

**Future district heating plant integrated with municipal solid waste (MSW) gasification for hydrogen production**

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## Abstract:

The characterization of municipal solid waste (MSW) is a critical step in planning, designing, operating or upgrading solid waste management systems. The characterization of Norwegian MSW performed and the data from the characterization used for a theoretical investigation of hydrogen production by gasification, and water-gas-shift reaction. Three different gasification setups named as 'A-1', 'A&S-2' and 'S-3' were modeled using Aspen plus simulation software for direct and indirect gasification processes according to the different gasification agents. The result from the characterization of MSW showed a reasonable agreement with existing studies in different countries. The maximum hydrogen yield achieved in setup 'S-3', which was around 94% of the maximum theoretical hydrogen yield from specified MSW and at steam to syngas ratio of 0.5, 199.6 g of hydrogen per one kg of MSW could be produced, and 4 liters of water at 100 °C for district heating. From the study integrating indirect gasifier in preexisting MSW-fired plants can play a significant role in recovering energy from MSW in the form of energy carrier hydrogen. However, if it is necessary to construct a new waste incinerator, from the result found in this study, building a direct gasification system is recommended.

**Keywords:** MSW characterization, waste-to-energy, gasification, heat, hydrogen.

## 1. Introduction

The continuously increasing population, lifestyle behavioral changes and the growth of the economy are the critical driving force behind increasing global waste generation. Also, it leads to high demand for energy, whilst at the same time the issue of sustainability and environmental problems come in connection with waste management and energy generation from fossil fuel-based energy sources. Therefore, identifying future 4th generation district heating systems [1-2] is essential in order to address such aspects of the issue and to inform management as well as decision-maker.

The Norwegian government has a goal of developing a low-emission society and achieving carbon neutrality by 2050 [3]. The government has also implemented, through the EEA/EFTA agreement, the EU Renewable Directive with a national goal of 67.5% renewable energy sources by 2020 from a 2012 value of about 64.5% [4]. The employment of environmental policies, especially waste management policies, is one of the European Union's key priorities, as long-established by its suggestion for a 7th Environment Action Programme and the Roadmap to a resource efficient Europe (EC, 2011) [5]. The report from the Statistics Norway in July 2017 shows that the amount of household waste generated in 2016 increased by 9 percent compared to the amount produced in 2010. From this household waste sent for incineration, almost 80 percent of the waste was utilized for energy recovery [6]. At the same time, the Norwegian waste to energy (WtE) sectors had shown growth from a total waste handling capacity of 1.3 million tonnes/year in 2010 to 1.7 million tonnes in 2016. The WtE plants currently account for 17 plants, spread all across Norway [4]. Optimizing these existing waste management infrastructures will be an economically efficient approach to tackling the continual rise of the waste generation rate. Also, it can help in the optimal recovery of valuable energy that exists in the waste.

Researchers from different countries have reported their findings of physical and thermochemical characteristics of MSW for a specific location. Though estimation of the energy content of MSW using average physical compositions empirical models is a quick and inexpensive method, the type of waste in the country where the empirical model was developed probably differs substantially from that in the country where the model is applied [7]. Analyzing the thermochemical characteristics of MSW preprocessing of small representative samples is very difficult due to the heterogeneity of MSW. Robinson et al., [8] discussed different comminution techniques to prepare small samples and the influence that grinding and sieving had on the composition of the refuse derived fuel (RDF). Hla and Roverts [7] used a random sample collection method and categorized the waste sample according to the constituent material type. They used two methods to analyze the chemical properties of the waste. The first one was examining for each category of material type individually and the second was for the entire MSW by mixing according to their initial weight ratios. Baawain et al., [9] reported the result from ultimate analyses of MSW with various physical and chemical characteristics for specific site location in Oman. The method they used for sampling in the study was that all the fractions were hand sorted according to their waste categories and weighted according to their size fraction. Analysis and comparison of the essential properties from the energy standpoint investigated in Spain by Montejo et al. , [10], was to prove the advantages of RDF incineration over MSW in function of the composition. The method used in the study to determine the composition of the sample was performed by manually sorting and weighting the waste. They found out that RDF was a better fuel than MSW. Eisted and Christensen [11] characterize the household waste in Greenland by sorting household waste into material fractions and by determining the composition of each material fraction by chemical analysis. In the literature discussed above, all the authors used a method of sorting the waste by material fractions as Hla and Roberts [7] justified the characteristics of MSW by studying individual material and the mixed MSW agreed admirably.

A technology which can manage the waste and at the same time contribute to the energy sector is waste-to-energy (WtE) processing unit. WtE technology is any waste treatment process that uses waste as a fuel/feedstock to produce energy in the form of power, and heat, at the same time it helps in a reduction of the waste volume and weight [12]. Energy recovery from waste provides a double environmental benefit, the diversion of solid waste from landfill and the production of renewable energy, displace the use of fossil fuels and reducing carbon emissions. MSW gasification technology is evolved and improved, and many companies offer a commercially proven technology on WtE gasification-based plants around the globe [13-15]. Gasification mentioned as the accepted technology for solid waste conversion, including residual waste from a separate collection of MSW. Energos is one of the companies that offer commercially proven technology. The company has several essential gasification plants in Norway, Germany and the United Kingdom [16]. These gasification technologies use product gas directly to produce heat energy. A thermal conversion takes place in two stages. At the first stage gasification of the waste occurs in the primary chamber equipped with a fixed horizontal grate and in second stage oxidation of syngas happens in the secondary chamber. The most stable state-of-the-art gasification technologies in combination with fundamental aspects of the process, comparative analysis of reactor configurations and environmental performance of the primary commercially available gasifiers for MSW are discussed by Arena [17]. Porteous [18] investigated the emissions performance of MSW gasification in comparison with MSW incineration. They found out that gasification has the advantage of lower emissions, compared to MSW incineration. The report by Belgiorno et al. , [19] describes the state of gasification technology, pre-treatments,

and perspective to syngas use with particular attention to the different process cycles and environmental impacts of solid wastes gasification. Cost competitiveness of gasification in comparison with combustion, besides the potential for better environmental performance, and makes it an attractive technology in recovering energy from solid waste [20]. Freedonia Group reported in 2014 that the annual world hydrogen demand is rising by 3.5% annually, and production is projected to have increased to more than 300 billion m<sup>3</sup> by 2018, whilst out of this around 95% of the produced hydrogen is from fossil fuel-based methods [21]. Thus, using MSW as potential hydrogen source by gasification would contribute to the increasing global hydrogen demand.

Energy carrier hydrogen can be produced using various domestic resources including, biomass, MSW, and other renewable sources. Much work has been done on the focus of production of chemicals and fuel by the gasification of solid fuel. Turn et al., [22] performed an experimental investigation of hydrogen production from biomass using a bench scale fluidized bed gasifier. They investigated the effects of reactor temperature, equivalence ratio, and steam to biomass ratio on hydrogen yield. They found out that, hydrogen yield potential proved to be most sensitive to equivalence ratio. The two main MSW or biomass gasification reactors configurations used commonly are fluidized bed reactors and fixed bed reactors [23, 24]. Different outers use Aspen plus thermochemical simulation software to analyze their work for different reactor configuration and pathways. Rudra et al., [25] discussed the upgrading of the existing co-generation plants to quad-generation. They examined the quad-generation processes to produce power, heating, cooling, and SNG was modeled and compared regarding design and energy efficiency analysis. Chen et al., [26] have studied the effect of flue gas on syngas composition and conversion characteristics by simulation of MSW gasification using updraft fixed bed reactor in Aspen Plus. They investigated the improvement of the heat conversion efficiency and the lower heating value (LHV) of syngas by the introduction of flue gas into the gasification section. Regarding carbon conversion, it increases with the increasing gasification temperature and air equivalence ratio in both reactors. Pala et al., [27] developed an integrated model for steam gasification of biomass and subsequent syngas adjustment using shift reaction based on Gibbs free energy minimization using the Aspen Plus process simulator.

