

# Supplying hydrogen vehicles and ferries in Western Norway with locally produced hydrogen from municipal solid waste

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## Abstract

Gibbs free energy minimization has been used to estimate the hydrogen production potential of air gasification of the wet organic fractions of municipal solid waste available in the Bergen region in Western Norway. The aim of this work was to obtain an upper limit of the amount of hydrogen that could be produced and to estimate of the number of vehicles: passenger ferries and cars that could be supplied with an alternative fuel. The hydrogen production potential was investigated as function of waste composition, moisture content, heat loss, and carbon conversion factor. The amount of hydrogen annually available for both gasification and gasification combined with water-gas-shift-reaction was calculated for different scenarios. Up to 2700 tonne H<sub>2</sub> per year could be produced in the best case scenario; which would, if only utilised for maritime operations, be enough to supply nine ferries and ten fast passenger boat connections in the Hordaland region in Western Norway with hydrogen.

## Highlights

- Investigation of biomass gasification of wet organic solid municipal waste
- Application of Gibbs free energy minimization in a Matlab program
- Hydrogen production potential as function several process parameters
- Up to 2700 tonne of H<sub>2</sub> per year with gasification and water-gas-shift-reaction
- Several H<sub>2</sub>-ferries and fast passenger boats in Western Norway could be supplied

**Keywords:** hydrogen, biomass, municipal solid waste, gasification, Gibbs energy minimization

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## Introduction

Norway's contribution to the annual worldwide emission of greenhouse gases is negligible on a global scale: less than 0.15 % of the global greenhouse gas emissions in 2015 originated in Norway [1, 2]. However, the Norwegian government has set itself and its population the aim of reducing the emission of greenhouse gases to at least 60% or less of the national emissions in the year 1990 by the year 2030 [3]. This means a maximum emission of 31 million tonne CO<sub>2</sub>-equivalents in 2030 because the emissions in 1990 were 53.9 million tonne CO<sub>2</sub>-equivalents. Compared with 1990, the emissions increased by 2.2 million tonne to 53.9 million tonne CO<sub>2</sub>-equivalents by 2015. A decrease by 22.9 million tonne CO<sub>2</sub>-equivalents during the next 15 years is therefore necessary. This is to be achieved by increasing the efficiency of energy use as well as a reduction in the use of fossil fuels. As the electricity generated in Norway comes almost exclusively from hydropower (95.8% in 2015 [4]), reduction of fossil fuel use in the transport sector on land and sea is one focus area. For example, cargo trucks, ferries and passenger boats are driven by fossil fuels with the exception of a few local pilot projects like the electric car ferry across the Sognefjord between Larvik and Oppedal in Western Norway. In 2015, 19.1 % of the Norwegian greenhouse gas emissions came from road traffic (10.3 million tonne CO<sub>2</sub> equivalents) and about 11.9% from aviation, navigation, fishing, auxiliary motors etc. (6.4 million tonne CO<sub>2</sub> equivalents) [1]. Further contributors to the emissions of greenhouse gases in 2015 were oil and gas extraction (28.0 %), manufacturing industries and mining (22.1 %), energy supply (3.2 %), heating in other industries and households (2.2 %), agriculture (8.3 %) and other unspecified sources (5.2%) [1].

The decrease of crude oil prices to below \$70 per barrel (Brent) in 2014, has led to a crisis in the Norwegian gas and petroleum industry. Many offshore-related businesses changed their focus towards new markets and products in 2015. One of these new areas of interest is environmentally friendly propulsion in coastal waters. Many communities along the Norwegian coast are connected by fast-going passenger boats with capacities ranging from 10 to more than 100. Car ferries are in many places the only means to cross the fjords, sounds and narrows along the coast. For economic reasons, many of these passenger-carrying vessels use active thrusting while staying in port instead of mooring. This leads to unwanted and avoidable local emissions not only of greenhouse gases, but also particulate and NO<sub>x</sub> emissions. Much of the long distant transport of cargo is transported on few long distance train connections or by ship along the coast. The main part of cargo transportation on the road, however, does not travel further than 50 km and is therefore another source for local emissions. While the number of electric passenger cars has increased significantly in the past years in Norway, they are still relatively few compared with the total number of passenger cars in the whole country. At the end of the year 2016 only 3.7 % of all registered cars in Norway were pure electric cars [5] even though it meant an increase by more than 40 % from the year before. Compared with cars with an internal combustion engine, the limited range of electric cars running on batteries only is still a problem for many people, especially those who live in the outlying districts and regularly have to travel long distances that cannot be done with public transport. Electric cars with a fuel cell running on hydrogen offers the possibilities of a much longer range and faster refill time compared with charging a battery.

