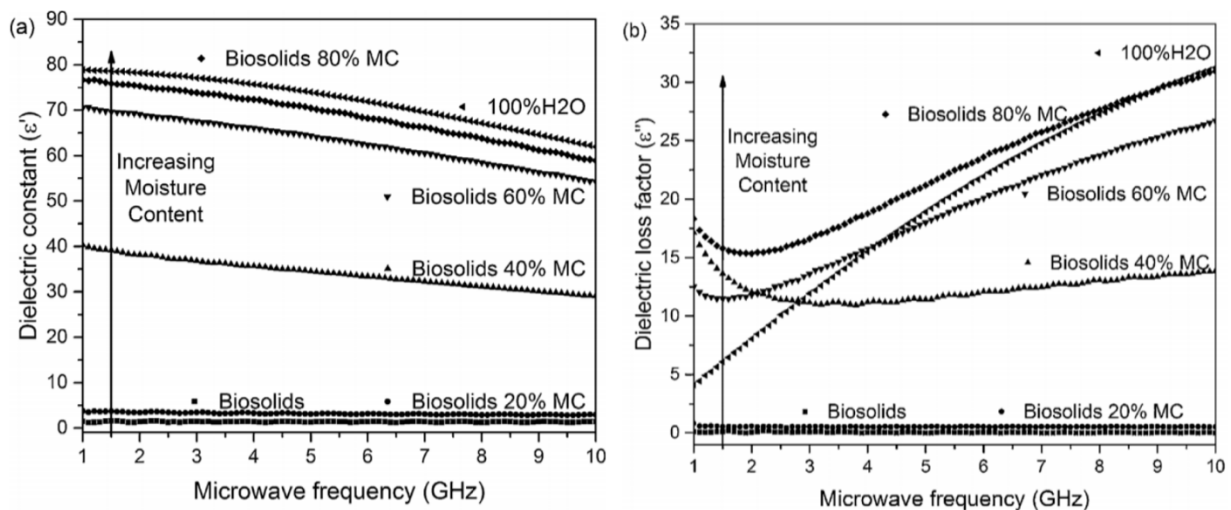


FIGURE 11: DIELECTRIC CONSTANT (A) AND DIELECTRIC LOSS FACTOR (B) WITH VARYING MOISTURE CONTENT (MC) AND FREQUENCY

The MW power output in MAP is usually performed at a constant frequency. The graphs show small variations in the dielectric properties in the range of 0-20% MC. The moisture content will affect the power requirements for heating, but it will also affect the syngas composition. In chapter 2.5 the reaction MC equations for syngas production are given, showing that increased levels of  $H_2O$  will yield more  $H_2$  and  $CO$ , which in turn will react and give an increase of  $CH_4$  (eq. 14 – eq. 17).

Besides the carbon based MW absorbents, there are several other highly efficient substances to be used. Among the more efficient absorbents, there are several metal based ones, such as Iron (Fe), Copper oxide (CuO), calcium oxide (CaO), iron oxide (Fe<sub>3</sub>O<sub>4</sub>) etc. [35] These additives are, however, often expensive and may contaminate the bio-char.

#### 2.1.5. Dielectric mixtures

In order to determine the dielectric properties of solid mixtures, an approximation must be calculated. There are several different equations for estimating the dielectric loss factor and the dielectric constant [36] [37]. The following formula has been applied in calculating dielectric properties [36]:

$$\varepsilon_e = \Phi\varepsilon_1 + \Phi\varepsilon_2 \quad (7)$$

Where  $\Phi$  is the fraction of given substance.

Eq. 7 is assumed to be extendable to:

$$\varepsilon_e = \Phi\varepsilon_1 + \Phi\varepsilon_2 + \dots + \Phi\varepsilon_N \quad (8)$$

Jouban et. al. also lists three other equations for determining the dielectric properties of mixtures [36]:

$$\ln \varepsilon_m = \phi_1 \ln \varepsilon_1 + \phi_2 \ln \varepsilon_2 + \phi_1 \phi_2 \sum_{i=0}^2 K_i (\phi_1 - \phi_2)^i \quad (9)$$

Where K is the model constant,

$$\varepsilon_m = M_0 + M_1\phi_1 + M_2\phi_1^2 + M_3\phi_1^3 + M_4\phi_1^4 \quad (10)$$

Where M<sub>0</sub>-M<sub>4</sub> are the model constants,

$$\ln \varepsilon_m = \frac{\alpha_0 + \alpha_1 \phi_1}{\beta_0 + \beta_1 \phi_1} \quad (11)$$

Where  $\alpha_0, \alpha_1, \beta_0, \beta_1$  are the model constants.

In analysing the results from tests against the equations, the equations deviated from the final measurements with ca. 1.5-4% in measuring liquid solvent mixtures. Similar studies in regards to solid mixtures have not been as thoroughly conducted.

The model constants in eq. 9 - eq. 11 are representations of the interaction between solute and solvent, and solvent and solvent. This excludes them from any practical use in

regards to solids. Eq.8 has the highest degree of uncertainty, with 4%, but has also been applied in estimating dielectric properties in other studies. It does, however, assume a linear relationship between the different dielectric values, and must therefore be seen as an estimation, not certainty.

## 2.2. Energy and Waste

The amount of energy found in waste will naturally have great variations depending on the kind of waste in question. On board cruise ships, for example, there is a lot of sewage sludge, as one would expect from any compact settlement. There is also a lot of food waste and packaging (cardboard, plastic etc.), all of which contain energy. Estimating exactly how much potential energy is lost in waste at a certain place during a certain amount of time will therefore carry with it uncertainty and should be used as an estimate, rather than a set value.

In regards to thermal energy, the specific heat capacity,  $C_p$ , is often used as an indicator, rather than the total amount of energy. This is because the specific heat capacity indicates the ability to store internal energy while the temperature is changing [38].

TABLE 2: SPECIFIC HEAT CAPACITY OF COMMON SUBSTANCES

Substance	Specific heat capacity [ $\frac{kJ}{kg \cdot K}$ ]
Wood	1.26
Solid waste	1.8
Plastic (PVC)	0.9
Carbon	1.5
Biosolids	1.4

Table 2 shows the heat capacity of dry wood [39], solid waste from landfill [38], solid plastic [40] [32], pyrolyzed wood char [41], and biosolids [42]. These values were presented due to their abundance in waste.

### 2.3. Energy requirements

In order to calculate the energy required to heat a substance, the following eq. is used:

$$E = m \cdot C_p \frac{dT}{dt} [kJ] \quad (12)$$

Where m is the mass [kg]

$C_p$  is the specific heat capacity

$\frac{dT}{dt}$  is the temperature change over time [K]

This value will give an answer to how much energy that must go in to a substance in order to heat it in a given temperature interval.

While pyrolyzing, there will be differences in product composition depending on the heating rate. In order to evaluate the energy requirements for a given heating rate, eq. 13 is applied:

$$E = C_p \cdot HR \left[ \frac{kW}{kg} \right] \quad (13)$$

### 2.4. Evaporation/gasification

In order for substances to release gas, a change of phase is necessary. With increasing temperature, many substances goes from solid to liquid to gas. However, sublimation is the process of going directly from solid to gas form. A well-known example of this is dry ice, the solid form of carbon dioxide, which sublimates from solid to gas in room temperature and atmospheric pressure [43]. As depicted in figure 12, the pressure is not great enough to force the substance over in to liquid form, the result being that the

transition from solid goes directly to gas. This is also what happens to most of the waste during the MAP process when it is pyrolyzed in the cavity.

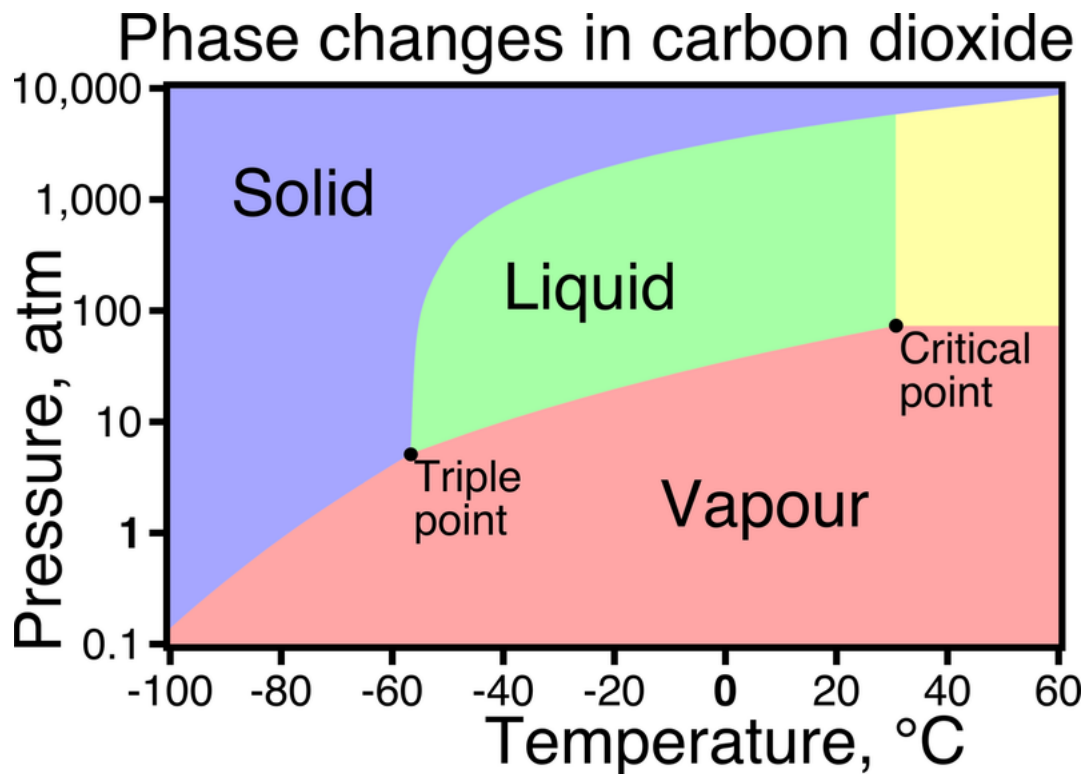


FIGURE 12: EXAMPLE OF PHASE CHANGE IN CARBON DIOXIDE [43]

## 2.5. Syngas

Syngas is a term used for synthetic gas. Even though there is no set definition of the relation between the different components of syngas, it refers to gases containing mainly carbon monoxide (CO) and hydrogen (H<sub>2</sub>) [44] [45]. For comparison purposes, natural gas is composed mainly of methane (CH<sub>4</sub>) [46]. This also gives syngas and natural gas different energy densities and flammability characteristics. A comparison between Norwegian natural gas and syngas gives following higher heating values (gross energy density):

TABLE 3: COMPARISON OF NATURAL GAS AND SYNGAS IN REGARDS TO HHV

	Natural gas (Norway 2018) [47]	Syngas [48]
HHV	39 263 kJ/m <sup>3</sup>	9 300 – 15 000 kJ/m <sup>3</sup>

As table 3 shows, syngas cannot compete with natural gas in regards to the energy contents. The composition of the gases will naturally vary with the different geographical sources for natural gas, and different raw material in the case of syngas from pyrolysis. Syngas is therefore not a product used exclusively to compete with other energy sources, but a product of a pyrolysis process that has a usable calorific value. Given that the calorific value is of great enough value to be utilized, it is only rational that it not go to waste.

Besides the calorific value and composition of syngas, there are a number of other differences. The energy density is a given difference, as table 3 shows, but there are also differences in the contaminants (like H<sub>2</sub>S, hydrogen sulphide) of the gases, and the flammability [48] [44]. This does not, however, imply that syngas is of significantly less utilization in power generating operations on a general basis.

The composition of the syngas is dependent on the conditions of the pyrolysis. Syngas does indeed contain a fair amount of CH<sub>4</sub> and CO<sub>2</sub>. With higher temperatures during pyrolysis, H<sub>2</sub> and CO concentrations increase while the concentration of CO<sub>2</sub> decreases. The changes in CH<sub>4</sub> is not as clear [49].

The chemical reactions that provide the basis for the syngas are the following [50]:

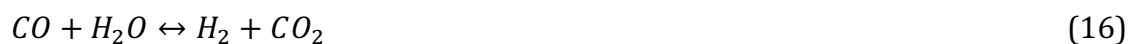


Table 4 shows syngas composition based on pyrolysis of lignocellulose bio-solids [14]:

TABLE 4: SYNGAS COMPOSITION FROM BIOSOLIDS PYROLYSIS

Gas	H <sub>2</sub>	CH <sub>4</sub>	CO	CO <sub>2</sub>
Fraction [vol%]	32	9	33	23

If the moisture contents of the pyrolyzed waste is high, the moisture will lead to an increase of H<sub>2</sub> and CO<sub>2</sub> in the syngas, while it will provide a gaseous mixture with less CO [50], as shown by eq. 16 and eq. 17. It is also the case that slow heating rates tend to yield a greater amount of syngas (section 2.9).

The reactions for producing syngas starts when a substance is heated. As moisture evaporates from the surface of a given compound, the thermal degradation starts. At this time, the production of tar will also start [50]. After the surface moisture is evaporated, the volatile substances of the compound are released. He et. al. breaks it down to two steps when pyrolyzing MSW (figure 13) [51]:

1. Thermochemical decomposition where water, char, tar and other volatiles are produced at temperatures typically ranging from 300-700°C. The remaining particles are devolatilized.
2. Tar cracks and releases mainly heavy hydrocarbons. The heavy hydrocarbons are then cracked again into lighter compounds.