The number of different uses of energy carrier gases shows the flexibility of the gasification process and therefore allows it to integrate with several industrial processes, transportation and power generation systems. Integration of electric, heating and transportation systems provides an efficient utilization of energy and the best smart energy system. For the best management, usage, and participation in greener energy carrier production of MSW, it is essential to look for the flexible technologies to produce energy carrier fuels like hydrogen from the sustainable primary energy source. Studying and identifying of potential hydrogen yield of MSW by gasification in the Norwegian waste context can help in integration of MSW gasification technology with CHP/DH plants in the focus of heat and hydrogen production. To identify the potential hydrogen yield of an MSW, first, it is vital to study physical and thermochemical characteristics of the waste. In this work, to address the issue characterization of Norwegian MSW was performed in the University of Agder (UiA) laboratory using statistical data of the Norwegian waste fraction. With the help of the data, potential hydrogen production, and excess deliverable heat of the waste by gasification was studied, using a commercial process simulation software.

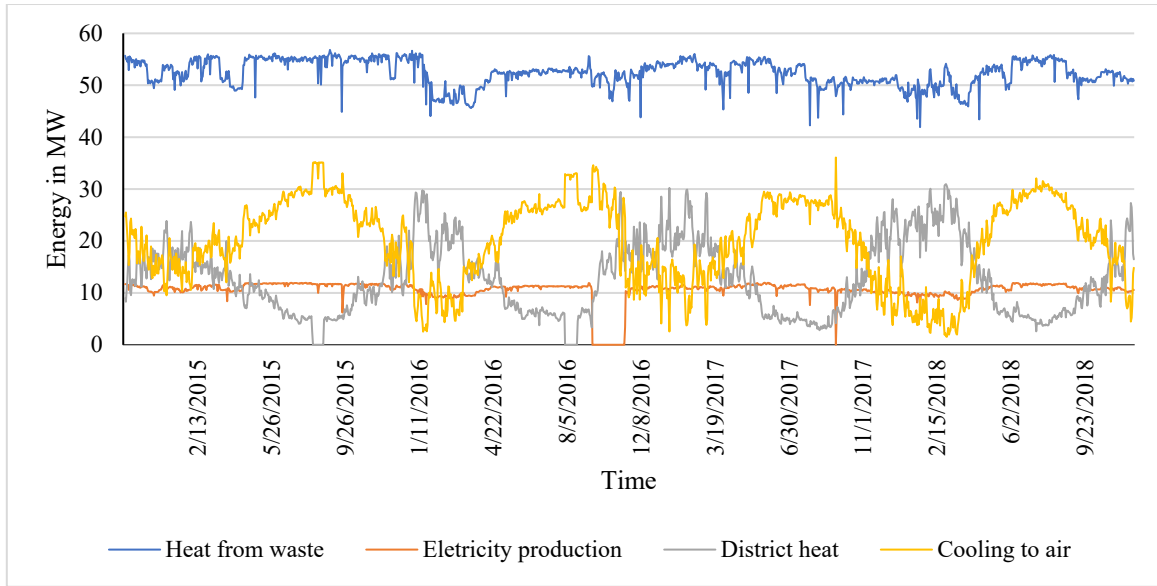


Fig. 1: The amount of heat production from waste, electricity production, district heat and heat cooling to air from Returkraft AS, Norway.

## 2. The scope of the article

In most incineration plants, waste incineration keeps on continuous throughout the whole year since the waste could not store as a long-term energy source due to the characteristics of the waste. Energy loss occurs from the MSW-fired CHP or DH plants due to customer energy consumption behavior and seasonal heat energy demand variation. An example of this scenario, Returkraft AS, Norway [28] data is considered in this study. Fig. 1 shows the energy loss by cooling hot water to the air from the year 2014 to 2018. In 2017, heat production in the boiler was 349319 MWh which used to produce 88763 MWh electricity and 108053 MWh of district heating. That means the rest 152503 MWh was considered cooling to air. All the other MSW fired plants in Norway reflect almost the same scenario. Also, the waste handle capacity of existing incineration plants compares to continue rising of waste generation will be insufficient in the future. Building new incineration facility will be costly, so, modifying the existing plants is an alternative to tackle mentioned problems. Integrating gasifier with a CHP/DH plant to convert and store the waste in the form of high energy density gaseous fuel increases waste handling capacity of the plant at the same time minimize the energy loss due to the fluctuation of customer energy demand. Introducing H<sub>2</sub> production integrating with heat will increase the total efficiency of that plant. In addition, it will also decrease CO<sub>2</sub> emission to the air. This case may also be economically feasible as the plant can utilize H<sub>2</sub> production as a transportation fuel.

## 3. Material and Methods:

### 3.1. MSW Sampling

Only a few grams of the sample was used for thermochemical characteristic analysis. The sample in this work was carefully sampled to make it representative of the average large waste pile generated in Norway. The samples were collected from different combustible waste categories which have high percentage composition in Norwegian waste categories according to 2015 waste scenario (wood waste 18.15%, paper and, cardboard 0.38%, plastics 3.3% and mixed waste 64.46%)[19]. The mixed waste comprises of plastics, paper, clothes and textiles, leather and rubber, and diapers. Though the mixed waste contains a lot of combustible materials, only plastics, and paper

were used for test sample modeling. In 2009, Avfall Norge reported the household mixed waste incinerated in Norway comprises of 15.4% paper, 7.8% plastic bags in weight and the rest is wet organic or another type of waste [30]. This data is used to model the percentage composition of paper and plastic in mixed waste from all types of sources, assuming that the mixed waste generated from all sources have a similar physical composition as that of household mixed waste. Then the calculated data from the mixed waste (paper and plastic bags) added to the respective waste category and the physical percentage composition of the sample in this work consist of 49% wood, 28% paper, and cardboard and 23% plastics waste prepared. During the collection of the sample, the attempt has been made to make it as representative as possible using self-experience and consulting experienced people in this area.

### 3.1.1. Sample Preparation

The test sample was collected during the winter season; hence, the collected samples had a high moisture content. Each waste category was stored for 2 to 15 days at room temperature prior to comminution. Due to the unavailability of milling machine which mills the waste sample size as small as 0.25mm in the laboratory, the comminution technique used for the three air-dry constituent test samples was performed by manual knife milling and sieving, and therefore it was a highly time-consuming task. Table 1 shows the weight of test sample acquired from the comminution of the test sample and the sieving. Sieving was performed in two sieve sizes 0.25 and 1mm sieve sizes. The plastic materials are relatively resistant to size reduction, and this resistance causes the ground material to become diminished as it passes through the sieves.

Table 1: Prepared test sample weight and size

Sieve size (mm)	Paper and cardboard (g)	Plastic (g)	Wood (g)
Total Milled sample	8.15	16.72	8.92
< 0.25	1.17	0.27	2.2
<1	6.18	7.88	5.23

After mixing of the sample according to percentage composition, 1g and 10g of the test sample was prepared out of the sample size, which passed through the 0.25 mm and 1 mm sieve size respectively. The two prepared test samples were stirred to make the sample as homogeneous as possible both manually and by using a magnetic stirrer. Those samples used in the characterization of the waste were considered according to a specific sample size requirement of test standards.

### 3.2. Proximate Analysis

In the proximate analysis, the moisture content (MC), volatile matter (VM) and ASH content were determined using three duplicate samples of MSW.

#### Moisture content

For the moisture content measurement, three test samples of the air-dried material with a weight of 1g each were used from less than a 1mm particle size sample. The three weighted samples in crucibles without lids were placed in the drying oven with the oven set temperature of 105°C for two days. The difference in weight between oven dried and air-dried samples are giving mainly due to the inherent moisture content of the sample and some part of surface moisture left after air drying. The percentage composition of moisture content on the dry basis was calculated using Eq. (3.1) [31].

$$\%MC_{dry} = \frac{W_{wet} - W_{dry}}{W_{dry}} \times 100 \quad (3.1)$$

### **Volatile matter**

For the VM content determination, three approximately 1g samples with a particle size of less than 1mm were used. The samples were placed simultaneously in the furnace with a furnace temperature of 900°C for seven minutes. After two hours, the samples were measured to find the loss in weight after thermal decomposition; the weight loss during decomposition includes the MC and VM of the test sample. The percentage composition of VM on dry-basis can be determined by excluding the weight of moisture dried off at 105 °C in the analysis of MC of the sample.