The transition from fossil fuels to hydrogen as a fuel for both fuel cell powered passenger cars and land and sea transport has come into the focus of both government, companies and local industrial interest groups. The aim is to use hydrogen to solve the problems with both emission of greenhouse gases and local pollution. Another driving force behind these activities this transition is the aim to develop both hydrogen-related technology and products as well as hydrogen as fuel to become more independent of the sale of fossil fuels to the global market.

Based on its natural resources, Norway has three main sources for hydrogen. One is electrolysis using electricity generated from hydropower. The second is steam reformation of methane sourced from its natural gas resources in combination with CO<sub>2</sub> capture and storage. The third option is the gasification of biomass with CO<sub>2</sub> capture and storage. The biomass could come from either agricultural waste and forestry or municipal solid waste.

The aim of this work was to obtain an upper limit of the amount of hydrogen that could be produced by gasification of municipal solid waste available in the region around Bergen, which is located in the Hordaland region on the Norwegian west coast. With this annual hydrogen production rate, an estimate of the number of vehicles of different types that could be supplied with locally produced hydrogen as a fuel is to be given.

Gasification is the partial oxidation of a biomass, which results, depending on the process parameters and gasification agent, in a hydrogen and carbon monoxide rich product gas (also called synthesis gas or syngas) [6]. Atmospheric air, pure oxygen and steam can be used as gasifying agents. Among the thermal processing methods for solid municipal waste, incineration of waste in combined heat and power plants is still preferred among the thermal treatment methods. This is mainly due to technical problems with the control of the gasification process because municipal solid waste is a chemically inhomogeneous fuel. However, improvements in gasification technology have been made and along with the possibility to produce hydrogen from waste, a renewable source in the sense that there is a constant to increasing availability of waste, gasification of biomass has seen much renewed interest.

Previous studies of hydrogen production by means of gasification have investigated different fuels and gasification processes. Tian et al. analysed the effects of biochemical composition of lignin, cellulose, hemicellulose and other biomasses on the hydrogen production potential in experiments with an updraft fixed-bed reactor [7]. It was found that biomass with more lignin produced more hydrogen than the other biomasses in the study. The simulations carried out by Ibrahimoglu et al. [8] analysed the hydrogen production potential in coal plasma-gasification with steam injection in a down-draft-gasifier. Favas et al [9] used Aspen Plus to study the plasma-gasification process of three different types of biomass and validate the results with experimental findings. Microalgae were the biomass used in chemical-loop-gasification experiments conducted by Liu et al. [10] while citrus peels were used as biofuel by Chiodo et al. [11] in a steam-gasification process. The potential of plasma-gasification processes for the treatment of solid wastes in general (not only biomass) was recently reviewed by Sanlisoy and Carpinlioglu [12]. The combined recovery of hydrogen and aluminium from unrecycled plastic waste was studied by Lu and Chiang [13]. High recovery efficiency of high purity aluminium was achieved in a lab-scale fixed bed gasifier. Different types of coal as fuel for a combined gasification and power plant were studied by Seyitoglu et al. [14].