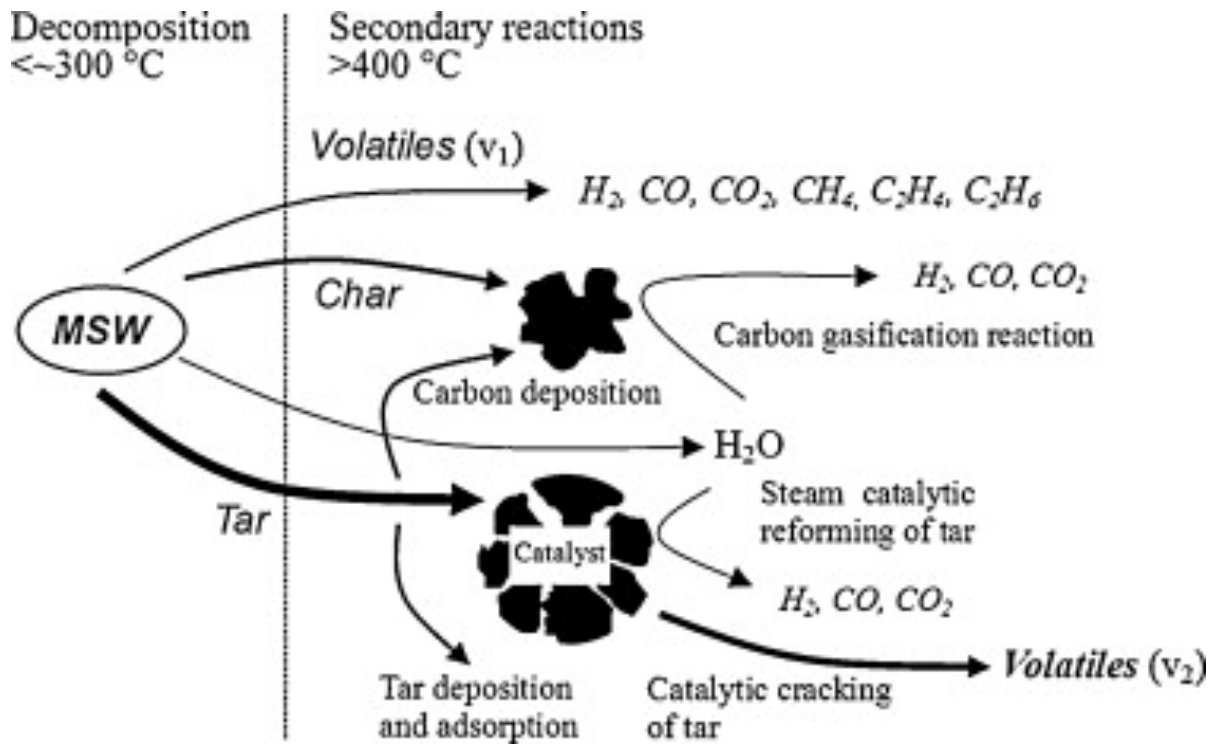


FIGURE 13: SYNGAS FROM MSW USING MWP

He et. al. also showed that the higher temperature pyrolysis is performed at, the more tar will undergo secondary reactions and release lighter hydrocarbons for a higher syngas yield. In addition to the importance of heating rate and pyrolysis temperature, the water content is of great importance in regards to the syngas yield. With water present in the mixture, water-soluble substances are dissolved by the water, resulting in fewer gas products and thus a less ideal syngas mixture [50]. It has also been shown that higher temperatures results in higher yields of  $H_2$  [52]. A higher yield of  $CO$  and  $CO_2$  in the syngas may also be an indication of high contents of oxygen,  $O$ , in the biomass [53]. Further cracking of heavy hydrocarbons may also increase the amount of lighter hydrocarbons in the syngas mixture, like  $CH_4$  and  $C_2H_6$ .

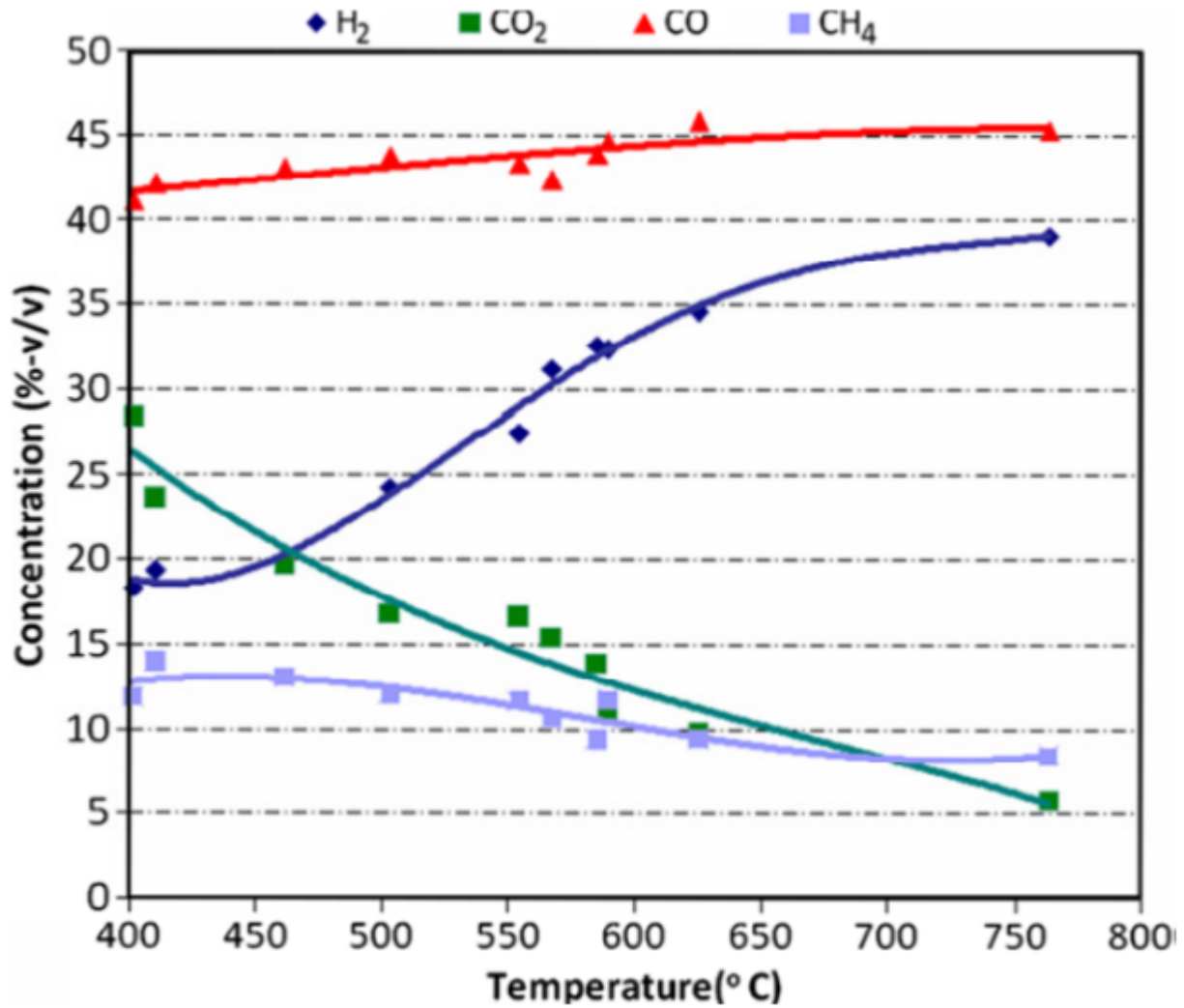


FIGURE 14: CONCENTRATION OF SYNGAS COMPONENTS AT DIFFERENT TEMPERATURES [54].

Figure 14 shows different pyrolyzation temperatures with corresponding different yields and different compositions of H<sub>2</sub>, CO<sub>2</sub>, CO, and CH<sub>4</sub> by cotton stalk pyrolyzation.

There is as of today, little solid research done to produce an equation that will estimate the amount of gas, solid, and liquid yield from a given substance. There is, however, several empirical equations for specific substances that have been produced.

When studying lignocellulosic composition of agricultural waste, Huang et. al produced following empirical observation [55]:

$$H_2 \text{ yield } \left[ \frac{mg}{g} \right] = 0.1331 \cdot H(\text{wt}\%) + 0.0486 \cdot C(\text{wt}\%) + 0.0647 \cdot L(\text{wt}\%) \quad (18)$$

$$CH_4 \text{ yield } \left[ \frac{mg}{g} \right] = 0.1965 \cdot H(\text{wt}\%) + 0.2937 \cdot C(\text{wt}\%) + 0.0854 \cdot L(\text{wt}\%) \quad (19)$$

$$CO \text{ yield } \left[ \frac{mg}{g} \right] = 2.3494 \cdot H(\text{wt}\%) + 3.3577 \cdot C(\text{wt}\%) + 2.0532 \cdot L(\text{wt}\%) \quad (20)$$

$$CO_2 \text{ yield } \left[ \frac{mg}{g} \right] = 1.4510 \cdot H(\text{wt}\%) + 0.8023 \cdot C(\text{wt}\%) + 0.6097 \cdot L(\text{wt}\%) \quad (21)$$

Where H is the amount of hemicellulose, C is the amount of cellulose, and L is the amount of lignin, all in wt%.

In a paper published by Beneroso et. al. in 2014, the relationship between syngas production, added absorbent (bio.char), and power, was studied in regards to MSW [56]. The following formulas were produced:

$$S[\text{vol}\%] = 75.247 + 0.087P - 0.787A + 0.02PA - 1.171 \cdot 10^{-4}P^2 - 7.885A^2 \quad (22)$$

$$SP \left[ \frac{L_{STP}}{g_{MSW}} \right] = 0.039 + 1.765P - 0.393A + 3.395 \cdot 10^{-5}PA - 1.870 \cdot 10^{-6}P^2 + 0.253A^2 \quad (23)$$

Where S is the syngas (H<sub>2</sub>+CO) concentration

P is the power [W]

SP is the syngas production

The same paper produced equations for estimating the syngas composition:

$$H_2[\text{vol}\%] = 42.367 + 0.048P + 8.242A + 6.475 \cdot 10^{-3}PA - 6.183 \cdot 10^{-5}P^2 - 8.162A^2 \quad (24)$$

$$CO[\text{vol}\%] = 32.870 + 0.039P - 9.013A + 0.018PA - 5.533 \cdot 10^{-5}P^2 + 0.271A^2 \quad (25)$$

$$CO_2[\text{vol}\%] = 9.114 - 0.019P + 2.693A \quad (26)$$

$$CH_4[\text{vol}\%] = 9.768 - 0.039P + 1.524A - 0.015A + 6.508 \cdot 10^{-5}P^2 + 2.667A^2 \quad (27)$$

## 2.6. Liquid Products

Bio-oil is the liquid product of pyrolysis. Given its complex composition of compounds, over 65 different, it is hard to define it specifically. In many cases, bio-oil is a suitable substitute for fossil oil, with research showing heating values up to 50% of hydrocarbon fossil fuel [57]. There are several clear advantages with using bio-oil for energy generation purposes. These include a more positive CO<sub>2</sub> balance, possibility of generating power, easily stored and transported (compared to gas), higher energy density than bio-gas [58].

The main drawback of using bio-oil is the unstable nature of the substance. The stability and viscosity has been shown to change over time [58], making it unreliable as a fuel source. Even though these factors are not fully understood, they vary depending on heating rate, residence time, and temperature. In addition, there has been a correlation between lower yields of bio-oil and increased stability [58].

The composition of the liquid fraction of the pyrolysis process will, like the other fractions, vary depending on the pyrolyzed material, heating rate, temperature, residence time etc. Inguanzo et. al. analysed the chemical properties of the organic fraction from pyrolyzation of sewage sludge [59], given in table 5. Testing was performed at HR 5 K/min and 60 K/min with T at 450°C, 650°C, and 850°C. The values are given as wt%.

TABLE 5: ELEMENTAL ANALYSIS OF SYNGAS

Sample	L5-450	L60-450	L5-650	L60-650	L5-850	L60-850
C	62.6	61.8	56.1	49.4	56.7	55.8
H	11.5	10.8	10.2	10.2	10.0	9.8
N	5.1	5.6	5.1	5.1	5.1	5.5
O	20.4	21.2	28.2	34.9	27.8	28.5
S	0.44	0.56	0.44	0.43	0.44	0.45
LHV[kj/kg]	22 446	28 054	27 004	23 271	27 658	27 983

## 2.7. Bio-Char

Bio-char is the solid product of a pyrolysis process, extracted in a loose structural form after thermal degradation [57]. In the production of bio-char, pyrolysis is considered to be the most energy efficient technique when desiring high yields [60]. Consisting mainly of carbon, other elements are present in bio-char. This includes primarily nitrogen, N, and hydrogen, H, though in very small concentrations [61].

BET measurements have shown surface areas of bio-char from bio-solids in the range of 450-800 m<sup>2</sup>/g from MAP. This is a higher value than CP and shows that MAP produces a more porous char. The BET increases with increases in temperature, and some differences depend on the composition of the bio-solids [62]. Other factors that affect the porosity of the carbon is the activation method used, the pre-pyrolyzation treatment of carbon, pressure and heating rate, and other various operating parameters [63] [64].

Bio-char may be used for producing activated carbon, solid fuel for boilers, H<sub>2</sub>-rich fuel through thermal cracking, or terra preta [58] [65]. When used as a soil enhancement additive, bio-char also serves as a carbon storage, reducing the GHGs in the atmosphere. In some cases, bio-char contains elements of contaminants, reducing its utilization, though more research is needed to be conclusive in regards to this. Terra preta has also shown promising, but varying, results [65]. This implies that soil examination might be necessary before adding bio-char.

The yield of bio-char from pyrolyzation will vary depending a variety of factors. However, the higher the temperature, the lower the yield tends to be [66]. Figure 15 exemplifies this, showing yields of bio-char at different pyrolyzation temperatures [67].

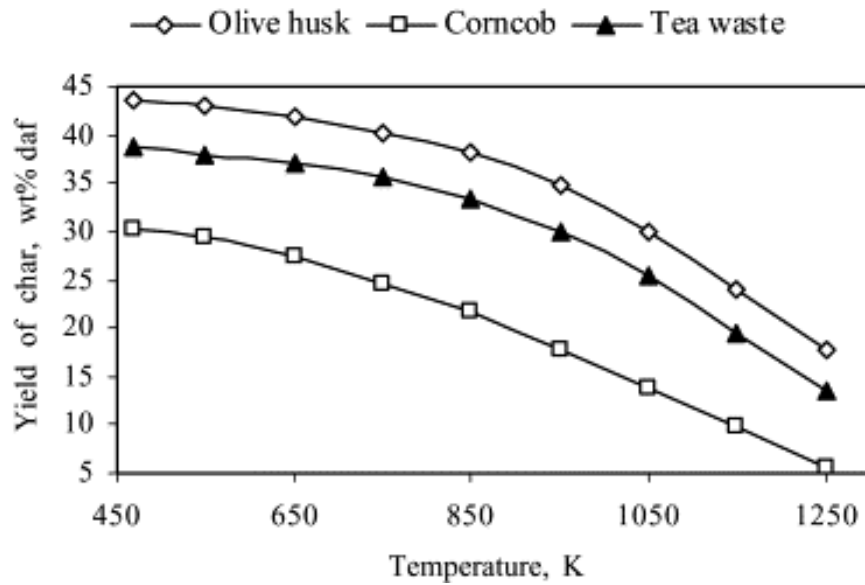


FIGURE 15: BIO-CHAR YIELD AS A FUNCTION OF TEMPERATURE [67]

This example is taken from pyrolysis of olive husk, corncob, and tea waste. As the difference between the three of them show, there are significant differences in the yield from different types of bio-solids.