### **Fixed carbon and ash content test**

The standard test method for ash in biomass ASTM E1755 covers the determination of ash, which expressed as the mass percent of residue remaining after dry oxidation [32]. The method used to determine the ash content of the sample in this work was adopted from this standard. Similarly, three duplicate samples of weight 1g each with a particle size of less than 1mm were used. The percentage composition of ash in the sample calculated taking the weight left after combustion. The percentage composition of FC of the sample is the difference.

### **3.3. Ultimate Analysis**

The percentage composition of carbon, hydrogen, nitrogen in the MSW sample was measured by using PerkinElmer 2400 Series II CHNS/O Elemental Analyzer. The instrument determines the C, H, N, S and O contents in organic and other types of materials. The principle of determining the elemental composition of a sample is, based on the classical Pregl-Dumas method, samples combusted in a pure oxygen environment, with the resultant combustion gases measured in an automated fashion [33].

The experiments were replicated nine times to determine their repeatability using the sample of size less than 0.25mm. The sample was put in the tin vial, weighed again and the data transferred to the instrument. The net mass of the samples used for elemental analysis was approximately in the range 1 to 2mg, then each encapsulated sample in the tin vial was placed on the integral 60-position autosampler.

The analysis starts by running two tests of calibrating material (Acetanilide) with known percentage composition of C, H, and N to assure optimal analyzer performance. The three new runs were carried out to purge the system, followed by nine samples, in every three-test sample run three blanks runs were conducted to purge the system which helps to remove the remains from preceding run.

The percentage composition of constituent elements was analyzed, and the average is taken for each constituent element. The average result obtained from the direct measurement was in air-dried base since the teste sample was on the air-dried basis. The result converted to a dry basis and the hydrogen content from moisture reduced from the measured percentage hydrogen composition. The percentage composition of sulfur was taken from relevant literature, while the ash content is the ash obtained in the proximate analysis. The oxygen percentage composition can calculate as follow (Eq. 3.2).

$$C + H + O + N + S + Ash + MC = 100\% \quad (3.2)$$

### 3.4. MSW gasification plant design

The two-feasible gasification systems for hydrogen production from MSW by gasification and followed by water-gas-shift reaction WGSR were considered in this study. One uses only steam gasifying medium which is indirect gasification, whereas the other one could use oxygen/air and steam as a gasifying agent which is a direct gasification system. In both systems, the WGSR has a similar process.

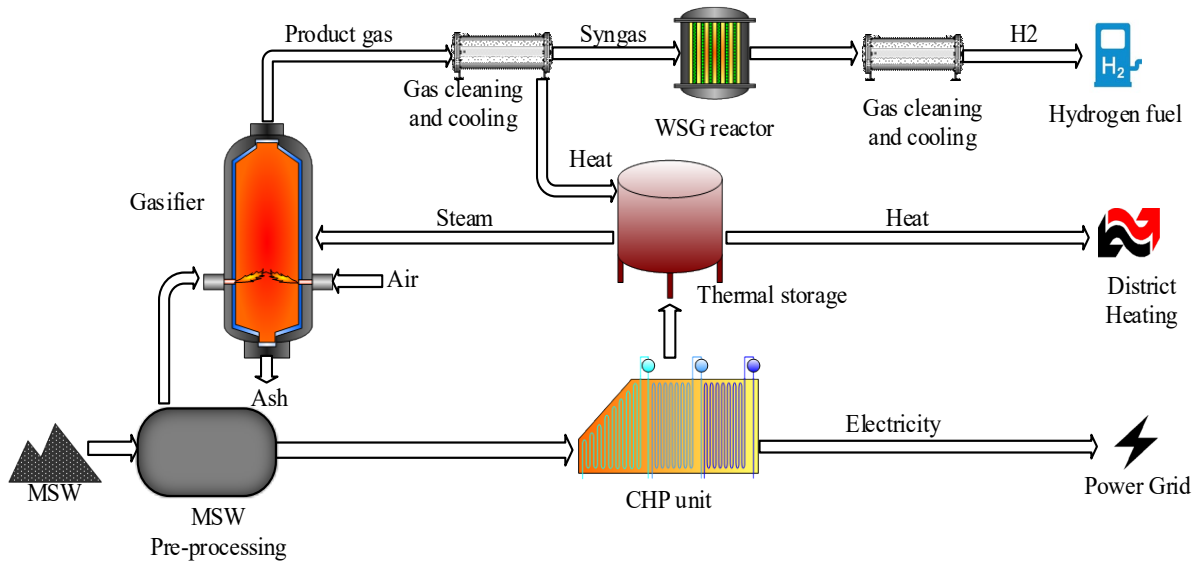


Fig. 2: Schematic diagram of hydrogen production plant with MSW gasification

Fig. 2: illustrates a schematic diagram of a hydrogen production plant with an allo-thermal fixed bed downdraft gasifier. The pre-processed MSW is fed to the gasifier and the existing incineration plant. The feedstock feed to the preexisting plant produces electricity and/or heat. The heat from this plant uses both district heating and gasification processes to produce hydrogen-rich product gas in the presence of steam. The product gas from the gasification process is conditioned to get low-temperature syngas and then it sends to the WGS reactor for enhancement of hydrogen. After that, the gas is compressed for storing after cleaning and cooling of the product. The surplus heat of the gasification process is utilized for producing steam and is used as a gasifying agent in gasifier and WGS reactor. The surplus heat from the WGS reactor could be utilized for district heating, using the existing grid infrastructure.

For the direct gasifier, the heat for gasification supplied by partial combustion of the MSW, unlike indirect gasification in which the heat is supplied from the external source. The partial combustion of the MSW takes place in the presence of air. The surplus heat, from the gasification reactor, product gas cooling, and WGS reactor could be used for district heating.

#### 3.4.1. Simulation method

A comprehensive process model is developed and simulated for direct and indirect MSW gasification system. The model developed is an atmospheric fixed bed reactor and followed by atmospheric WGS reactor using the Aspen Plus V9 process simulation software. The simulation models predicted the yield of hydrogen and the surplus heat produced in the system. Sensitivity analysis also carried out to investigate the effects of different operating parameters such as gasification temperature, equivalence ratio, and steam to MSW rate on the yield of hydrogen. Similarly, the effect of temperature and steam flow rate in the WGS reactor is simulated.



The simulation for gasification and WGSR is set up based on thermodynamic equilibrium, and chemical equilibrium of the overall process. For the equilibrium modeling of the system, stoichiometric and nonstoichiometric methods are used. The base for simulations in Aspen plus is the schematic diagram of the plants in Fig. 2:. Besides the gasification and WGSR process, the model includes the pre-drying process of the MSW. The following assumptions were introduced in this study to model the whole process:

- The process was in a steady state, and the reactions reach chemical equilibrium.
- The gasification product stream contains only  $H_2$ ,  $CO$ ,  $CO_2$ ,  $CH_4$ ,  $N_2$ ,  $H_2O$ .
- Heavy hydrocarbons are considered negligible.
- The separators are ideal.
- Carbon is fully converted to gaseous products.
- The temperature of the gasifier output and inside WGS reactors are considered as isothermal.
- The product of the water-gas-shift reaction contained only  $H_2$  and  $CO_2$ .

### 3.4.2. Process description

The main stages used in the simulation of the process are pre-drying, decomposition, gasification and WGSR. In both direct and indirect gasification processes, all the models used in all the stages are same, except for the gasification stage. For the direct gasification, air and steam are used as a gasifying medium while only steam used in the indirect gasification process. The surplus heat from gasification and WGS reactors are retrieved using a heat exchanger and used in gasification and WGS reactors. The left-over heat from the two reactors is used in the district heating system.

The components used in the simulation can be divided into two categories. They are conventional and non-conventional components. For the two component types used, the properties are selected using the Aspen plus property method selection assistant. One of the suggested property methods was PENG-ROB thermodynamic method to calculate the properties of conventional components. The HCOALGEN and the DCOALIGT models are used to calculate the nonconventional solid properties (enthalpy and density). The simulation model flowsheet of the direct gasification is illustrated in fig. 3.