Dincer and Acar [15] have evaluated 14 different methods of hydrogen production with respect to sustainability by comparing the different methods' global warming potential, social cost of carbon, production costs and energy and exergy efficiency. Gasification of biomass into syngas was one of the methods in this comparison. Although biomass gasification has highest energy and exergy efficiencies among the thermal methods, it has also higher social costs of carbon and global warming potential compared with many of the non-thermal methods. The relatively large SO<sub>2</sub> emissions can be dealt with by exhaust gas cleaning and capture and storage or use of CO<sub>2</sub> can reduce the global warming potential of gasification. The production cost of hydrogen by biomass gasification is one of the lowest (less than \$2/kg H<sub>2</sub>), only beaten by plasma arc decomposition of fossil fuels, coal gasification and fossil fuel reforming). It has the lowest cost among the methods which involve the use of both renewable energy and renewable fuel, although the low Norwegian electricity prices lead to comparable or even lower costs for electrolysis. The latter has a cost of more than \$2.5/kg H<sub>2</sub> [15]. Solheimslid calculated

hydrogen-from-biomass-gasification production costs to be between \$1.52/kg H<sub>2</sub> and \$3.53/kg H<sub>2</sub> in 2017 US dollars [16]. The price depends, among other factors, on both plant size and biomass costs. In this case the plants had production capacities of 8471 kg H<sub>2</sub>/h from biooils for the lower price and 1979 kg H<sub>2</sub>/h from waste biomass for the higher price [17]. The difference in biomass cost was a factor three with waste biomass being the cheaper alternative compared to dedicated biofuels. However, a more recent study for the U.S. Department of Energy Hydrogen and Fuel Cells Program [18] from 2011 gives a price range of \$3.19/kg H<sub>2</sub> to \$6.16/kg H<sub>2</sub> (converted from the 2009 values to 2017 US dollars with consumer price index (CPI) values from the website of the Bureau of Labor Statistics [19]). The lower price is for a plant, which can process 2000 dry tonne per day (dtpd) of biomass and produce 5625 kg H<sub>2</sub>/h, while the higher price is for a plant with 500 dtpd capacity and a production rate of 1350 kg H<sub>2</sub>/h. Woody biomass was taken as fuel. A report from 2015 by Albrecht et al. [20] estimates the costs of compressed gaseous hydrogen from biomass gasification to be between ca. \$5.70/kg H<sub>2</sub> and \$6.90/kg H<sub>2</sub> by 2030 (2017 US dollars). The prices are based on steam gasification of wood chips with a production rate of 270 kg H<sub>2</sub>/h for the lower price and 90 kg H<sub>2</sub>/h for the higher price.

The prediction of gaseous products from gasification and combustion processes can be carried out with different types of methods. One type of model is the so-called zero-dimensional or equilibrium models. Within this approach, it is assumed that the gasification reactions are in chemical equilibrium. Actual dimensions of a physical gasifying apparatus are not taken into account. Based on a given chemical reaction equation, the distribution of the reaction products is obtained by minimizing the total Gibbs free energy of the product gas. This type of model is relatively easy to implement and well-suited to obtain upper limits on the hydrogen production potential for a certain biomass under given conditions such as, for example: mass flows, oxygen deficiency and gasification temperature which are independent of the actual type of gasifier.

Altafini et al. used the Gibbs free energy minimization method to compare numerical results for the product gas composition with data from an experimental investigation on saw dust gasification with air [21]. Baratieri et al. used this method to compare the syngas composition of different biomass fuels like pine and poplar saw dust [22]. Jarunghammachote and Dutta employed Gibbs free energy minimization in order to compare actual and predicted syngas composition for municipal solid waste in a downdraft gasifier [23] and charcoal and coconut shell in spouted bed and spout-fluid bed gasifiers [24]. Melgar et al. [25] compared results from their equilibrium model, which is based on defining equilibrium constants for the expected reactions, with experimental results for rubber wood gasification obtained by Jayah et al. [26]. Néron et al. extended the Gibbs free energy minimization method with a kinetic constraint in order to study ethane cracking [27]. The kinetic constraint was employed in order to take into account the slowest reaction in the whole system and introducing time as a further variable in the model.

For the current study an equilibrium model has been chosen [28] to help estimate the hydrogen production potential from locally sourced municipal solid waste (MSW). The aim is to find out how many fossil fuel vehicles of various types registered in the Hordaland region in Western Norway could be replaced with vehicles of an equivalent type that use the produced hydrogen as fuel. Hydrogen from MSW by gasification has been identified as having the second largest exergy efficiency in a study of five different routes of turning bio-waste into biofuels by gasification [29]. Only the production of synthetic natural gas ranked higher. With respect to the energy efficiency, hydrogen production by gasification of biomass was the most efficient process in this study.