Bio-char yield from a pyrolyzation process may be calculated using [3]:

$$Y_c = \frac{A-C}{B} \tag{28}$$

Where  $Y_c$  is the yield

A is the weight of dry bio-char after pyrolyzation

C is the weight of MW absorbers mixed in

B is the weight of dry biosolids

The composition of bio-char will also vary depending on the pyrolyzed material. While carrying out pyrolysis of sewage sludge, Inguanzo et. al. tested the composition of the solid fractions and found large variations depending on the pyrolysis temperature and heating rate [59]. The results are given in table 6 with the values given in wt%.

TABLE 6: ANALYSIS OF PYROLYZED CHAR

Sample	S	S5-450	S60-450	S5-650	S60-650	S5-850	S60-850
Ash content	29.5	50.7	58.0	60.3	62.2	62.3	66.3
Volatile matter	60.7	23.1	18.4	11.9	11.0	4.6	5.7
Elemental analysis							
C	35.7	36.0	29.0	20.8	29.2	33.0	29.6
H	5.2	2.6	1.8	1.2	1.2	0.7	0.7
N	3.5	3.8	3.2	3.0	2.7	1.7	1.4
O	25.4	6.4	6.5	4.2	4.1	1.7	1.5
S	0.72	0.55	0.56	0.55	0.54	0.58	0.52
LHV [kJ/kg]	16 558	12 429	11 533	11 904	11 058	11 016	11 958

The samples in table 6 are analysed at HR 5 K/min and 60 K/min with T at 450°C, 650°C, and 850°C. S is the unpyrolyzed sample of sewage sludge.

## 2.8. Heating Value

The heating value of a substance is a measurement of heat, or energy, available in a given substance. It is usually given as the energy per unit of mass. Heating values are often divided into two or three different measurement: the higher heating value (HHV), lower heating value (LHV), or the real heating value.

## HHV

The HHV gives the total amount of energy released during a combustion process where water produced during the combustion stays in liquid form. Seeing how this is not the actual case, HHV remains a theoretical maximum of energy output. The HHV of substances cannot be calculated, but is found through experimentation.

## LHV

When fuel reacts with oxygen, the hydrogen will form H<sub>2</sub>O. As the combustion is above 100 C°, and assuming 1 atm, this steam will exit the combustion in gas form along with the other products of the combustion. To estimate the LHV, the energy required to heat and vaporize the steam is subtracted from the HHV in the following equation:

$$LHV = HHV - \Delta H_{vap} \cdot X_{water} \quad (29)$$

Where  $\Delta H_{vap}$  refers to the enthalpy change of vaporization, and  $X_{water}$  is the amount of water as a molar percentage of the substance in question.

## Real heating value

In addition to the water vapour formed in the combustion process, there is often a certain amount of water going in to the process as well. This water will have to be heated and vaporized before combustion, adding to the required energy. To account for this, the real heating value (RHV) can be expressed by:

$$RHV = LHV - \Delta H_{vap} \cdot X_{water} \quad (30)$$

## 2.9. Heating Rate

The heating rate during pyrolyzation gives a measurement of how much the temperature increases in a certain interval of time, often measured in kelvin per second. The Heating rate is vital to the analysis of MAP, given that research has shown significant differences



in product yield given different heating rates [57]. Classification of heating rate is generally divided into three: slow, fast, and flash pyrolysis.

TABLE 7: TYPICAL PARAMETERS FOR DIFFERENT HEATING RATES [66]

Pyrolysis	Residence time [s]	Heating rate [K/s]	Particle size [mm]	Temperature [K]	Oil yield [wt%]	Char yield[wt%]	Gas yield [wt%]
Slow	450-550	0.1-1	5-50	550-950	30	35	35
Fast	0.5-10	10-200	<1	850-1250	50	20	30
Flash	<0.5	>1000	<0.2	1050-1300	75	12	13

Table 7 is gathered from Jahirul et. al. (2012) and shows typical values for pyrolyzation of different bio-solids under different heating rates [57].

#### 2.9.1. Slow Pyrolysis

Slow pyrolysis is characterized by having a slow heating rate. At different temperatures, the products will vary, for instance by delivering a higher yield of char at low temperatures. If the desired product is higher yields of gas, this is typically achieved by pyrolyzing at a high temperature [66].

#### 2.9.2. Fast Pyrolysis

Fast pyrolysis results in a production of mainly liquids. Pyrolyzing at a low temperature with a high heating rate and short residence time, produces the highest yields of liquid products. By lowering the heating rate, going to a higher temperature with long residence time, the yield of gas will increase [66] [68]. In fast pyrolysis, there are identified four important features [57]:

1. High heating rates, often requiring finely ground feed
2. Controlled reaction temperature of 700-775 K, typically
3. Short vapour residence time, usually below 2 seconds

#### 4. Vapour and aerosols are rapidly cooled for bio-oil

##### 2.9.3. Flash Pyrolysis

Flash pyrolysis is characterized by the rapid heating rate and low residence time [57]. When aiming for the highest amount of bio-oil yield, flash pyrolysis may be preferable due to yields up to 75% [57]. There is unfortunately a problem with utilizing the bio-oil due to the poor thermal stability, lower heating value and flame temperature, because of increases in water contents shown in some research [69].

### 2.10. Penetration Depth

The penetration depth describes how deep into a material the microwaves penetrate. When exposed to microwave radiation, the intensity of the microwaves will decrease as they travel towards the centre of given substance [3] [70].

$$D_p = \frac{c}{2\pi f \sqrt{2\epsilon' [\sqrt{1 + (\frac{\epsilon''}{\epsilon'})^2} - 1]}} \quad (31)$$

The penetration depth is an important measure when constructing a MAP cavity. Over dimensioning the cavity may lead to an incomplete pyrolysis in the centre of the mass, given how the centre will be pyrolyzed entirely by heat transfer from neighbouring particles. In order to achieve complete pyrolysis, this will in turn also lead to an increase in pyrolyzation time, which is not desirable in a commercial application, where short residence time is desirable.

## 3. Methodology

In order to evaluate the differences between different waste compositions, calculations have been conducted based on results from gathered literature. The basis for the simulations is different ratios of wood, plastic, carbon and bio-solids. These materials have been chosen based on what is commonly found in waste.

### 3.1. Basis for Estimation

In the simulations, it is assumed that the substance is heated from 20°C to 550°C. 550°C is chosen as the end temperature in order to make the results relatable to the future work on the Scanship MAP system. Testing has shown some problems when pyrolyzing at higher temperatures. This includes devitrification of the cavity glass, cracks, and some problems with leakage from the gaskets when the system runs on maximum effect. When focusing on the gaseous product of the pyrolyzation process, it would be ideal to aim for higher temperature levels, in the range of 800°C to maximize the yield of gas and minimize the yield of liquids [68]. 20°C is chosen as the starting temperature because most waste is either in room temperature or stored outside before utilization. Six different material compositions have been chosen:

TABLE 8: FIVE DIFFERENT COMPOSITIONS FOR ESTIMATIONS

Material	C1	C2	C3	C4	C5	C6
Wood	33.3	31.7	30	28.3	26.7	23.3
Plastic	33.3	31.7	30	28.3	26.7	23.3
Carbon	0	5	10	15	20	30
Bio-solids	33.3	31.7	30	28.3	26.7	23.3

Table 8 shows the different compositions based on wt%. C1, C2,.. etc. are abbreviations for composition 1, composition 2.. etc. Besides the carbon, all other materials are weighed equally. This is done in order to isolate the effect of the carbon as reliably as possible, and at the same time evaluate a realistic waste composition. The density of the waste has been weighed in previous tests by the author for previous tests done at an industrial scale. It has shown very little variation, and no variation big enough to make certain assumptions regarding the varying density. The weight of pelletized matter is  $0.49 \frac{kg}{l}$ . The carbon used is assumed to be bio-char.

### 3.1.1. Definition of biosolids

Merriam-Webster defines bio-solids as such [71]:

*Solid organic matter recovered from a sewage treatment process and used as fertilizer – especially used in plural.*

Although there is a set definition of bio-solids in the English language, there is a tendency in pyrolysis literature to use bio- solids a term for a variety of organic waste.

## 3.2. Energy Requirements

TABLE 9: ENERGY REQUIREMENTS FOR HEATING

	C1	C2	C3	C4	C5	C6
$C_p$	1.367	1.375	1.380	1.385	1.395	1.405
$E[\frac{kJ}{l}]$	354.888	357.010	358.386	359.762	362.204	364.956
$E[\frac{kWh}{kg}]$	0,1712	0,1736	0,1757	0,1778	0,1804	0,1846

Table 9 shows the energy required for heating the different compositions. In order to determine the energy input needed for the values given in table 9, eq. 12 was used.

### 3.3. Dielectric Properties

TABLE 10: DIELECTRIC PROPERTIES OF THE DIFFERENT COMPOSITIONS

	C1	C2	C3	C4	C5	C6
$\epsilon'$	2.479	2.840	3.193	3.547	3.908	4.614
$\epsilon''$	0.065	0.559	1.053	1.548	2.042	3.030
$\tan\delta$	0.026	0.197	0.330	0.436	0.523	0.657

Table 10 shows the dielectric properties of the different mixtures, based on eq.8.

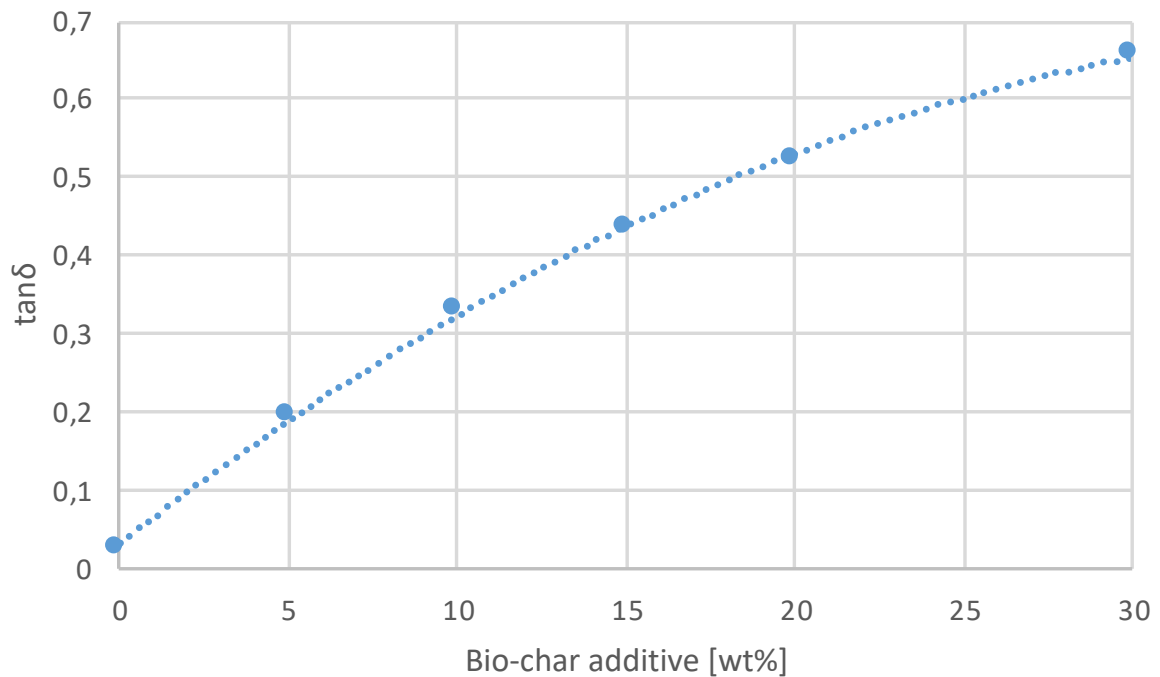


FIGURE 16: THE VARIANCE OF  $\tan\delta$  RELATIVE TO RECEPTOR ADDITIVES

Figure 16 depicts the relation between  $\tan\delta$  and the amount of added bio-char, from the values in table 10. In the range of 0-30 wt% bio-char, the following formula is deduced:

$$\tan\delta = 0.0004 \cdot A^2 + 0.0334 \cdot A + 0.0327 \quad (32)$$

Where A is the added bio-char receptor in wt%.  $R^2=0.99$ . It is worth noting that this gives a maximum  $\tan\delta$  at  $A=41.75$  and should therefore be used with caution at additive levels exceeding 30 wt%.

### 3.4. Penetration Depth

Based on eq. 31, the following values were calculated:

TABLE 11: PENETRATION DEPTH OF THE DIFFERENT COMPOSITIONS

	C1	C2	C3	C4	C5	C6
$D_p$ [cm]	47.28	5.89	3.35	2.42	1.94	1.45

Table 11 clearly shows a significant decrease in penetration depth, as expected. In the current cavity design, even five percent carbon additive might hinder the pyrolyzation of the core of the cavity. The core will have to rely on conduction heat, potentially increasing the required residence time.