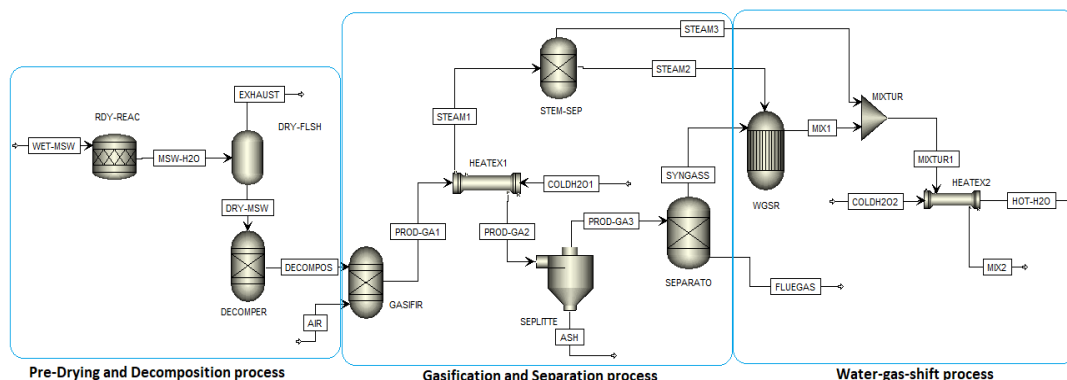


Fig. 3: Process flowsheet of the direct gasification system

### MSW pre-drying and decomposition process

The drying and decomposition section of the process is illustrated in the first section of Fig. . The feedstock stream ‘WET-MSW’ is fed to the drier ‘RDY-REAC’ block, the stream specified as a non-conventional component with the ultimate, proximate analysis and particle size distribution input. In the stoichiometric reactor (RDY-REAC) block, at 200 °C reactor temperature, a portion of moisture present in the feedstock was converted into conventional component liquid H<sub>2</sub>O. The (RDY-REAC) block was supplemented and controlled by the external FORTRAN statement to reduce and control the moisture content of the feedstock to 15% on a wet basis. ‘DRY-MSW’ stream moves through an equilibrium reactor ‘DCOMPER’.

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Table 2: The reactions considered in the gasification process and water-gas-shift reaction for the simulation.

Char Partial Oxidation	$C + 1/2 O_2 \rightarrow CO$	$- 111 \text{ kJ/mol}$	(R3.1)
Boudouard	$C + CO_2 \leftrightarrow 2CO$	$+ 172 \text{ kJ/mol}$	(R3.2)
Water-gas	$C + H_2O \leftrightarrow CO + H_2$	$+ 131 \text{ kJ/mol}$	(R3.3)
Tar creaking	$Tar \rightarrow CO_2 + CO + H_2 + CH_4$		(R3.4)
Hydrogasification	$C + 2H_2 \leftrightarrow CH_4$	$- 74.8 \text{ kJ/mol}$	(R3.5)
	$CO + H_2O \rightarrow CO_2 + H_2$	$- 41 \text{ kJ/mol}$	(R3.6)
	$CH_4 + H_2O \rightarrow CO + 3H_2$	$+ 206 \text{ kJ/mol}$	(R3.7)
	$H_2 + 0.5O_2 \rightarrow H_2O$	$- 242 \text{ kJ/mol}$	(R3.8)
	$C + O_2 \rightarrow CO_2$	$- 394 \text{ kJ/mol}$	(R3.9)
WGSR	$CO + H_2O \leftrightarrow CO_2 + H_2$		(R3.10)

### Gasification process

The gasifying medium and decomposed MSW is fed to the gasification block. The stream moves to a RGIBBS block (GASIFIR). In this block, the RGibbs model is used to simulate gasification of the decomposed MSW in the presence of the gasifying medium. MSW type influences the tar product. Thermal creaking converts tar into smaller and lighter hydrocarbons (R3.4). The significant reactions occurred in the gasification process, and water-gas-shift reaction (WGSR) summarized in table 2. The heat from product gas and the ash retrieved in ‘HEATEX1’ block. The steam from the heat exchanger is sent to ‘WGSR,’ and the rest is sent to the second heat exchanger for

adjustment of the output temperature. Then the syngas fed to the WGS reactor for enhancement of hydrogen. Like that of the gasification reactor in the WGSR RGibbs model is used. After WGSR, the mixture gas containing hydrogen passes through a heat exchanger for extraction of surplus heat. The heat used for heating water at a temperature of 100°C for district heating application.

## 4. Result and Discussion

### 4.1. Proximate analysis

The experimental data presented for the proximate analysis in this work corresponding to the measurement results are the mean values of the three duplicate tests. The FC content determined by the difference of hundred percent to the sum of the average percentage value of MC, VM and ash tests. In Table 3, the results presented together with the result reported by Hla and Roberts [7] for comparison. Hla and Roberts reported the results for the measured reconstituted sample and calculated from an individual sample of combustible components in Greater Brisbane, Australia.

Table 3: Proximate analysis results of the present sample and from literature

Parameters	Present result	Measured [7]	Calculated [7]
Moisture (%wb)	6.3	N/A	N/A
Volatile matter (%db)	78.6	77.4	78.4
Fixed carbon (%db)	9.0	15.1	14.5
Ash (%db)	12.4	7.6	7.2

The MSW characterization conducted in Greenland by Eisted and Christensen [11] indicated that the chemical composition of the material fractions in Greenland was similar to the composition of material fractions in Danish household. This study shows that chemical composition and a material fraction of MSW dependent on geographical location, socioeconomic status, and other reasons.

The comparison of the results in table 3 shows some differences; the differences could be due to the reasons mentioned above. Thus, the present finding can give a reasonable approximation of the average Norwegian MSW proximate analysis. Though the two study locations are in entirely different geographical location, they have some similarity in economic issue and lifestyle. Therefore, it can be concluded that the result obtained in this work suggests that the method used for sampling of the MSW using statistical data was reasonable. However, for the as-received moisture content of the waste since it depends highly on the geographical location, the waste sorting and categorization method in a specific area and season in which the sample analyzed. Therefore, it is entirely reasonable to study the as-received moisture content of MSW for a place in which the incineration plant operates.

### 4.2. Ultimate analysis

The experimental data of C, H, and N corresponding to the measurement results are the mean values of the nine runs carried out. The oxygen content determined by difference and the ash content is the result found in the proximate analysis. As mentioned in the method section of this work, the sulfur content is taken from relevant literature [7], [9]. In those mentioned literature the mass percent composition of sulfur ranges from 0.18 to 0.21 %, in this work the sulfur content approximated to 0.2%.

In general, the results obtained were as expected, most chemical characteristics of MSW samples presented in Table 4, are the typical chemical composition of biomass, since mass percentage composition of the MSW sample in this study dominated by biomass which is around 77%. The result also has not a considerable deviation from results reported by the different investigator [7], [9], [11]. The results from the ultimate analysis along with the result from literature [9] presented in table 4. It showed that carbon and oxygen were the most dominated chemical elements in the MSW.

Table 4: Chemical composition of MSW sample

Element	C (%db)	H(%db)	N(%db)	O(%db)	S(%db)	Ash(%db)
Present sample	51.6	6.3	0.8	28.7	(0.2)	12.4
Measurement [7]	52.8	6.4	1.29	31	0.18	7.6

The general chemical equation of the studied MSW can be approximated using the ultimate analysis data provided in Table 4 as  $C_xH_yO_zN_aS_b$  where x, y, z, a, and b represent the mole fraction of each element in MSW. This general chemical equation can use to determine the stoichiometric air-to-fuel ratio of combustion and, the air-to-fuel ratio became approximately eight.

#### 4.3. Heating value calculation

The heating value of the MSW calculated using different empirical formulas. These empirical formulas determine the heating value of the MSW using the ultimate analysis. In this work, the calculation performed using the empirical formulas and the elemental analysis data of the MSW presented in table 3. The results of the comparison analysis are presented in table 5.