In the following, a short summary of the amount and chemical composition of the available waste in the Bergen region is given. After that, the model employed in this article is explained; where some minor modifications have been made compared with the original one published by Fournel et al. [28].

The results section contains data on the hydrogen production potential from three different fractions of wet organic waste, the first and second law efficiency of the gasification process and how the hydrogen amount could be increased if the water gas shift reaction is employed to make use of the carbon monoxide content in the product gas as well. The gasification process was investigated at different temperatures, moisture content of the biomass, carbon conversion factors and heat loss from the process. The result section ends with an overview over the fraction of fossil fuel powered vehicles and vessels in the Hordaland region that could be replaced by hydrogen driven ones. The method and results are discussed before the conclusions are drawn.

## Data

The local waste incineration plant is a combined heat and power plant with a maximum capacity of 220 000 tonne (as received) solid municipal waste per year. Its energy output are, at a maximum, 8 MW electricity and 60 MW district heat at 120 °C in winter and 110 °C in summer. Waste is collected mainly from households in Bergen and eight surrounding municipalities, which represented 69.6% of the total population in the Hordaland region (516 497 inhabitants) in 2016 [30]. The remaining waste capacity is filled up with waste from industrial customers. Waste composition [31] and efficiencies of the energy conversion process for the year 2013 [32] were investigated earlier.

*Table 1: Dry combustible mass and weight percentages (on dry basis) for the five most important elements, ash and moisture in the complete waste and the different wet organic (w.o.) waste fractions. 'Combined w.o.' means the sum of industrial and household wet organic (w.o.) waste).*

Waste fraction	dry mass (tonne)	wt% C	wt% H	wt% O	wt% N	wt% S	wt% ash	wt% moist.
complete	139 806	52.13 %	7.31 %	27.90 %	1.02 %	0.249 %	11.39 %	21.49 %
combined w.o.	35 843	37.42 %	4.74 %	29.80 %	1.64 %	0.529 %	25.87 %	51.33 %
industrial w.o.	13 837	44.02 %	5.86 %	36.92 %	2.26 %	0.633 %	10.30 %	31.92 %
household w.o.	22 006	33.23 %	4.03 %	25.3 %	1.25 %	0.464 %	35.73 %	63.62 %

Table 1 shows the composition of the whole waste from 2013, of its wet organic (w.o.) fraction (*combined wet organic*) and the contributions to the combined wet organic fraction from both household and industrial waste. The dry combustible mass of each waste fraction and the weight percentages on dry basis for the elements, C, H, O, N, and S as well as ash and moisture content are given. The wet organic fraction from the household waste is mainly food waste and therefore differs from the composition of the industrial wet organic waste. The amount of fixed carbon is ca. 15 % in all three waste fractions [31].

*Table 2: Higher heating values (HHV) as determined from the Phyllis2 database and by correlation function together with the deviation between these values. In addition, the chemical exergy and the molar mass of the complete waste and the different wet organic (w.o.) waste fractions is given. All values are given on dry basis (db).*

Waste fraction	molecule	HHV <sub>Phyllis</sub> (MJ/kg)	HHV <sub>Ch.&amp;P.</sub> (MJ/kg)	Deviation (%)	$X_{chem}$ (MJ/kg)	$M$ (kg/kmol)
complete	CH <sub>1.667</sub> O <sub>0.402</sub> N <sub>0.017</sub> S <sub>0.002</sub>	23.67	23.69	0.11	24.33	23.037
combined w.o.	CH <sub>1.506</sub> O <sub>0.598</sub> N <sub>0.038</sub> S <sub>0.005</sub>	15.36	15.05	2.1	15.76	32.098
industrial w.o.	CH <sub>1.584</sub> O <sub>0.630</sub> N <sub>0.044</sub> S <sub>0.005</sub>	18.60	18.27	1.8	19.13	27.283
household w.o.	CH <sub>1.440</sub> O <sub>0.571</sub> N <sub>0.032</sub> S <sub>0.005</sub>	13.33	13.0	2.5	13.63	36.138

Table 2 shows heating values and chemical exergy as calculated for the composition values in Table 1 with the methods described in [32]. The comparison between the higher heating values shows acceptable agreement between the values from the Phyllis2-database provided by the Dutch ECN [33] and the correlation given by Channiwala and Parikh [34], which is used in the method described in the next section. The chemical exergy of the waste fractions were calculated by the correlation for solid biomass developed by Song et al. [35] and used in the calculations of the second law efficiency of the gasification process.