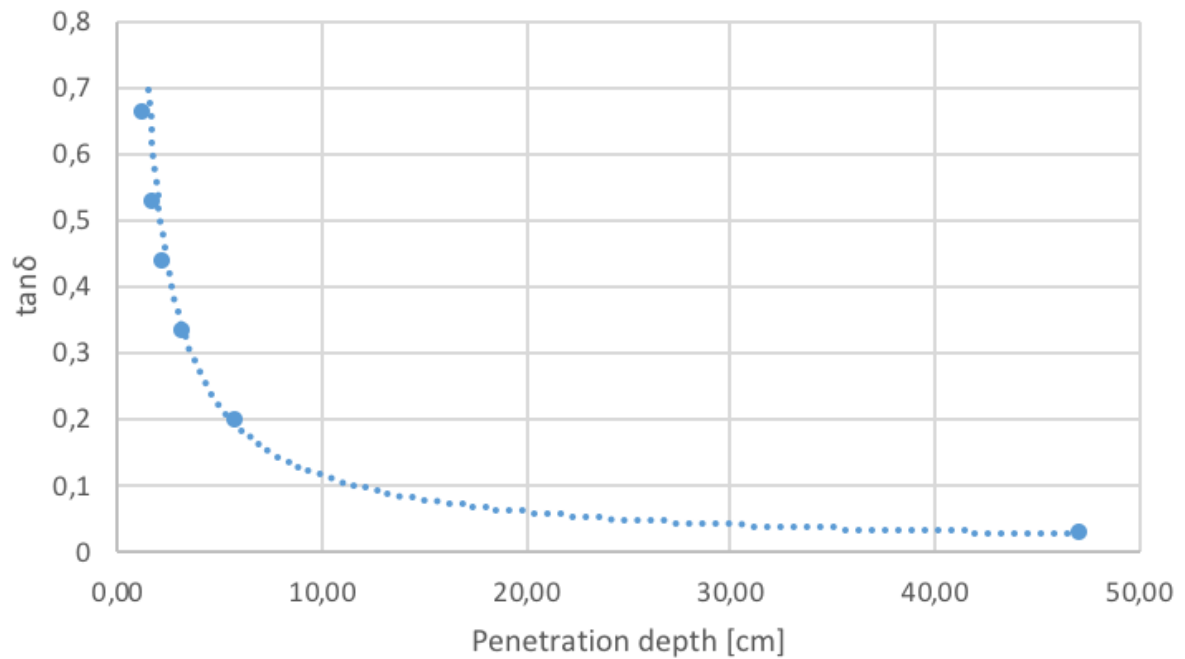


FIGURE 17: PENETRATION DEPTH PLOTTED WITH  $\tan\delta$

Figure 17 visualizes the penetration depth dependent on the  $\tan\delta$ , based on the values given in table 11. This figure clearly visualizes the problem of adding carbon receptors without a correctly designed cavity. Further challenges with optimizing the carbon additive in regards to penetration depth and heating rate will be elaborated upon in chapter 4.

### 3.5 Composition of Syngas, Bio-oil, and Char

#### 3.5.1 Co-pyrolysis of plastic and wood

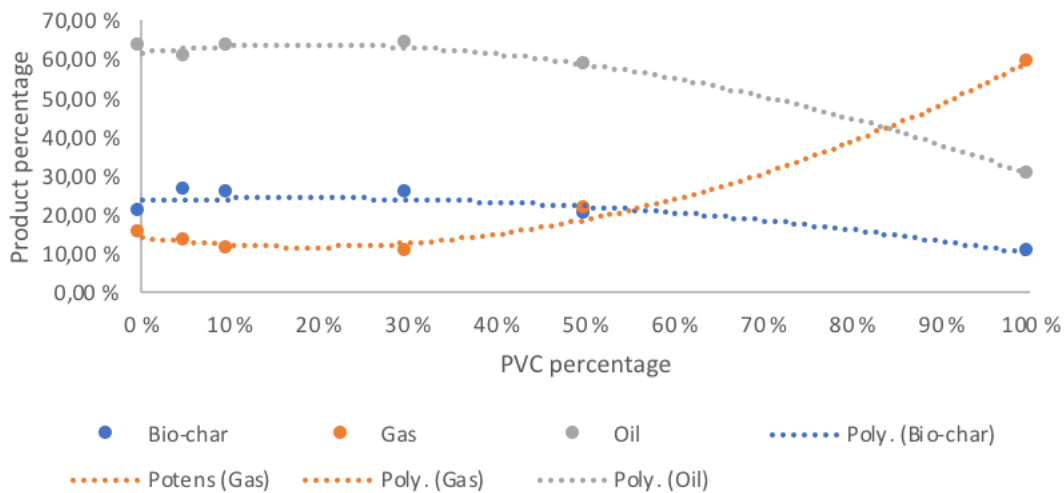


FIGURE 18: PRODUCT COMPOSITION OF CO-PYROLYSIS OF PVC AND POPLAR WOOD

Using the results from Ephraim et. Al [72] and plotting the values, figure 18 shows added trendlines to better understand and deduct empirical formulas from the results.

TABLE 12: EMPIRICAL FORMULAS OF THE CO-PYROLYSIS OF PVC AND WOOD

Product	Formula	R <sup>2</sup>
Bio-char	$BC(PVC) = -0.0037 \cdot X^2 + 0.1527 \cdot X + 23.394$	0.9634
Gas	$G(PVC) = 0.0027 \cdot X^2 - 0.2662 \cdot X + 14.309$	0.9905
Bio-oil	$BO(PVC) = -0.0034 \cdot X^2 + 0.1134 \cdot X + 62.297$	0.9743

Table 12 contains the formulas for predicting the amount of bio-char, gas, and bio-oil from co-pyrolysis of PVC plastic and poplar wood. X is the amount of PVC in percentage (0-100).



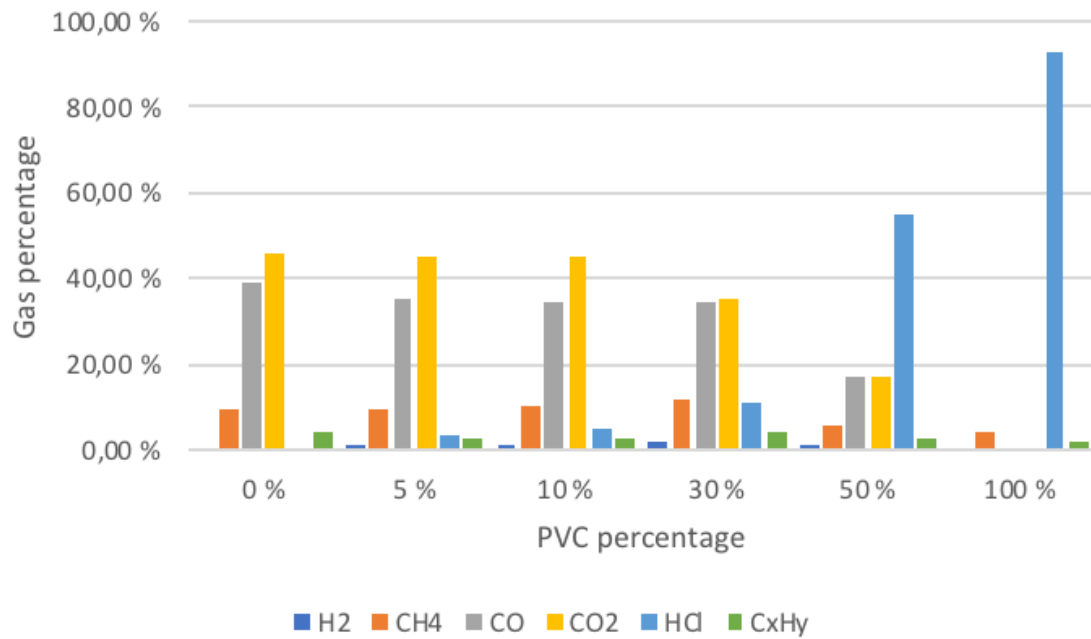


FIGURE 19: GAS COMPOSITION OF CO-PYROLYSIS OF PVC AND POPLAR WOOD

Figure 19 shows a plot of the test results of Ephraim et. al [72], when plotted in a diagram. It is clear that increasing the amount of PVC plastic will increase the amount of HCl gas exponentially.

Using the same method as for figure 18, empirical formulas based on the trendlines were estimated. Figure 20 shows the plot of the gas composition containing trendlines.

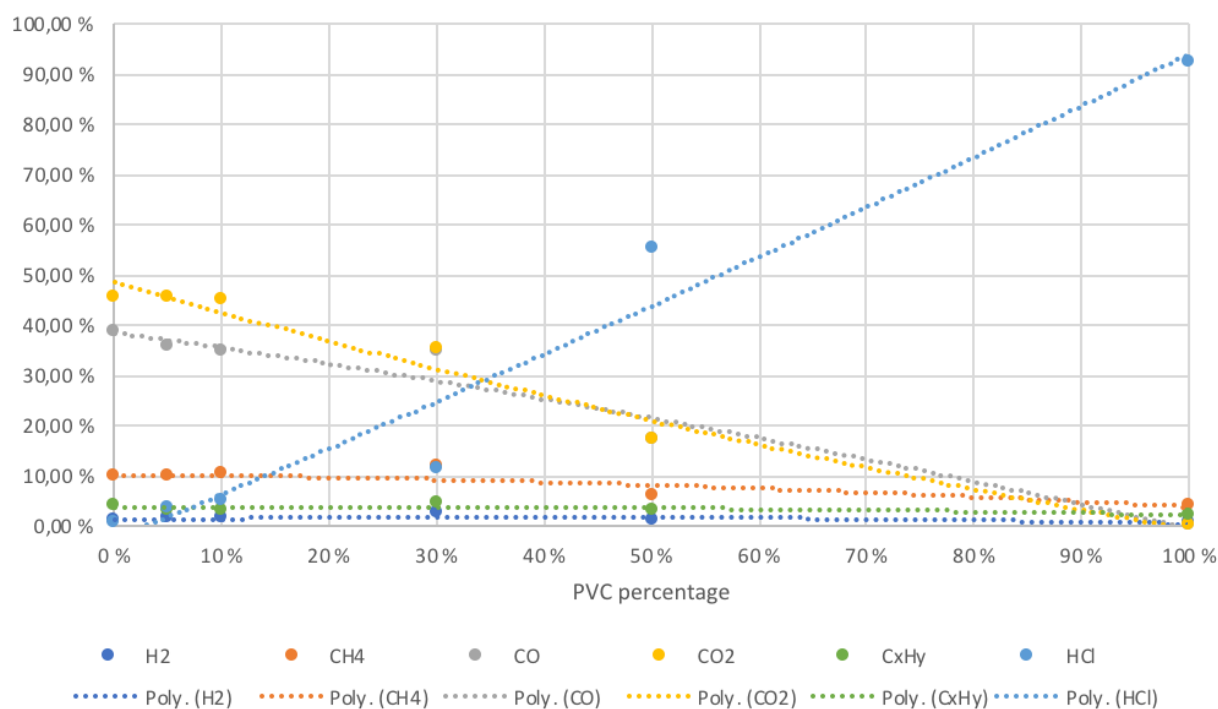


FIGURE 20: GAS COMPOSITION WITH VARYING PVC CONTENTS

The empirical expressions from figure 20 are summarized in table 13.

TABLE 13: GAS COMPOSITION OF CO-PYROLYSIS OF PVC AND POPLAR WOOD

Gas	Formula	R <sup>2</sup>
H <sub>2</sub>	$f(H_2) = -0.0345 \cdot X^2 + 0.0264 \cdot X + 0.0133$	0.5716
CH <sub>4</sub>	$f(CH_4) = -0.0452 \cdot X^2 - 0.0196 \cdot X + 0.1039$	0.717
CO	$f(CO) = -0.0994 \cdot X^2 - 0.2913 \cdot X + 0.3863$	0.9538
CO <sub>2</sub>	$f(CO_2) = 0.1159 \cdot X^2 - 0.6073 \cdot X + 0.4857$	0.9743
HCl	$f(HCl) = 0.0722 \cdot X^2 + 0.8958 \cdot X - 0.0262$	0.9539
C <sub>x</sub> H <sub>y</sub>	$f(C_xH_y) = -0.0276 \cdot X^2 + 0.0141 \cdot X + 0.0364$	0.519

X is the wt% of PVC in the PVC/wood mixture.

### 3.6 Heating Rate

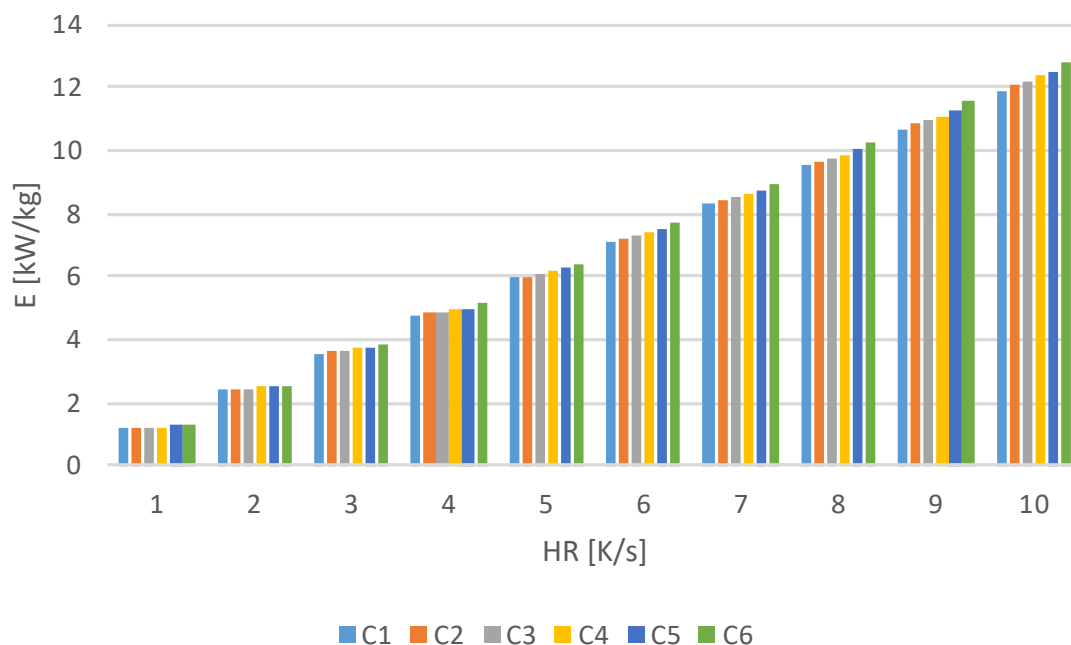


FIGURE 21: RELATION BETWEEN HR AND ENERGY INPUT

Figure 21 shows the energy requirements for heating the different waste compositions at different heating rates, based on eq. 13.

Antunes et. al. analysed the heating rate of different MW receptors under similar conditions [33]. The results are rendered in figure 22. The tests were performed at 2.45 GHz and 1.2 kW with a 20 wt% mixture of receptors and 80 wt% of biosolids.