Table 5: Heating value of the analyzed MSW and heating value of MSW from literature

Formula	Boie	Dulong	Reed	Average
HHV <sub>db</sub> (MJ/kg)	22.3	21.3	21.7	21.8
HHV <sub>db</sub> from literature				
Literature	[9]	[11]	[12]	[13]
HHV <sub>db</sub> (MJ/kg)	22.5	22.2	18.97	21.2

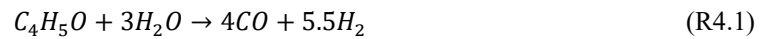
The HHV<sub>db</sub> of the MSW was calculated and found out 22.3 MJ/kg, 21.3 MJ/kg and 21.7 MJ/kg by using the empirical formulas proposed by Boie, Dulong, and Gaur and Reed respectively. The heating value of the MSW sample is in good agreement with the result reported in [7], [9]. These results from those literature used as a reference point to get a picture of the heating value of an MSW. The HHV<sub>db</sub> obtained in this work was higher than HHV<sub>db</sub> of wood, paper, cardboard and lower than plastic reported in [7], [9], [11]. So, the presence of plastic in MSW has the advantage of increases the overall heating value of the waste, though fossil fuel nature of the plastic requires high consideration in fuel gas cleaning for downstream use, flue gas control system and ash characteristics.

#### 4.4. Simulation model validation

The developed simulation model is validated using two methods. The first method was by comparing the predicted hydrogen yield of the gasification and WGSR with the theoretical attainable hydrogen yield of the dry ash-free MSW. The second method conducted by comparing the present model output with the existing experimental result. The product gas composition of the developed model using steam as a gasifying agent compared with an

experimental study conducted by Fremaux et al. , [34]. Though the experimental research was on a fluidized-bed reactor, the gas composition pattern of this validation test can be used to see the performance of the present model.

The balanced general chemical reactions for the dry ash-free MSW with steam as a gasifying agent for the gasification stage and WGSR are shown below in (R4.1) and (R4.2) respectively. Moreover, sulfur and nitrogen contents of the MSW are neglected in the calculations.



The possible attainable theoretical maximum hydrogen yield under the assumptions of dry ash-free MSW can be calculated from the balanced chemical reactions. The hydrogen yield of steam gasification (R4.1) and WGSR (R4.2) is calculated as 236g of H<sub>2</sub> per kg of dry ash-free MSW. This value is used to validate the present model. Practically the theoretical yield of hydrogen cannot achieve due to the molecular structure of MSW. The uncontrolled and complex decomposition the fuel undergoes upon heating, system losses, and irreversibility of the process.

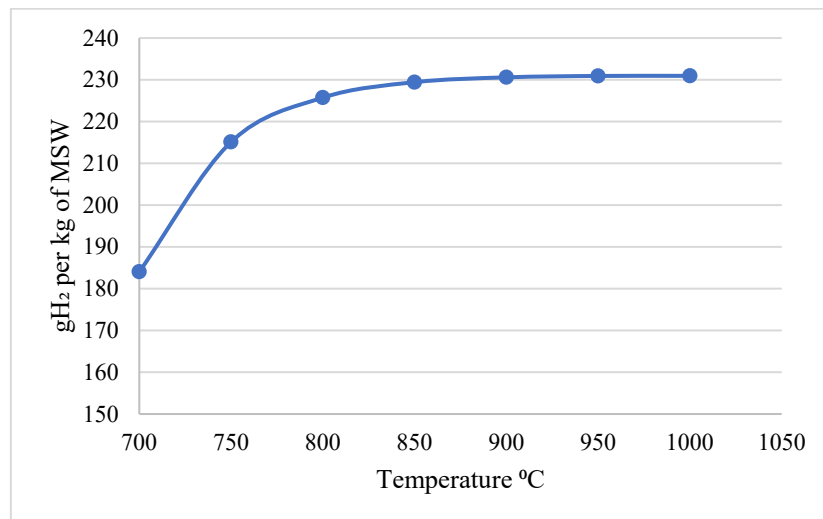


Fig. 4: Hydrogen yield of the model from MSW at a different gasification temperature

Fig. 4: illustrates the hydrogen production attained by the present model both from gasification and WGS reactors. *MSW/steam* and *CO/steam* ratios obtained from of (R4.1), and (R4.2) are used for the simulations. At an atmospheric gasifier and WGS reactor pressure when the WGS reactor temperature is continuously kept at 300°C, hydrogen yield increased with the increase of gasification temperature.

The highest attained hydrogen yield in this model was 230.9 gH<sub>2</sub> per kg of dry ash-free MSW at a temperature of around 950°C, and above this temperature, the yield becomes almost constant. The lowest is 184.1 gH<sub>2</sub> per kg of dry ash-free MSW at 700°C. The hydrogen yield of the present model had no significant difference from the theoretical maximum yield of the MSW; the differences range from around 2.2% to 22% at 950°C and 700°C respectively. The motives for the reduction could be the participation of hydrogen in the formation of methane and miss much of the optimum condition in the reactors.

The second model validation method conducted by using wood residue characteristics used by Fremaux et al. , [34]. Their experimental study on the effect of steam to biomass ratio between 0.5 to 1 at gasification temperature of 700°C used for comparison of the present model. The characteristics of wood residue used in their experimental study adopted for validation of the present model.

Fig.5 shows the comparison of the percentage composition of product gas in experimental steam gasification of residue wood performed by Fremaux et al. and by simulation of gasification with steam as a gasifying agent modeled in this work. The result from the present model shows that similar trends as it found in the experiments study of Fremaux et al. The same approach was used by Pala et al., [27] on validating of their simulation model and they also found a similar trend as it was in the present work.

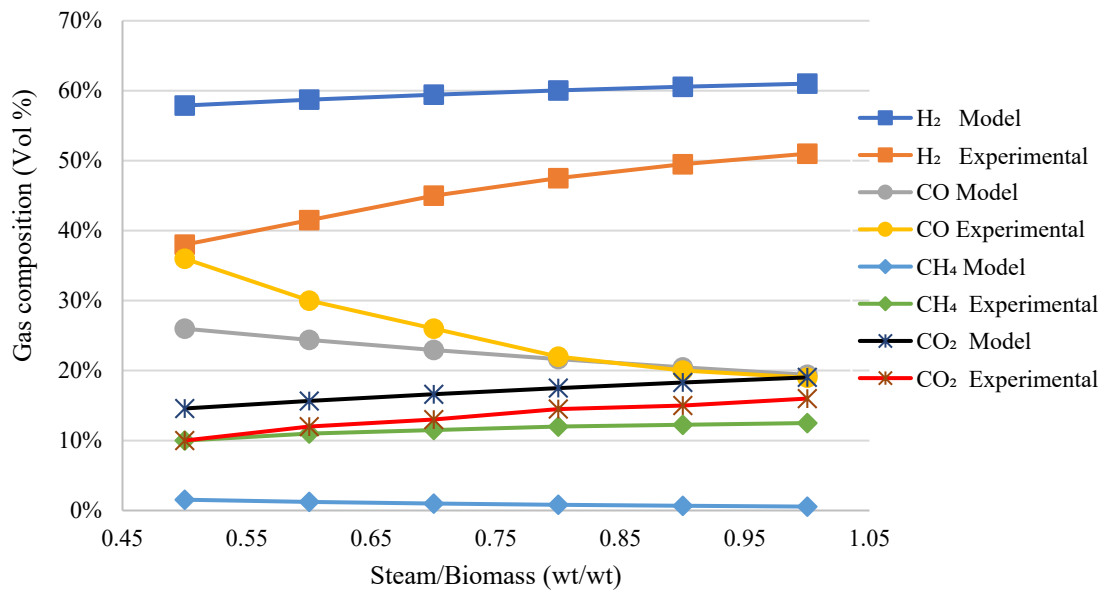


Fig.5: Comparison between model and experimental (Fremaux et al. , [34]) results at the gasification temperature of 700°C

The model predicted higher hydrogen concentrations than the experimental study done by Fremaux et al. on the same feedstock. Pala et al., [27] stated that the reason for the higher hydrogen concentrations is that the model does not consider the formation of higher hydrocarbons. Similar to Pala et al., this work does not consider higher hydrocarbons, and it could be the reason to obtain the same conclusions. The other reason could be that the experimental study was conducted in a fluidized-bed reactor, but the present work was performed in a fixed-bed reactor. The hydrogen yield of the fluidized-bed reactor is lower compared to a fixed-bed reactor with air as a gasifying medium [35]. The concentration of CH<sub>4</sub> underestimated in this model, which was an entirely common problem in equilibrium modeling [36].