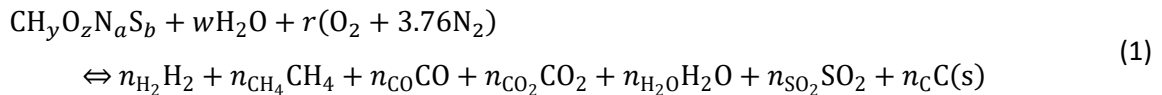
Table 3: Annual hydrogen consumption of different types of vehicles and their number in the Hordaland region in Western Norway in 2016. The number of vehicles is taken from data available from the website of the official national statistics provider Statistics Norway and, Norwegian Public Roads Administration and the regional public transport provider Skyss. For the ferries, crossing time is given in addition to the capacity in passenger car units (PCU; 1 PCU = 4.25 m x 1.65 m).

Vehicle type	annual H <sub>2</sub> need in kg per vehicle	number of vehicles in the Hordaland region (2016)
car	121 [36]	235 075 [37]
taxi	640 [36]	922 [38]
bus	3 826 [39]	1 385 [37]
cargo van	219 [40]	33 606 [37]
truck	2 049 [41]	4 573 [37]
ferry (< 50 PCU, 45 min)	138 065 [42]	5 [43]
ferry (< 50 PCU, 20 min)	113 228 [42]	4 [43]
ferry (120 PCU, 35 min)	370 000 [36]	15 [43]
passenger boat (100 passengers)	142 082 [44]	10 [45]

Average annual hydrogen consumption and number registered vehicles of different types in the Hordaland region of Norway have been compiled in Table 3. The number of road vehicles in 2016 were taken from the databases of the national statistics provider, Statistics Norway. The number of ferries and their capacities was taken from the database of the National Public Road Authority. Ferries are considered to be a part of the public road network in Norway. The average annual hydrogen consumption for the different road vehicle types was calculated based on the hydrogen consumption per 100 km (given in the various sources, as indicated in the corresponding column in Table 3) and the average annual distance travelled in 2016 [46].

## Methods

The Gibbs free energy minimization model employed is a slightly modified version of the one used by Fournel et al. [28]. As shown in Table 2, the biomass is represented by the sum formula CH<sub>y</sub>O<sub>z</sub>N<sub>a</sub>S<sub>b</sub>. The reaction formula used in the calculation of the gasification products is



where  $y$ ,  $z$ ,  $a$  and  $b$  are the mass fractions of hydrogen, oxygen, nitrogen and sulphur per carbon atom in the biomass, respectively. The amount of moisture  $w$  per kilomol dry biomass is the sum of the moisture contained in the biomass,  $w_{\text{bm}}$ , and the moisture contained in the gasifying agent (moist atmospheric air),  $w_{\text{ga}}$ . The factor  $r$  is the product of ratio of the actual to stoichiometric air-fuel-ratio

$\lambda$  (less than one for gasification) and the theoretical air  $a_{th}$ , necessary for stoichiometric combustion of the fuel.

The amount of moisture in the gasifying agent (in kmol H<sub>2</sub>O per kmol dry biomass) is calculated from the relative humidity  $\phi$  by first calculating the partial pressure of the water vapour in the moist atmospheric air

$$P_v = \phi P_{sat}(T_0) \quad (2)$$

and then  $P_v$  is inserted into

$$w_{ga} = \left(\frac{P_v}{P}\right) r(1 + 3.76) / \left(1 - \frac{P_v}{P}\right) \quad (3)$$

The amount of moisture per kmol dry biomass,  $w_{bm}$ , can be calculated with

$$w_{bm} = \frac{M_{bm,dry}}{M_{H_2O}} \cdot \left(\frac{\text{weight \% moisture (dry basis)}}{100}\right) \quad (4)$$

Values for  $M_{bm,dry}$  can be found in the last column of Table 2 while 18.015 kg/kmol were used for  $M_{H_2O}$ .