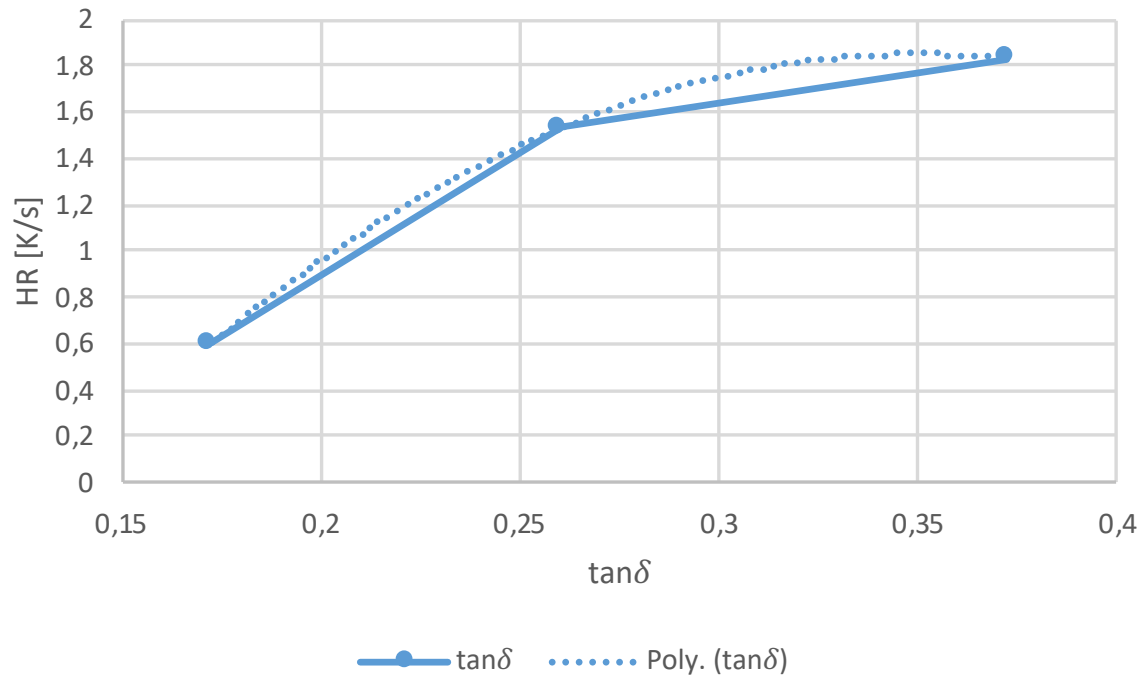


FIGURE 22: HEATING RATE WITH VARYING  $\tan\delta$

The  $\tan\delta$  value is the value of the receptor in use. The heating rate was calculated from the temperature profile, shown in figure 23 [33].

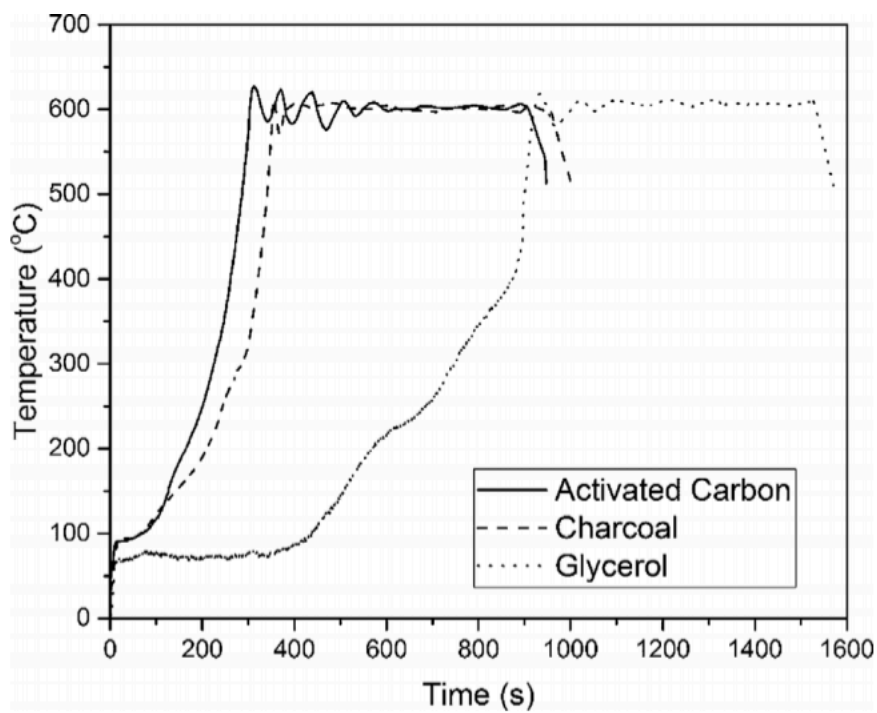


FIGURE 23: TEMPERATURE PROFILE WITH DIFFERENT MW RECEPTORS

From figure 23 it should be pointed out that the heating profiles are uneven. This underlines the point that the deducted formulas should be viewed as approximations.

## 4. Results and Discussion

### 4.1. Gas Composition

Table 14 shows the gas compositions based on eq. 24-27 and the values from figure 20.

TABLE 14: ESTIMATED GAS COMPOSITION

Gas [wt%]	CO	CO <sub>2</sub>	C <sub>x</sub> H <sub>y</sub>	CH <sub>4</sub>	H <sub>2</sub>	HCl	LHV [MJ/kg]
C1	31.58 %	20.38 %	2.05 %	7.76 %	2.57 %	35.65 %	11.117
C2	31.34 %	20.53 %	2.05 %	7.80 %	2.63 %	35.65 %	11.187
C3	31.06 %	20.70 %	2.05 %	7.84 %	2.82 %	35.65 %	11.407
C4	30.75 %	20.88 %	2.05 %	7.90 %	2.78 %	35.65 %	11.349
C5	30.39 %	21.08 %	2.05 %	7.97 %	2.86 %	35.65 %	11.446
C6	29.51 %	21.57 %	2.05 %	8.19 %	3.03 %	35.65 %	11.673

Table 14 shows the estimated gas compositions when combining the results from the co-pyrolysis of wood and PVC plastic and the pyrolyzation of biosolids with varying carbon absorbers [56] [72]. The composition assumes there is no co-pyrolysis other than with wood and PVC. As a results, it does not take in to account any co-pyrolysis involving the biosolids. This would imply that the results are not as accurate as they would be in a real test, but given the lack of understanding in regards to co-pyrolysis, it is considered to be a reasonable estimation.

When calculating composition, the energy input was set to 2.9 W. This was done because of the small sample size of 3g. in the study, making a power input of over 50 W/g unrealistic for commercial use. Based on the Scanship cavity, a bulk pellet density of 0.49kg/l, and 40 000 kW power input, 2.9 W/g was chosen as a reasonable power input.

The results given in table 14 show the LHV given as a specific value pr. kg of gas. Given that the amount of carbon absorbers are varying, it is also interesting to evaluate the amount of gas pr. kg. of pyrolyzed material, including the carbon absorbers. In the MAP literature, there are significant variances in the gas yield, and the scalability of the tests are uncertain. Typical gas fractions from BS with comparable HR and pyrolysis temperature are in the range of 20-35wt% gas and in some cases as much as 60 wt% [73] [57] [74]. On that basis, it is assumed that the gas yield from BS will be 30 wt%. The gas yield from the co-pyrolysis of wood and PVC is 22.4 wt% [72]. The weight of the different gas components are given in table 14.

The yield is not based on eq. 22-23 for two reasons. The first reason is that the syngas is defined as H<sub>2</sub>+CO, ignoring the other gaseous products. The other reason is that the result is an extremely high syngas production, with some values of P and A yielding over 100% syngas. This might simply be an error in the equation, but it might also be an example of how scaling up from 3g test samples is not always possible. Eq. 24-27 give results more in line with what is observed in other tests, and is therefore considered more reliable.

TABLE 15: WEIGT AND ENERGY WHEN ADJUSTED FOR ADDED MW ABSORBERS

	C1	C2	C3	C4	C5	C6
Gas [g]	249.31	236.89	224.40	211.91	199.49	174.51
LHV [MJ]/kg waste+BC]	2.772	2.650	2.560	2.405	2.283	2.037
kWh/kg	0.1712	0.1736	0.1757	0.1778	0.1804	0.1846
kWh/kg waste	0.1712	0.1828	0.1953	0.2092	0.2255	0.2638

Table 15 shows the LHV for the different gas compositions pr. kg. of waste and BC combined. It also gives the energy requirements for heating up one kg. of given waste

composition. When assuming that the added BC does not significantly affect any secondary reactions, it is worth looking at the energy requirements of heating the waste, i.e. the total energy required divided by only the weight fraction, not the BC fraction. This will be particularly important when evaluating the cost of the MAP system, as it is from the waste fraction of the pyrolyzed matter that the energy is extracted in the form of syngas.

#### 4.1.1. Comparison to Large Scale Testing

Even though there is a lack of large scale testing in the scientific literature, Scanship has recently conducted a large scale test and analysed the test results. These results show a similarity between the estimated values and the values obtained by Scanship. The test was conducted over 48 hours, with a pelletized mixture of biosolids, wood, and plastic. The results are copied and shown in figure 24.

		Concentration (%VOL)							
		N2	CH4	CO2	C2H2_C2H4	C2H6	CO	H2	
Dag	1	3.29	7.63	20.13	0.78	0.58	34.98	32.61	
Dag	2	5.53	8.11	16.98	1.06	0.58	35.84	31.91	
Snitt		4.41	7.87	18.555	0.92	0.58	35.41	32.26	
Net Heating value (MJ/nm3)		0	35.9	0	56.5	64.1	12.6	10.8	
MW (kg/kmol)		28	16	44	26	30	28	2	
Density (kg/nm3) 20degC, 1atm		1.2	0.7	1.8	1.1	1.2	1.2	0.1	
Mass split (kg/nm3)		0.051	0.052	0.339	0.010	0.007	0.412	0.027	0.9
Cons (wt%)		6%	6%	38%	1%	1%	46%	3%	
Energy MJ/nm3)		0.0	2.8	0.0	0.5	0.4	4.5	3.5	11.7 MJ/nm3
Energy split (%)		0%	24%	0%	4%	3%	38%	30%	

FIGURE 24: RESULTS FROM SCANSHIPS LARGE SCALE TESTING

The mass split of 0.9 and energy of 11.7 MJ/nm<sup>3</sup> gives a specific energy of  $(11.7)/(0.9)=13$  MJ/kg. This is slightly higher than the estimations, but it is assumed to come from the plastic components. In the estimations, PVC is used in the waste composition, but in the Scanship test, polyethylene is the main plastic component. This is the same type of plastic used in most plastic bottles, and is carbon based, unlike the chlorine rich PVC. When pyrolyzing, this is probably the reason for the high levels of HCl from PVC while polyethylene gives of a gas richer in hydrocarbons. However, this is a clear indication that

the estimations are within a reasonable level of reliability. Even though this is a clear indication, it should not be over emphasized given the lack of exact ratios of waste composition, added char, and other process parameters. The reason for this is that some companies are reluctant to share the results in order to maintain an advantage over competitors.

## 4.2. Heating Rate and Dielectrics

From figure 22, the relation between HR and  $\tan\delta$  can be described as:

$$HR = -1.5779(\tan \delta)^2 + 5.0486 \cdot \tan \delta - 2.1891 \quad (33)$$

In the interval  $0.7 < \tan\delta < 1.7$ , where the HR is given in K/s. This is given a 1.2 kW energy input.

Given the decreasing effect of the  $\tan\delta$  value, figure 22 indicates that the ideal  $\tan\delta$  is in the area of  $\approx 0.3$ . This will correspond to somewhere between the C2 and C3 waste compositions. The reason for pointing out this as the ideal value is based on the value corresponding to a good microwave absorbent, well above  $\tan\delta=0.2$ , but also in regards to the penetration depth of the MWs. If the penetration depth becomes too small, the cavity design process will become more difficult, as the cavity will have to be of a very low diameter, also reducing the capacity.

## 4.3. Energy requirements

From table 15 the LHV of the gas from 1 kg. of waste and BC shows 2.65 MJ for C2 and 2.56 MJ for C3. Extracting more from table 15, it is given that the heating requirements for C2 and C3 are 0.1828 and 0.1953 kWh/kg waste, corresponding to 0.658 and 0.703 MJ/kg waste. The values are given pr. kg. of waste because this is assumed to be the best way of evaluating the energy requirements. Heating the BC is necessary in order to reach desired HR, but in the bigger picture it is important to know the specific energy requirements in order to estimate the energy cost of pyrolyzing a given mass of waste.



It reasonable to assume an efficiency of 80-85% on modern MW generators [10]. Given an efficiency of  $\eta=0.8$ , the required energy for a MW generator can be calculated for C2 and C3:

$$C2: \quad E_{MWC2_1} = \frac{0.658}{0.8} = 0.823 \frac{MJ}{kg \text{ waste}}$$

$$C3: \quad E_{MWC3_1} = \frac{0.703}{0.8} = 0.879 \frac{MJ}{kg \text{ waste}}$$

These values correspond to the energy needed for 1 kg of waste with the added BC. The power input needed to the MW generator in order to heat up 1 kg of waste and BC is, using the values from table 15:

$$C2: \quad E_{MWC2_2} = \frac{0.625}{0.8} = 0.781 \frac{MJ}{kg \text{ waste} + BC}$$

$$C3: \quad E_{MWC3_2} = \frac{0.632}{0.8} = 0.790 \frac{MJ}{kg \text{ waste} + BC}$$

Given the LHV for the gas, the amount of gas, and the energy requirements, the net energy output from the syngas can be calculated:

$$C2: \quad E_{out,C2} = 2.650 - E_{MWC2_2} = 2.650 \frac{MJ}{kg \text{ waste} + BC} - 0.781 \frac{MJ}{kg \text{ waste} + BC} = 1.869 \frac{MJ}{kg \text{ waste} + BC}$$

$$C3: \quad E_{out,C3} = 2.650 - E_{MWC3_2} = 2.560 \frac{MJ}{kg \text{ waste} + BC} - 0.790 \frac{MJ}{kg \text{ waste} + BC} = 1.770 \frac{MJ}{kg \text{ waste} + BC}$$

The total energy balance of the MAP process will be presented in chapter 5 – Energy Balance.

These results assume that there is no heat loss. When there is no heat loss, the energy input remains the same regardless of the residence time. However, the residence time is relevant since the reactions forming the gas happens over time. The exact residence time needed is not possible to pin down to a certain value, but some estimations show that about 20 minutes is needed for the waste to fully pyrolyze [16]. This will also be dependent on the heating rate and pyrolysis temperature.