#### 4.5. Sensitivity analysis (direct gasification)

In this study, the moisture content of MSW was used to be 15% in all the following simulations performed. The moisture from MSW may also be involved in chemical reactions, such as WGSR, water-gas, and steam methane reforming reaction. Also, it can affect the chemical reaction equilibrium and change the component distribution in the product gas [34].

#### 4.5.1. Effect of gasification temperature

The effect of gasification temperature on the product gas composition at an ER of 0.3 was studied. Fig.6: shows the gas composition obtained from direct gasification of MSW as a function of gasification temperature in the range of 550 to 1000°C with the increment of 50. Fig. 6 also shows a comparison with a parametric study [36] with the process result. The percentage composition of N<sub>2</sub> not displayed in the figure and the nitrogen content can calculate by subtracting the sum of other components from 100% for both models.

Le Châtelier's Principle states that a change in pressure, temperature, or concentration will push the equilibrium to one side of the equation. As expected, the trends are in good agreement with the chemical reaction laws stated. Raising reaction temperature favors the endothermic reactions, while the reverse is true in an exothermic reaction. In the result obtained the concentration of H<sub>2</sub> and CO increased with the increase of gasification temperature while the concentration of CO<sub>2</sub> and CH<sub>4</sub> decreased as the gasification temperature increased. A null value for methane concentration was usually predicted in equilibrium modeling above 800 °C [36]. The result shows that H<sub>2</sub> increasing from approximately 18% at 550°C to maximum point of 24% at 750°C and then slightly reduced to 23% at 1000°C. CO shows a dramatic increase in the temperature range of 550°C to 750°C from approximately 6% to 26% and then reaches 28% at 1000°C. Quite similar general gas composition trends were reported for their study of the effect of gasification temperature [36].

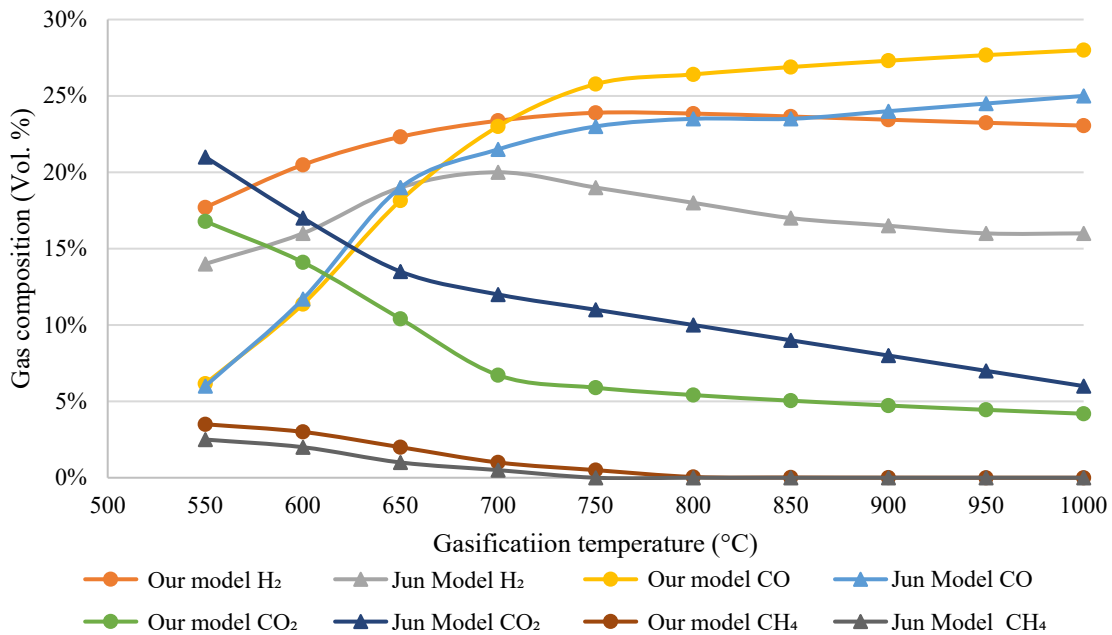


Fig.6: Effect of gasification temperature on product gas composition in direct gasification only air as a gasifying agent.

The endothermic reaction is more sensitive to the temperature changes. Therefore, the endothermic reaction will increase faster with increasing temperature than the exothermic reaction — the increases of H<sub>2</sub> concentration in the product gas as a function of temperature attributed to endothermic water gas and steam methane reformation reactions. The increasing of gasification temperature provides the necessary energy for these endothermic reactions which are the most significant contributor to H<sub>2</sub>. Similarly, the primary CO contributors such as Boudouard, water-gas, and steam methane reformation reactions get the necessary energy for endothermic reactions. Thus, the CO

concentration increases with increasing the gasification temperature. Besides the increasing of H<sub>2</sub> and CO in steam methane reformation endothermic reaction, it decreases the concentration of CH<sub>4</sub> with increasing gasification temperature.

The decreasing CO<sub>2</sub> concentration with increasing gasification temperature could be because of the Boudouard reaction and reverse reaction of water gas shift reaction. As mentioned above in forwarding WGSR the favorable temperature is in the range of approximately 200-400°C. Increasing the temperature above this, favor the reverse reaction of water gas shift, so that it could be the reason for the reduction in the concentration of CO<sub>2</sub> product gas.

#### 4.5.2. Effect of air equivalence ratio

Air equivalence ratio represents the ratio of the actual amount of air introduced, to the amount of stoichiometric air needed for complete combustion. The effect of ER on percentage composition of product gas presented in fig. 7. ER was increased from 0.35 to 0.75 (fuel-lean condition) in increments of 0.25 by increasing the air flow rate while holding mass flowrate of MSW constant at constant gasification temperature of 900°C.

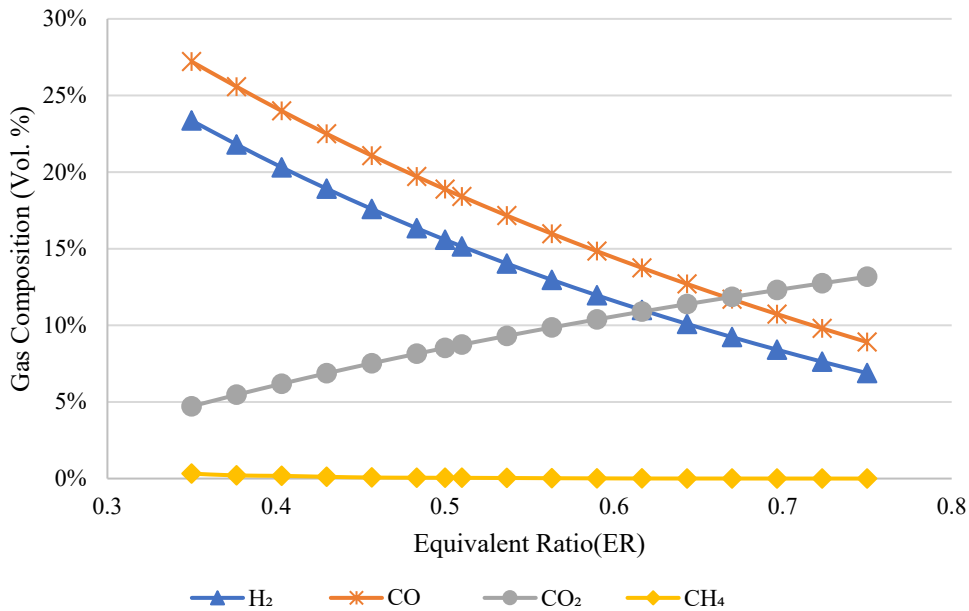


Fig. 7: Effect of equivalence ratio on product gas composition

In the study of the effect of ER on the percentage composition of the gas, the trends were opposite to that of trends obtained in the effect of gasification temperature study this is because air reached gasification is favorable for combustion than gasification. It can observe that the percentage composition of H<sub>2</sub> and CO decreased with increasing of ER while the percentage composition of CO<sub>2</sub> increases with increasing ER. It can be concluded that product gas composition in direct gasification using air as a gasifying agent is highly sensitive to ER.