#### **4.4. Temperature measurement technique**

Regarding the measurement techniques in pyrolysis study, there are several uncertainties. In some cases, the temperature is given, but not how it is measured. It is especially interesting to know if the temperature is in some way measured in the centre of a given sample, or if it measured on the surface. The most common temperature measurement seems to be IR. This would imply that the temperature measured is in fact the surface of the test sample, begging the question if that is indeed a satisfying parameter for evaluating what happens inside the sample itself. The distance between the sample surface and the IR measurement is also rarely given, another parameter that affects the accuracy of IR measurements.

#### **4.5. Elements in sample**

Another concern regarding the numbers found in published studies, is the elements that are found in said samples. Some studies include an analysis of the test samples, with fractions of the different elements listed. However, several studies clarify in a satisfying manner the samples being used and how it is collected (i.e rice husk, MSW, coffee hull etc.), but fail to include a more detailed analysis of the elements making up the studied sample. The lack of standardized terms also hampers the ability to compare the outcomes of different studies. As an example, bio-solids is a commonly used term and case of study. The problem is that bio-solids is a widely used term for practically any bio-based substances. When analysing pyrolysis of bio-solids, the studies vary from corn shuck to sewage sludge etc.

#### **4.6. Parameters often overlooked**

The standardized method of measurement seems to be wt% of the different substances going in and out of the cavity. By all means, this is a very easy and understandable way of measuring different fractions, but it is not without problems. When regarding pyrolysis as a waste-to-energy process, the weight fractions alone are not always enough. A more

interesting way of measuring would be for instance the total enthalpy in versus the total enthalpy of the fractions out. This would also give an indication of the losses through the process, a factor that today is rarely addressed. Another problem with the measurements of wt% is the measurement of gas. Bio-char and the liquid products are fairly easy to measure, but attaining reliable mass of a gas is more difficult and expensive. The wt% is therefor often calculated using the difference between the mass in and the mass of bio-char and liquids. This makes it easy to overlook energy loss in the system and potential leakage of gas. Given that a fair amount of the gas produced is H<sub>2</sub>, the problem with leakage should be addressed more. That being both leakage in the system itself and leakage while storing the gas. The time elapsed between attaining the gas and measuring it should be commented in a greater degree than is presently common. The different pressures during the pyrolysis process is also often not measured, raising the question of the potential impact of varying pressure on the outcome of a study. Lastly, the reaction time and residence time is not often commented, and as with pressure, raises the question if these parameters might play a larger role than one might believe.

#### **4.7. Heating rate and pyrolysis temperature**

Different studies discuss pyrolysis at different temperatures and different heating rates. This makes it hard to find multiple papers that show pyrolysis under the same conditions. As a case in point, two different papers might have performed pyrolysis at the same temperature, but with heating rates at 10 K/min and 20 K/min. Both of these heating rates correspond to a slow pyrolysis, but the comparability of them is uncertain. Of course, regarding the differences in temperature, it begs the same question combined with the uncertainties in measurements discussed above.

#### **4.8. Scalability**

Another uncertainty regarding the pyrolysis literature is the scalability of the studies. Most studies are performed at small samples, down to only a couple of grams in some cases. In addition to the small samples, the microwave generators used might be as

simple as a commercial kitchen microwave oven. If these results are scalable, remains speculation. Going from a couple of grams and a kitchen size microwave oven, to a large scale plant with several kilowatts of power, might reveal new difficulties that are not considered today.

#### **4.9. Dielectric properties**

The understanding of different substances dielectric properties still has a long way to go. Solid data for dielectric properties is still missing for a lot of substances, giving rise to the uncertainties of many estimations. Regarding mixtures, there is also more research needed to evaluate the calculation of dielectric properties of mixtures and if eq. no 7-8 truly are reliable.

#### **4.10. Understanding co-pyrolysis**

When mixing substances for pyrolysis, there is still uncertain how the substances interact. Several studies have been performed with co-pyrolysis of different materials, but they indicate a non-linear relation regarding the fraction size of the materials in question [72]. Understanding this relation and how the different dielectric properties and elements behave together is as of today not fully understood. Further testing designed to understand the mechanisms of co-pyrolysis, will be needed to increase the current understanding of how one product in the cavity will serve as a reactant in relation to another product.

#### **4.11. Pyrolysis of pellets in bulk**

In commercial operations, the pyrolysis is performed on pelletized waste. This means that when the pellets fill the cavity, there will be empty space between the pellets, and this void will affect the microwave distribution and thus the temperature distribution. Previous large scale simulations have shown great variations in the heat distribution

depending on the placement of pellets. Given that the pellets are poured in to the cavity, the placement will be random. The effects of this might be greater than the dielectric properties and is a clear argument that more large scale testing is needed. If indeed the effects of bulk void turns out to be more significant than the dielectric properties themselves, it will serve as an indication that increases of efficiency is more of an engineering problem, not a problem regarding the waste composition of the input.

## 5. Energy Balance

In order to evaluate the energy consumption of the MAP system, the following energy equation will be evaluated:

$$E_{total,in} = W_D + W_s + W_p + W_f + W_{mw} \quad (34)$$

$E_{in}$  is the total amount of energy going in to the system.

$W_D$  is the power required for drying the biosolids

$W_s$  is the power consumption of the shredder

$W_p$  is the power consumption of the pellet press

$W_f$  is the power consumption of the fan

$W_{mw}$  is the power consumption of the microwave generator

For drying the bio-solids, there is a two-step process of dewatering by centrifugation and drying with a hot air rotary dryer. That means:

$$W_D = W_C + W_{RD} \quad (35)$$

Where  $W_c$  is the power for the centrifuge

$W_{rd}$  is the power for the rotary dryer

In order to evaluate the energy balance related specifically to the MAP cavity, the following equation will also be evaluated:

$$E_{in} = E_{MW} \quad (36)$$

This gives a clearer idea of the energy balance of performing MAP, rather than a full set-up. The reason for simplifying the energy balance like this, is that the energy consumption of the other components in a set-up is in some part more uncertain because the moisture contents and efficiency of different components will vary depending on manufacturer, set-up solutions etc. Figure 25 shows the flow of the complete process and where the energy is consumed and gained.

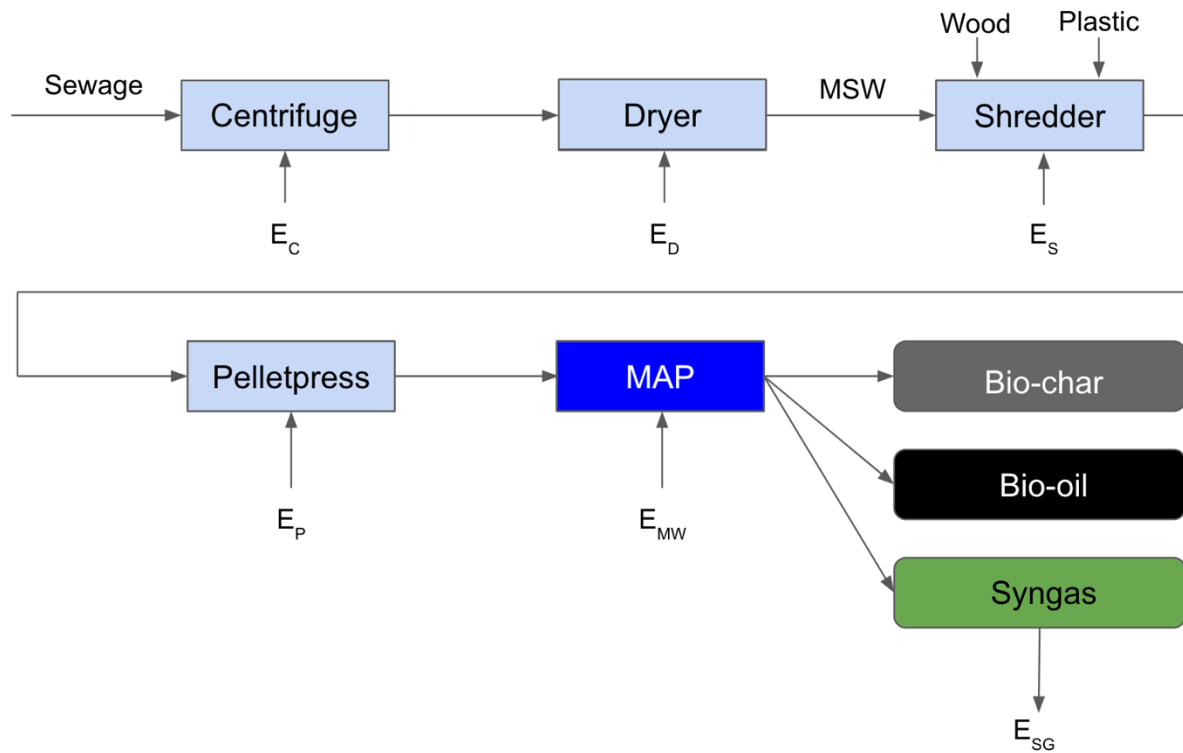


FIGURE 25: COMPLETE FLOW-CHART INCLUDING ENERGY FLOW

When evaluating the energy balance focused on the MAP cavity and products, in regards to eq. 36, the process may be depicted as:

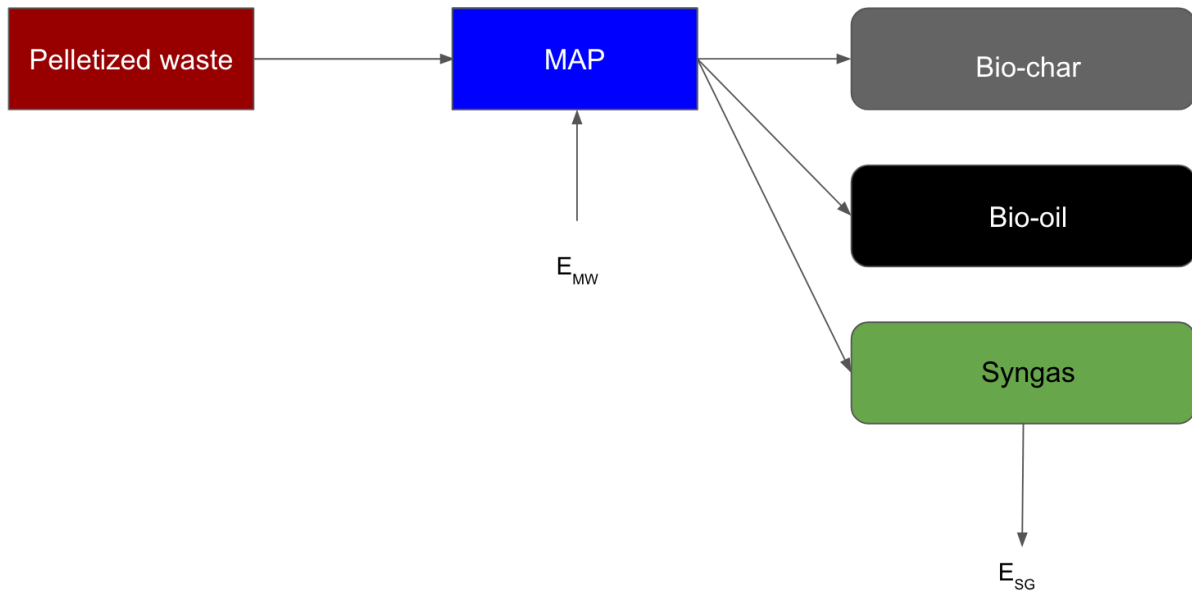


FIGURE 26: FLOW-CHART FOR ISOLATED CAVITY PROCESS

### 5.1. MW Energy

While evaluating the effect of the heating rate and penetration depth, the compositions C2 and C3 were seen as the most ideal. For the following calculations, the two values will be averaged out in order to keep the calculations based on one single value. This value assumes that there is no heat loss in the MW cavity.

$$E_{MW} = \frac{E_{MWC2_2} + E_{MWC3_2}}{2} = \underline{0.7855} \frac{MJ}{kg \text{ waste} + BC}$$

### 5.2. Centrifuge

As described in section 1.3, the biosolids in the system will likely undergo a drying process before entering the MAP cavity. The calculations are given in full in appendix 2.

The first step of the drying process is dewatering. In the case of dewatering, the sludge is assumed to consist of 2 wt% biosolids and 98 wt% water. It is further assumed that the centrifuge will dewater the sludge to a mixture containing approximately 15 wt% water. Following data is calculated based on the Hillier DP31 decanter centrifuge [75]:

TABLE 16: PROPERTIES OF CENTRIFUGATION

Power consumption	Maximum rate
15 kW	11.36 m <sup>3</sup> /h

By using the values presented in table 16, the energy required can be calculated to be:

$$E_{centrifuge} = 228.92 \frac{kJ}{kg \text{ biosolids}}$$

### 5.3. Dryer

After centrifugation, the biosolids go through a drying process. The biosolids are assumed dried from 15 to 5 wt% water. In the calculations, it is assumed that a single pass rotary hot air dryer is used. This is due to its advantages of low maintenance cost, large capacity, and that it is the most common dryer for drying bio-solids [76].

With the enthalpy of both air and biomass calculated, the amount of air needed for drying is calculated [77]:

$$G = \frac{L_{bio} \cdot X_{end} - L_{bio} \cdot X_{start}}{H_{start} - H_{end}} = -0.00265 \frac{kg}{kg \text{ biosolid}} \quad (37)$$

Where G is the mass of dry air needed

$L_{bio}$  is the amount of dry bio-solids in one process

It is worth noting that the negative connotation of the value G comes from the direction of reference, where the air-flow is going upstream relative to the bio-solids. The value of  $L_{bio}$  has also been set to 1 in order to evaluate the results regarding one kg of bio-solids.

The final step is calculating the energy required [77]:

$$Q_{dryer} = G \cdot (h_{air \text{ in}} - h_{out}) + L_{bio} \cdot (h_{in} - h_{out}) \quad (38)$$

$$Q_{dryer} = 418.5 \frac{kJ}{kg \text{ biosolid}}$$



The complete calculations are given in appendix 1.

## 5.4. Other components

In a MAP set-up there will also be a shredder, a pellet press, and a fan to extract the gas. The energy consumption of these components are collected from manufacturers in order to calculate the energy balance based off of components that could realistically be used.