As mentioned above the concentration of methane was underestimated in this model, which was an entirely common problem in the equilibrium modeling [36]. Quite similar trends in gas composition were reported by [22], [26] in the study of the effect of ER, except that H<sub>2</sub> had high percentage composition than CO. The reason for the domination of hydrogen in those studies was the introduction of steam in the gasification to produce a hydrogen-rich product gas.



#### 4.5.3. Effect of temperature in WGS reaction

Fig.8: shows the result of the WGS reaction temperature effect on the percentage composition of H<sub>2</sub>, CO, and CO<sub>2</sub>. The simulation performed at steam to CO ratio of 0.6, and the WGS reaction temperature was increased from 200°C to 750°C in an increment of 50°C. The gasification parameters of the gasifier held constant, at a temperature of 900°C and ER of 0.3.

As expected, from the thermodynamic equilibrium that the concentration of H<sub>2</sub> and CO<sub>2</sub> reduced with increasing temperature while the concentration of CO increases with temperature. The phenomenon is due to that the preference of the backward endothermic shift reaction at high temperature than forwarding shift reaction of an exothermic process. The result obtained for the study of the effect of temperature in the WGS in this work was in good agreement with the result reported by [27], in the report percentage conversion of CO, and CO<sub>2</sub> reported, and the trend shows similarity with the result obtained from the present model.

#### 4.1. Sensitivity analysis (indirect gasification)

The sensitivity analysis results and discussion of indirect gasification (Allo-thermal) process to study the effect of gasification temperature and steam to MSW ratio on the gas composition of product gas presented as follow. In indirect gasification, there is no nitrogen contamination involved. Only MSW contributes to a negligible amount of nitrogen in the product gas.

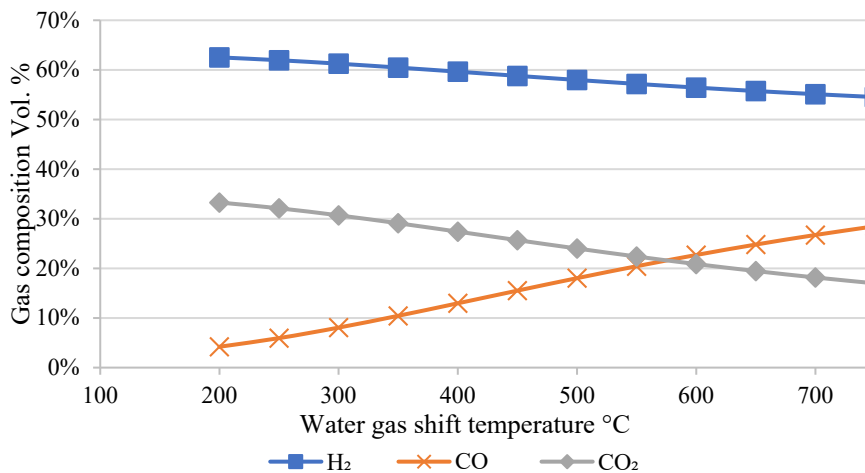


Fig.8: Effect of the WGS temperature on the gas composition

#### 4.1.1. Effect of gasification temperature

The effect of gasification temperature on the product gas composition studied by holding steam to MSW ratio steady at 0.6. Fig.9: shows the gas composition obtained in indirect gasification of MSW as a function of gasification temperature in the range of 550 to 1000 °C with the increment of 50.

It can observe from the result that the concentration of hydrogen increased slightly from approximately 48% at 550°C to 57% at 800°C and kept constant until 1000°C. Like direct gasification, the composition of carbon monoxide shows a fast increase in the temperature range of 550°C to 750°C from approximately 9% to 36% and then reaches 40% at 1000°C. Trends obtained in the product gas composition coincide well with results of Pala et al. , [27] who performed simulations in the gasification temperature range of 750°C to 950°C and constant steam to biomass ratio of 0.6.

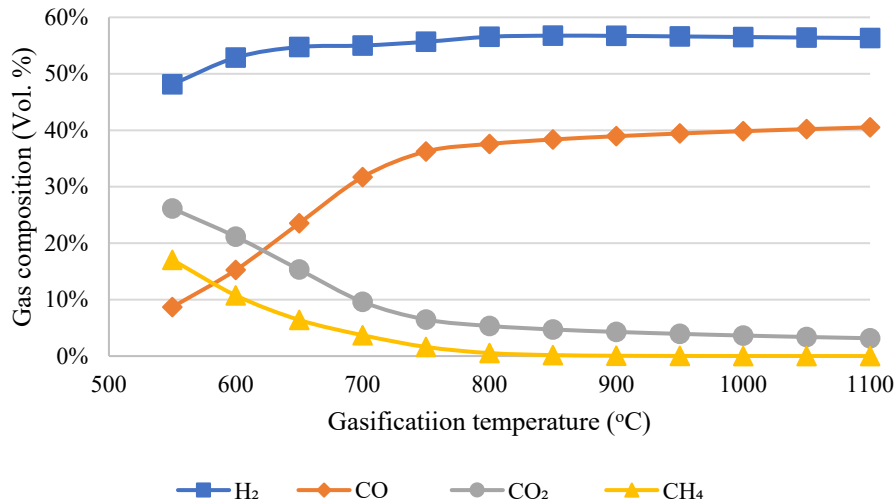


Fig.9: Effect of gasification temperature on product gas composition in indirect gasification

As expected, the trends of gas compositions in fig. 9 are in good agreement with chemical reaction laws. The gas composition trends obtained had similar trends as that of discussed in direct gasification (fig.6). The concentration of H<sub>2</sub> and CO increased with gasification temperature while the concentration of CO<sub>2</sub> and CH<sub>4</sub> decreased as the gasification temperature increased.

The presence of hydrogen in steam plays a significant role in increasing the composition of hydrogen in the product gas. Therefore the hydrogen composition trend dominates the other compositions. The addition of steam gives a favorable condition for endothermic water gas reaction and steam methane reformation, thus, increase the yield of H<sub>2</sub> and CO. The increasing of the gasification temperature with addition of steam as the gasification medium provides the necessary energy and reactant for those endothermic reactions which are the most significant contributor of H<sub>2</sub> and CO.

#### 4.1.2. Effect of steam to MSW ratio

The simulation was performed at a gasification temperature of 900°C and steam to MSW ratio increases from approximately 0.3 to 1 by increasing the steam flowrate while mass flowrate of MSW held constant. The result (Fig. 10) shows that the concentration of H<sub>2</sub> and CO<sub>2</sub> increases with steam to MSW ratio while the concentrations of CO and CH<sub>4</sub> decrease with increasing steam to MSW ratio. Similar trends have reported in [27] at gasification temperature of 900°C for wood residue.

The increase of H<sub>2</sub> and CO<sub>2</sub> with steam flow rate due to the conversion of CO and CH<sub>4</sub> via WGS and steam methane reforming respectively. Thus, the composition of CO and CH<sub>4</sub> decreases. The result showed that the effect of steam to MSW ratio on the hydrogen concentration was weak. Therefore, it is advantageous to feed only a low amount of steam because it can lead to an inconsiderable value of hydrogen-rich gas, and high amount of steam to MSW ratio will reduce the activity of the water gas shift reaction. Also, the production of steam is an energy-intensive process [27].

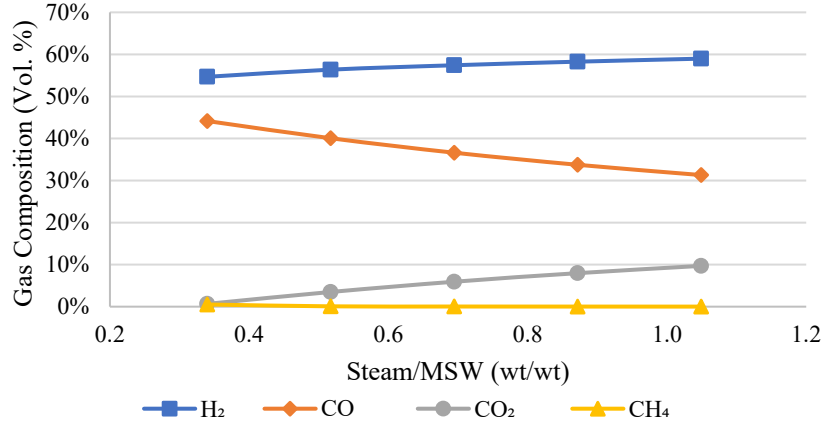


Fig. 10: Effect of steam to MSW ratio on product gas composition in indirect gasification

The increase of H<sub>2</sub> and CO<sub>2</sub> with steam flow rate due to the conversion of CO and CH<sub>4</sub> via WGS and steam methane reforming respectively. Thus, the composition of CO and CH<sub>4</sub> decreases. The result showed that the effect of steam to MSW ratio on the hydrogen concentration was weak. Therefore, it is advantageous to feed only a low amount of steam because it can lead to an inconsiderable value of hydrogen-rich gas, and high amount of steam to MSW ratio will reduce the activity of the water gas shift reaction. Also, the production of steam is an energy-intensive process [27].