$W_{\text{shredder}} = 2.23 \text{ kW}$  (Taskmaster TM14000) [78],  $W_{\text{fan}} = 0.75 \text{ kW}$  (MBRC 40-12) [79], and  $W_{\text{pelletpress}} = 50 \text{ kW}$  [80]

The total energy consumption, for one kg of waste, of these components are:

$$E_{\text{shredder}} = 11.15 \text{ kJ}$$

$$E_{\text{fan}} = 332.56 \text{ kJ}$$

$$E_{\text{pelletpress}} = 900 \text{ kJ}$$

The calculations are given in appendix 2.

## 6. Operating Cost and Savings

In addition to reviewing the existing literature on microwave pyrolysis, the operating cost of a large scale system has also been evaluated. This is considered to be of great importance before bringing MAP to the market. For estimating the cost and revenue, the Scanship MAP process has been the basis for input and output. It is of great interest to quantify the potential return of investment for future customers in order to build solid trust between the MAP provider and the customer. In general, it is also interesting to look at the economic aspect of waste management using MAP technology as the academic literature has been mainly focused on the technical performance and gaps in knowledge, not so much on the market potential.

## 6.1. Running costs

Assumption: The cost of extra weight is not included in the analysis, different waste management systems on ships have different weight that effects the fuel consumption.

When evaluating the operation cost of running the MAP system, eq. 34 gives:

$$E_{in,total} = 418.5kJ + 11.15kJ + 900kJ + 332.56kJ + 785.5kJ$$

$$E_{in,total} = \underline{2447.71 kJ}$$

The total energy out of the system is given as the lower heating value of the syngas:

$$E_{out} = E_{SG(LHV)} \quad (39)$$

Where the price on the energy is set to  $0.399 \frac{NOK}{kWh}$  [81].

From table 15, the LHV for one kg of waste and BC are taken for C2 and C3. The values are then averaged, giving:

$$E_{out} = 2.605 \frac{MJ}{kg \text{ waste} + BC} = \underline{2605 kJ}$$

The net energy output can then be calculated:

$$E_{net,1} = E_{out} - E_{in,total} = 2605 kJ - 2447.71 kJ = \underline{157.29 kJ} \approx \underline{0.044 kWh}$$

The economic gain will therefore be:

$$\begin{aligned} P_1 &= 0.044 \frac{kWh}{kg \text{ waste} + BC} \cdot 0.399 \frac{NOK}{kWh} \\ &= 0.0176 \frac{NOK}{kg \text{ waste} + BC} = \underline{1.76 \frac{\text{øre}}{kg \text{ waste} + BC}} \end{aligned}$$

Seeing how the different energy consuming components are mainly due to how a set-up might be, the economic gain is also calculated on the basis of eq. 36:

$$E_{net,2} = E_{out} - E_{MW} = 2065 kJ - 785.5 kJ = \underline{1279.5 kJ} \approx \underline{0.355 kWh}$$

With this estimation for net energy output, the economic gain will be:

$$\begin{aligned}
P_2 &= 0.355 \frac{kWh}{kg \text{ waste} + BC} \cdot 0.399 \frac{NOK}{kWh} \\
&= 0.1416 \frac{NOK}{kg \text{ waste} + BC} = 14.16 \frac{\text{øre}}{kg \text{ waste} + BC}
\end{aligned}$$

The profit estimation  $P_2$  is more descriptive for the economic evaluation of the MAP process than the  $P_1$  estimation. While it is the case that there are several other power consuming components involved in the process, that would be the case in other waste management systems as well. The need for other components in the set-up is also a potential case of improvement on the engineering side of the product development. The components presented here might be obsolete with a better set-up or a more energy efficient pre-treatment might be implemented before full commercialization.

While evaluating the energy balance and related cost, the energy contained in the bio-char and bio-oil has been left out of the equations. The reason for this is that the aim for development of the Scanship MAP system is to utilize the syngas for energy production, while there is to date no specific plans to include the bio-oil in any energy generation. This would also seem to be the most realistic use for any commercial plant, as the utilization of bio-oil requires further processing.

## 6.2. Internal Rate of Return and Net Present Value

To evaluate the investment in a MAP system, a common measurement within finance is the IRR and NPV. The IRR shows the return of the investment as a yearly percentage, given a cash flow analysis. NPV is the present value of a future cash flow and is expressed by [57]:

$$NPV = \sum_{n=1}^T \frac{CF_n}{(1+i)^n} - I_0 \quad (40)$$

Where  $T$  is the lifespan,  $CF_n$  is the cash flow in year  $n$ ,  $i$  is the discount rate, and  $I_0$  is the initial investment in year 0.

The initial investment cost is a fairly uncertain cost. Seeing how there are few actors in the market preparing for commercialization, and most still in development, few are willing to share the exact cost for a full MAP system. Still, estimates in the industry have

been placed at 10-15 MNOK, although few, if any, are willing to give an exact estimate. [82]. This is due both to the fear of exposing company secrets and that a MAP system is not “off the rack” and price will vary depending on factors varying from contract to contract. These factors include geographic placement, intended waste input, capacity etc. The same uncertainty applies to the estimated lifespan of a plant, but in order to compete with other waste management systems, a lifespan of 15 years is a reasonable assumption [83]. The energy recovery was calculated based on one kg of waste and BC. The real potential will be in the range of several tons pr. day [24]. With four tons being processed daily, the energy savings from section 6.1 would be equivalent:

$$\text{Energy savings} = 0.1416 \frac{\text{NOK}}{\text{kg waste} + \text{BC}} \cdot 4000 \frac{\text{kg}}{\text{day}} = \underline{\underline{566.4 \frac{\text{NOK}}{\text{day}}}}$$

Or 206,763 NOK/year.

Given an initial investment cost of 10 MNOK, a lifespan of 15 years, a discount rate of 2%, and a capacity of 4000 kg/day, the NPV would be:

$$\text{NPV} = -7\,343\,594.66 \text{ NOK}$$

With an IRR of -12%.

It must be pointed out that the cost of drying is not included in the evaluation of the return on investment. This is due to the fact that bio-solids would have to be dewatered and dried unrelated to what kind of waste-to-energy system one should choose. On that ground, it is considered to be more interesting to evaluate the economics of the waste-to-energy system by itself and not the entire waste management value chain. The true value of the MAP system should also be viewed in regard to the alternative cost of waste management.

### 6.3. Potential Value of Bio-Char and Alternative Cost

While evaluating the cost of the MAP system based on the energy regeneration, it is clear that the NPV and IRR is not satisfying for potential customers. However, the bio-char represents a potential source of income.

The cost of waste disposal is often negotiated and finding a set marked price is difficult, but assuming 1000 NOK/ton of waste is seen as a reasonable cost estimate. In addition, the bio-char may be used to store CO<sub>2</sub>, with the potential market value depending in large part on the cost of carbon. In Europe, this would be the EU Emission Trading System (EU ETS), which drives the cost of CO<sub>2</sub> and other greenhouse gases. Seeing how one ton of coal can store up to three tons of CO<sub>2</sub>, it is assumed that the marked price of bio-char can be 500 NOK/ton.

Adding up the alternative cost, the energy regeneration, and the possible profit from bio-char, a new estimate of the NPV can be estimated.

$$Savings = alternative\ waste\ handling + sale\ of\ biochar + energy\ savings$$

From one ton of waste, this would equal:

$$Savings = 1000 \frac{NOK}{ton\ waste} + \left( 500 \frac{NOK}{ton\ BC} \cdot 0.35 \frac{ton\ BC}{ton\ waste} \right) + 141.6 \frac{NOK}{ton\ waste + BC} \approx \underline{\underline{1\ 317 \frac{NOK}{ton}}}$$

When multiplying this with 4 tons/day this comes to 5266 NOK/day or about 1 922 236 NOK/year. Given these savings, the NPV is:

$$NPV = 18\ 699\ 317\ NOK$$

With an IRR of 17.5%. The discount rate is still assumed to be 2%.

## 5 Conclusions

Carbon additives should be added to the MAP process in order to increase the heating efficiency of the MWs. The exact amount requires further large scale testing, but between 5 and 10wt% of BC should yield satisfying results. This is based on estimations from lab scale testing and the scalability is uncertain.

The estimations for the penetration depth also supports the conclusion of keeping the bio-char additive below 10 wt%. If the penetration depth should be too low, this will lead to further challenges in cavity design, as well as lowering the energy efficiency of the MW heating since the centre of the cavity would only rely on conduction heating from the outer rims of the MW cavity.

The energy output of the MAP system is low, but gives the opportunity to utilize energy from waste and decreases the need for landfill or other waste management technologies that have a greater negative environmental impact.

The direct economic gain of using the MAP to generate energy is negative and the cost must be brought down in order to sell the system as a potential investment. Because of the negative NPV, the market for a MAP system should be sectors where the emphasis is on the need for waste management, not energy generation. The clearest example is the cruise industry, where massive amounts of waste is generated, but land based technologies are hard to implement. In such a scenario, the importance of waste management is acting in accordance with environmental regulations, and the energy savings will be of a secondary nature. Being a relatively new technology, the MAP also has the potential to be marketed as a new “green and cool” solutions, giving customers the possibility to use it actively in their marketing.

From another perspective, the MAP system may be very profitable when taking into account the alternative cost of waste handling and the potential for carbon storage from the bio-char.

## 6 The way forward

Current literature is practically all based on small scale testing with samples often as small as 1-3 mm in diameter, weighing only a few grams. In order to fully understand the potential for energy output, more large scale testing has to be conducted. Another problem with much of today's literature is a narrow focus, like heating rate or gas composition, with very specific input, like coffee hull or rice husk. To make the research more applicable by the industry, a more representative mixture of waste should be tested, and the connections between different input factors should be attempted to be quantified. Even though large scale testing is scarce, it is reasonable to assume that there are several factors, ranging from the energy efficiency to the gas composition, that will change in a non-linear way when samples are scaled up from a few grams to perhaps tens of kilos in a MAP cavity.

In order to gain a better understanding of how different parameters affect each other, more controlled testing of co-pyrolysis is required. This should be tests performed on samples while carefully adjusting one parameter at a time. If done carefully, reliable numbers will be able to determine an empirical expression given the variables of HR, pyrolysis temperature, applied power, added MW absorbents, and the dielectric values.

One of the big areas of uncertainty in this thesis has been the dielectric properties of a given mixture, as well as what effect the palletization of waste and bulk pyrolyzation has on the dielectric properties. One way of better understanding dielectric solid mixtures will be to first test the dielectric values of single pellets with varying levels of carbon additives. This should provide enough data to plot the  $\tan\delta$  value for the given pelletized matter in relation to the amount of carbon additives, or any MW absorber one might prefer. In evaluating how a bulk of pelletized matter effects the dielectric properties, the same process of testing should be performed with pellets in bulk.

As mentioned in this thesis, the data regarding residence time should be improved. Several studies have not taken this into consideration, while others have commented and compared it, without defining a satisfactory formulation for its impact. To better formulate the impact of residence time, testing should be performed where the isolated variable will be the residence time.

The results from both the calculations and from published work, shows a clear advantage of adding bio-char to the waste before pyrolyzing. Even though the effects from bio-char in regards to secondary reactions are not fully clear, the differences in dielectric properties with and without bio-char support adding bio-char in order to obtain a higher heating rate. This would support a commercial set-up where a portion of the bio-char is transported back and mixed in with the waste. The most efficient and cost-effective way to achieve this will vary with the given space available for a MAP system.

During the initial commercialization of the MAP, possibly on board cruise ships, the easiest use of the syngas is burning it to produce heat for boilers. In the future however, it is worth exploring a combined system with the MAP producing gas for electricity generation. In order to do this, a Rankine cycle should be installed and tested at a large scale. A future product may then be an onshore, small-scale, waste to electricity instalment.



## Summary

The carbon concentration in the atmosphere is higher than it has ever been during the last 800 000 years, resulting in 27.5 million climate refugees globally. There is consensus within the international community that the threat of climate change is one of the biggest challenges facing the 21<sup>st</sup> century. This has in turn resulted in an ever increasing amount of interest and potential for environmentally friendly technology solutions.

Microwave assisted pyrolysis (MAP) is the process of pyrolyzing waste with microwaves as the source of energy. When pyrolyzing, matter is heated in the absence of oxygen, resulting in three products: syngas, bio-char, and bio-oil. The different amount of each product is dependent on a variety of factors, like pyrolysis temperature, heating rate, residence time, waste composition etc. Pyrolysis may also be performed without microwaves, often referred to as conventional pyrolysis (CP), where the energy input usually comes from electric or gas heating. When performing CP, the waste is heated from the outside of a cavity, relying on conduction heating in to the centre of the cavity. When utilizing MAP, the mass is heated more uniformly, and more energy efficiently. The main problem with MAP, compared to CP, is that organic waste is not very receptive to microwaves. However, carbon is a great microwave receptor so adding bio-char back to the in-feed of the cavity will increase the microwave absorption, resulting in a more efficient heating. Based on this, the problem formulation was:

“In what way will varying carbon contents affect the mass balance of the MAP system and what are the operational costs associated with running the MAP on a daily basis?”

In addition to increasing the microwave absorption, the MAP system must compete with other forms of waste handling and energy regeneration processes, most notably anaerobic decomposition and incineration.

Microwaves are often defined as electromagnetic waves in the frequency range of 300 MHz to 300 GHz with wavelengths of 1m to 1mm. The standard for MAP is 915 MHz or 2.45 GHz with wavelengths of 12 or 33 cm. The ability to absorb microwaves is measured by a materials dielectric properties, most commonly the  $\tan\delta$  value, that quantifies a materials ability to absorb microwaves. Any value above 0.2 is considered a good absorbent, but sewage sludge has a value of about 0.06 while bio-char has a value of about 1.04.

Syngas is commonly defined as gas rich in H<sub>2</sub> and CO, although there is no set definition. Besides H<sub>2</sub> and CO, syngas contains CH<sub>4</sub> and CO<sub>2</sub>, although the gas composition depends on the composition of the input. Often heavier C<sub>x</sub>H<sub>y</sub> gases are also present. The bio-char consists of mainly carbon, often with varying amounts of ash. Other elements in the bio-char can be found depending on the composition of the input. The bio-oil will also contain a lot of varying elements, making it to unstable for use without further processing. However, the potential for future bio-fuel from the bio-oil is present.

Pyrolysis is often sorted into three different types, that being slow, fast, and flash pyrolysis. The heating rate varies between 0.1-1 K/s for slow pyrolysis, while flash pyrolysis is over 1000 K/s. Slow pyrolysis gives the highest amount of gas, about 35 wt%, while flash pyrolysis gives the least amount, but about 75 wt% oil.

To determine the impact of bio-char additives in waste, six different waste compositions were used as a basis for estimation, ranging from 0 to 30 wt% additives. The rest of the waste consisted of equal amounts of PVC plastic, wood, and bio-solids in the form of dry municipal solid waste. The penetration depth of the microwaves varied from 47.28 cm without additives, to 1.45 cm with 30 wt% additives. In regards to the gas composition, there were some, but small variances between the six different gases. Based on the impact on heating rate, dielectric properties, and penetration depth, it was determined that 5-10 wt% bio-char additive was the ideal amount. With the given amount of additive, the LHV of the gas was 2.605 MJ/kg waste and bio-char, equivalent to 11.297 MJ/kg gas.

Given a price on energy of 0.399 NOK/kWh and a gross energy input of 0.7855 MJ/kg waste and bio-char, the net energy savings were estimated to be worth 566 NOK/day. However, when adjusting for the alternative cost of waste management and the potential value of bio-char, the daily savings were estimated to be 5266 NOK/day. This is given a capacity of 4000 kg/day.

The thesis concludes that the ideal amount of additives is 5-10 wt%, because of the impact on heating rate and penetration depth. It also comments on the amount of small scale testing in academia and the need for more large scale testing. However, despite the relative low energy output, the technology is ideal when anaerobic decomposition is to large and time consuming, like on offshore instalments such as cruise ships. In the future there will have to be conducted more testing, not only to evaluate the correlation between

small and large scale operations, but also to examine the relation between heating rate, dielectric properties, waste composition, and output from the system.

## Summary (in Norwegian)

Konsentrasjonen av karbon i atmosfæren er høyere enn den har vært noen gang de siste 800 000 årene, noe som har ført til at det finnes over 27.5 millioner klimaflykninger globalt. Det er konsensus internasjonalt om at trusselen fra klimaendringer er en av de største utfordringene for det 21. århundre. Dette har ført til økt interesse og potensiale for miljøvennlige tekniske løsninger.

Mikrobølge-assistert pyrolyse (MAP) er en prosess som innebærer pyrolyse av avfall med mikrobølger som energikilde. Under pyrolyse varmes materie opp under fravær av oksygen, som resulterer i tre produkter: syngass, bio-kull, og bio-olje. Mengden av hvert produkt varierer med en rekke faktorer, som pyrolysetemperatur, oppvarmingsrate, oppholdstid, avfallssammensetning osv. Pyrolyse kan også gjennomføres uten mikrobølger, ofte kalt konvensjonell pyrolyse (CP), hvor energitilførselen vanligvis kommer fra elektrisitet eller gass. Når en pyrolyserer med konvensjonell pyrolyse blir avfallet varmet fra utsiden av reaktoren, og ledningsvarme fører til oppvarming i reaktorens kjerne. Når en benytter seg av MAP blir massen varmet mer uniformt, og mer effektivt. Problemet med MAP, i forhold til CP, er at organisk avfall ikke er ideelt for absorbering av mikrobølger. Karbon, derimot, er en god absorbent, så en tilsetning av bio-kull til avfallet ved inntak vil føre til en økt absorpsjonsevne. Basert på dette er følgende problemstilling fremsatt:

«På hvilken måte vil varierende karboninnhold påvirke massebalansen av MAP systemet og hva er driftskostnadene tilknyttet en daglig drift av MAP?»

I tillegg til mikrobølgeabsorpsjonen må MAP systemet konkurrere mot andre former for avfallshåndtering og energigjenvinning, spesielt anaerob nedbrytelse og incineratorer.

Mikrobølger blir ofte definert som elektromagnetiske bølger med frekvens fra 300 MHz til 300 GHz og tilsvarende bølgelengder mellom 1m og 1mm. Standarden for MAP ligger på 915 MHz eller 2.45 GHz med bølgelengder på 12 eller 33 cm. Evnen til å absorbere mikrobølger er gitt ved et materials dielektriske egenskaper, som oftest  $\tan\delta$  verdien, som kvantifiserer et materials evne til å absorbere mikrobølger. En Verdi på over 0.2 blir regnet som en god absorbent, men kloakkslam har en verdi på omlag 0.06 mens bio-kull har en verdi på 1.04.

Syngass er som oftest definert som en gass rik på H<sub>2</sub> og CO, selv om det mangler en offisiell definisjon. Utenom H<sub>2</sub> og CO inneholder syngass CH<sub>4</sub> og CO<sub>2</sub>, selv om gassammensetningen vil være avhengig av avfallssammensetningen som går inn. Tyngere C<sub>x</sub>H<sub>y</sub> gasser er også ofte til stede. Bio-kullet består i hovedsak av karbon, ofte med varierende mengder aske. Andre elementer kan bli funnet avhengig av avfallssammensetningen. Bio-oljen vil også inneholde mange forskjellige elementer, som gjør den for ustabil for bruk uten videre prosessering. Likevel er det et potensial for fremtidig produksjon av biodrivstoff fra bio-oljen.

Pyrolyse deles ofte inn i tre forskjellige typer: sakte, rask, og flash. Oppvarmingsraten varierer fra 0,1-1 K/s for sakte pyrolyse, til over 1000 K/s for flash. Sakte pyrolyse avgir mest gass, omtrent 35 vekt%, mens flash pyrolyse avgir minst gass, men omtrent 75 vekt% olje. For å avgjøre påvirkningen fra tilsatt bio-kull ble seks forskjellige avfallssammensetninger brukt som grunnlag for beregninger, med 0 til 30 vekt% tilsetning. Resten av sammensetningen besto av PVC plastikk, tre, og tørket avfallsslam. Penetreringsdybden til mikrobølgene ble estimert til å variere fra 47,28 cm uten tilsetninger, til 1,45 cm med 30 vekt% tilsetninger. I forhold til gassammensetningene var det noe, men små variasjoner mellom de seks forskjellige gassene. Basert på påvirkningen på oppvarmingsrate, dielektriske egenskaper, og penetreringsdybde, ble det vurdert at 5-10 vekt% tilsetning var den ideelle mengden. Med denne mengden tilsetning, fikk gassen en nedre brennverdi på 2,604 MJ/kg avfall og bio-kull, tilsvarende 11.297 MJ/kg gass.

Med en energipris på 0,399 NOK/kWh og brutto energitilførsel på 0,7855 MJ/kg avfall og bio-kull, oppnådde man energisparing på 566 NOK/dag. Ved å ta hensyn til alternativkostnaden med avfallshåndtering og potensiell verdi fra salg av bio-kull, kan man oppnå en besparelse på opptil 5266 NOK/dag. Dette forutsetter en kapasitet på 4000 kg avfall/dag.

Denne oppgaven konkluderer med at den ideelle tilsetningen av bio-kull er på 5-10 vekt%, grunnet påvirkningen det har på penetreringsdybde og oppvarmingshastighet. Det kommenteres også mengden småskala tester som er gjennomført i forskningslitteraturen og behovet for mer storskala testing. Tross det relative lave energiutbyttet er teknologien ideell når anaerob nedbrytning blir for stort og tidkrevende, eksempelvis på offshore installasjoner som cruiseskip. I fremtiden vil det

være behov for mer testing, ikke bare for å evaluere sammenhengen mellom stor og liten skala, men også for å utforske sammenhengen mellom oppvarmingsrate, dielektriske egenskaper, avfallssammensetning, og utbyttet fra systemet.

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## Appendix 1 – Dryer calculations

The following values are used for calculating the energy needs for drying [77]:

TABLE 17: VALUES FOR DRYING CALCULATIONS

Parameter	Symbol	Value	Unit
Steampressure at 100°C	$P_{100}$	101.3	kPa
Steampressure at 250°C	$P_{250}$	3976	kPa
Density of air at 100°C	$\rho_{air,100}$	0.946	kg/m <sup>3</sup>
Density of air at 250°C	$\rho_{air,250}$	0.681	kg/m <sup>3</sup>
Temperature of air into dryer	$T_{air,start}$	250	°C
Temperature of air exiting dryer	$T_{air,end}$	100	°C

The humidity of the air is given as H. To calculate the humidity in the dryer, the ideal gas law is applied:

$$\frac{n}{V} = \frac{P_{250}}{RT}$$

$$H_{start} = \frac{M_{air} \cdot \frac{n}{V}}{\rho_{air,250}} = 38.69 \frac{kg \text{ water}}{kg \text{ dry air}}$$

Where M is the molar weight

n is moles

V is the volume

The enthalpy of the hot air is found by [77]:

$$h_{hot\ air} = (1 + 1.88 \cdot H) \cdot T \cdot \Delta H_{vap} \cdot H = 115\ 165 \frac{kJ}{kg\ hot\ air}$$

Where  $\Delta H_{vap}$  is the enthalpy of vaporization at 0°C

Applying the same equations,  $H_{out}$  and  $h_{air\ out}$  is calculated:

$$H_{out} = 0.976 \frac{kg\ water}{kg\ dry\ air}$$

$$h_{air\ out} = 2\ 724.68 \frac{kJ}{kg\ hot\ air}$$

After calculating the enthalpy of the air, the enthalpy of the biomass going in and out of the dryer is calculated using [77]:

$$h_{bio} = (C_{p,bio} + C_{water} \cdot X) \cdot (T_{bio} - T_0)$$

Where X is the fraction of water in the bio-solids and

$T_{bio}$  is the temperature of the bio-solids going in or out of the dryer

$T_0$  is the reference point, set at 0°C

TABLE 18: VALUES FOR CALCULATING ENTHALPY IN BIO-SOLIDS

Parameter	Symbol	Value	Unit
Heat capacity, water	$C_{water}$	4.187	kJ/kg·K
Heat capacity, biosolids	$C_{p,bio}$	1.4	kJ/kg·K
Temperature in	$T_{in}$	20	°C
Temperature out	$T_{out}$	100	°C

The values used for calculating the enthalpy change in the bio-solids are given in table XX [77]. From equation XX, the enthalpy in and out of the dryer is calculated:



$$h_{in} = 40.56 \frac{kJ}{kg}$$

$$h_{out} = 160.94 \frac{kJ}{kg}$$

## Appendix 2 – Fan, Shredder, and Pellet Press

### Fan

The weight of each component was calculated on the basis of table 14 and multiplied with the weight given in table 15. The results are shown in **table 19**:

TABLE 19: WEIGHT AND MOLES IN THE GAS COMPOSITIONS

gram	C1	C2	C3	C4	C5	C6
CO	78.7	74.2	69.7	65.8	60.6	51.5
CO <sub>2</sub>	50.8	48.6	46.4	43.9	42.1	37.6
C <sub>x</sub> H <sub>y</sub>	5.1	4.9	4.6	4.3	4.1	3.6
CH <sub>4</sub>	19.3	18.5	17.6	16.6	15.9	14.3
H <sub>2</sub>	6.4	6.2	6.3	6.0	5.7	5.3
HCl	88.9	84.5	80.0	75.5	71.1	62.2
mol						
CO	2.8112	2.6503	2.4884	2.3499	2.1645	1.8388
CO <sub>2</sub>	1.1547	1.1053	1.0553	0.9966	0.9557	0.8553
C <sub>x</sub> H <sub>y</sub>	0.1500	0.1425	0.1350	0.1275	0.1200	0.1050
CH <sub>4</sub>	1.2059	1.1512	1.0966	1.0355	0.9910	0.8905
H <sub>2</sub>	3.1774	3.0936	3.1407	2.9658	2.8262	2.6223
HCl	2.4377	2.3163	2.1941	2.0720	1.9506	1.7063

To get the molar amount, the weight value was divided by the molar weight, with results given in **table 20**:

TABLE 20: MOLAR WEIGHT OF GAS COMPONENTS

Substance	molar weight				
H2	2.02	g/mol	H	1.008	g/mol
CH4	16.04	g/mol	C	12.0107	g/mol
CO	28.01	g/mol	O	15.999	g/mol
CO2	44.01	g/mol	Cl	35.453	g/mol
HCl	36.46	g/mol			
C2H4	28.0534	g/mol			
C2H6	30.0694	g/mol			
C3H8	44.0961	g/mol			

The volume was calculated using the ideal gas law, assuming 1atm and 550 °C:

$$V = \frac{nRT}{P}$$

And then converted to square meters, as given in [table 21](#):

TABLE 21: VOLUME OF GAS COMPOSITIONS

	C1	C2	C3	C4	C5	C6
V[L] =	738.74	706.48	682.90	644.88	608.45	541.60
V [m <sup>3</sup> ] =	0.7387	0.7065	0.6829	0.6449	0.6085	0.5416

The fan capacity was given as 5.64 m<sup>3</sup>/h, so the values from the last row of table XX was divided by 5.64 to determine the time used by the fan. The time used was then multiplied with the fans power consumption of 0.75 kW to determine the total energy consumption, given in [table 22](#):

TABLE 22: ENERGY CONSUMPTION FOR FAN WITH DIFFERENT WASTE COMPOSITIONS

	C1	C2	C3	C4	C5	C6
fan time [h]	0.13	0.13	0.12	0.11	0.11	0.10
fan time [s]	471.54	450.94	435.89	411.63	388.38	345.70
fan energy [kJ]	353.65	338.21	326.92	308.72	291.28	259.27

The value used to estimate the energy balance was found by calculating the average fan energy of the C2 and C3 values.

### Shredder

The power consumption of the shredder engine is said to be 3 HP, or 2.23 kW. A shredder is mostly used for shredding in bulk, so the total time consumption for shredding 1 kg of biosolids is uncertain. The time is set to 5 seconds, as this is assumed to be a reasonable time for shredding 1 kg of waste. The energy consumption will then be:

$$E_{shredder} = 2.23 \text{ kW} \cdot 5 \text{ sec} = \underline{11.15 \text{ kJ}}$$

### Pellet press

The pellet press has a capacity of 200 kg/h and a power consumption of 50 kW. The time it takes to pelletize one kg of waste can be calculated to:

$$t = \frac{1 \text{ kg}}{200 \frac{\text{kg}}{\text{h}}} = 5 \cdot 10^{-3} \text{ h} = \underline{18 \text{ sec.}}$$

The energy consumption will then be:

$$E_p = 50 \text{ kW} \cdot 18 \text{ s} = \underline{900 \text{ kJ}}$$