#### 4.2. Hydrogen yield

The overall prediction of hydrogen yield of the whole process by gasification and followed by WGS performed in three different process setups at atmospheric pressure. The main differences in the setups were the type of gasifying medium and the way energy is supplied for the gasification process. Direct and indirect gasification are simulated using air, steam and air/steam as a gasification medium. The results of the simulation, for hydrogen yield as a function of steam to syngas ratio in the WGS reactor for the three setups presented in fig. 11. The gasification and water-gas-shift reactor parameters used in the simulation presented in (Table 6). Among the considered three process setups, steam gasification was indirect gasification while the other two were direct gasification.

Table 6: Gasifier and WGS reactor parameters

Setups	Gasification Reactor			WGS Reactor		
	Gasification Agent	ER	Steam to MSW Ratio	Temp. (°C)	Temp. (°C)	Steam to Syngas Ratio
A-1	Air	0.25	-	1000	300	0.2-1
A&S-2	Air & Steam	0.25	0.5	930	300	0.2-1
S-3	Steam	-	0.5	1000	300	0.2-1

The first setup executed with air as a gasifying agent in the direct gasification system. The lowest hydrogen yield obtained was 112 g H<sub>2</sub>/ kg of dry-ash free MSW, and the highest yield was 169 g H<sub>2</sub>/ kg of dry-ash free MSW at steam to syngas ratio of 0.2 and 1 respectively. The temperature by partial combustion of MSW in the Gibes gasification reactor was 1000°C, which is in the range of a typical downdraft gasifier reactor temperature.

In the second setup besides air, steam was admitted as a gasifying agent in the first setup. As illustrated in fig. 11 the hydrogen yield improved by 11.6% at 0.2 steam to syngas ratio. With increasing steam to syngas ratio, the yield became almost the same as that of the first model. In this model, the temperature of the Gibes gasification reactor reduces to 930°C due to the addition of steam at a temperature of around 300°C.

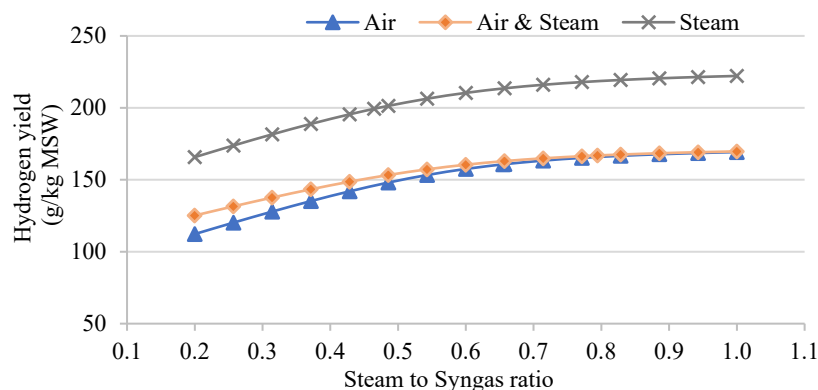


Fig. 11: Hydrogen yield from the gasification and WGS reactors with gasification agent of air, steam, and air/steam as a function of steam to syngas ratio

The third setup was indirect gasification with steam as a gasifying agent. In the third set up the hydrogen yield improvement was quite high and almost constant relative to the two setups for all the steam to syngas ratio values. In this setup hydrogen yield increases by 48% at 0.2 steam to syngas ratio and 31% at 1 steam to syngas ratio over that of the first setup. In this setup, the temperature in the reactor supplied and kept constant at 1000°C. The highest hydrogen yield potential attained out of the three setups was in the steam gasification, which was 222 g H<sub>2</sub>/kg of dry ash free MSW, representing 94% of the MSWs maximum theoretical hydrogen yield calculated above.

In agreement with Le Châtelier's principle, when the WGS reactor parameters are studied, the yield of hydrogen increased with the increase of steam to syngas ratio. Whereas, increasing temperature showed a decreasing trend of hydrogen yield (Fig.8:). According to Le Châtelier's Principle, increasing concentration of reactant let the reaction to the product side, whereas increasing temperature in an exothermic reaction favors the reaction to the reactant side.

The result showed that the addition of steam in gasification a positive impact in hydrogen yield since the hydrogen content of the steam contributes to increasing the concentration of hydrogen. The major problem associated with steam gasification is the production of tar, which causes a blockage in the pipes and equipment [35]. Although direct gasification uses air as a gasification agent to overcome the problem, in another hand the high concentration of nitrogen in syngas required high demand in the separation of nitrogen in downstream — the same with using oxygen as gasification agent, where it required high demand in the separation of oxygen in upstream. The choice of appropriate gasification media is a tradeoff among those mentioned. The performance of the gasifier type reasonably handles those issues among gasifier types is fixed bed downdraft gasifier [36].

#### 4.2.1. Hydrogen and heat production

The amount of hydrogen and heat can be delivered for district heating per one kilogram of MSW was predicted for the three setups discussed above. The simulation performed by holding steam to syngas ratio constant 0.6 for the first and second setups and 0.5 for the third setup. The reason for the reduction of steam to syngas ratio in the third setup was that the thermal energy content of the product gas from gasifier was not enough to produce steam for both gasification and WGS reactors. Therefore, steam to syngas ratio reduced to 0.5 while steam to MSW held as it is in Table . In this prediction of deliverable heat, it was assumed that the temperature of the hot water delivered for the district heating was 100°C and power generation from thermal energy not considered. The hydrogen and thermal energy output of the three simulation setups given in table 7.

Table 7: Hydrogen and thermal energy output of the three setups

Output per kg of MSW	Setup 'A-1'	Setup 'A&S-2'	Setup 'S-3'
Hydrogen [g]	157	165.3	199.6
Hot water at 100°C [l]	9.3	7	4

#### 5. Conclusion:

To aid in upgrading solid waste management systems for future heating plant integrated with hydrogen production, MSW samples were collected based on Norwegian waste statics and analyzed for their gasification-related properties. The result from the characterization of MSW used for theoretical investigation of the hydrogen yield of the MSW by gasification and WGS using air and steam as a gasifying medium. In this study, the characterization of MSW performed on the main constituents of the MSW, and most of the thermochemical properties of the waste agreed with other investigations in other countries with similar socio-economic status as Norway. It justifies the method used for the characterization of the MSW. The energy content (HHV<sub>db</sub>) of the MSW calculated by three empirical formulas and they are found out to be 22.3 MJ/kg, 21.3 MJ/kg, and 21.7 MJ/kg. The heating values of MSW mainly controlled by moisture content and the presence of incombustible materials in the waste (sorting process).

Three simulation model setups were conducted and compared in terms of theoretical investigation of hydrogen and heat production in different gasification medium. The highest hydrogen yield potential attained out of the three setups was in the steam gasification which was 222 g H<sub>2</sub>/kg of dry ash free MSW, representing 94% of the MSW's maximum theoretical hydrogen yield. At specific operating conditions, the hydrogen and heat produced in steam gasification per one kg of MSW were 199.6g of hydrogen, and the excess thermal energy heated 4 liters of water to 100 °C. The indirect gasification with steam as the gasifying medium showed the highest hydrogen production potential while the direct gasification was the lowest. The addition of steam in direct gasification showed an improvement in hydrogen yield. Therefore, combining district heating plant with hydrogen production facility could minimize the energy loss, and other MSW heating plants in Norway can adapt this approach.

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