The conversion of moisture content from as received to dry basis is carried out according to

$$\text{weight \% moisture (dry basis)} = \frac{\text{weight \% moisture (as received)}}{100 - \text{weight \% moisture (as received)}} \cdot 100\% \quad (5)$$

The  $n_i$  on the right hand side of equation (1) are to be determined by minimizing the molar Gibbs energy  $\bar{G}$  of the products under certain assumptions and constraints, similar to the works of Fournel et al. [28] and Jarungthammachote and Dutta [23, 24].

It is assumed that the process is a steady flow process where solid biomass with its inherent moisture content and the moist atmospheric air enter the reaction volume in separate streams at 25 °C and 1 atm. The residence time in the reaction volume is assumed to be long enough to reach chemical equilibrium before the reaction products leave the gasifier. Therefore, additional reaction products than those given in equation (1) can be neglected.

A further assumption is that the gaseous reaction products can be treated as ideal gases. The temperature in the gasification process investigated here is at least twice the critical temperature of each product compound, except for H<sub>2</sub>O. In the case of water however, its partial pressure among the products compared with its critical pressure is low enough so that it can also be treated as an ideal gas.

All nitrogen from the biomass is assumed to be converted into N<sub>2</sub>. The reaction equation employed in this work allows for incomplete carbon conversion. This is accomplished by means of a carbon conversion factor (ccf), that can be specified in advance. Complete carbon conversion (100 %, equivalent to ccf = 1) means that all carbon from the biomass is converted into carbon contained in the gaseous products. Incomplete carbon conversion (0 < ccf < 1) leads to a corresponding amount of solid carbon (graphite) among the products when an equilibrium model is used [24]. Biomass always contains a certain amount of fixed carbon, and the employed model should be able to consider this. Therefore, complete (100%) and two scenarios with incomplete carbon conversion (85 % and 70 %) were investigated in this study.

Since about 50 % of the sulphur content of the biomass may be contained in the ash in combustion products, the same is assumed for gasification [47] and the corresponding elemental mass balance will only take  $0.5b$  into account among the gaseous products.

The ash content of the biomass feedstock is assumed to be inert and therefore not included into both reaction equation and energy balance.

The heat loss from the gasifier is set to 1 % of the higher heating value of the biomass by default as is typical for industrial sized and operated gasifiers [48]. However, it has also been set to 5 % and 10 % respectively in a number of calculations in order to investigate the effect of heat loss on the composition of the product gas and air-fuel-ratio.

At thermodynamic equilibrium, the Gibbs energy of a system is minimal. Being constrained only by the conservation of the total mass input to the reaction and the mass conservation of each element, the total molar Gibbs energy  $\bar{G}$  of the gasification products (right hand side of equation (1)) is minimized

$$\bar{G} = \sum_{i=\text{species}} n_i \mu_i \quad (6)$$

Here,  $\mu_i$  is the chemical potential of product species  $i$  and calculated by

$$\mu_i = \Delta\bar{G}_{f,i}^0 + RT \ln y_i \quad (7)$$

for the gaseous product species. For graphite (in case of incomplete carbon conversion)  $\mu_C$  is zero because in

$$\mu_C = \mu_C^0 + RT \ln x_C \quad (8)$$

$\mu_C^0$  is zero for graphite. As graphite is the only solid substance among the products in equation (1),  $x_C$  is equal to one, and the second term on the right hand side is zero, too. Therefore, in all the following cases, the term products refers to the gaseous products if not explicitly mentioned otherwise.

$\Delta\bar{G}_{f,i}^0$  is the standard Gibbs free energy of formation of species  $i$  at the equilibrium temperature  $T$  and pressure  $P$  ( $= 1$  atm). It is zero for all elements regardless of the value of  $T$ .  $R$  is the universal gas constant and  $y_i$  is the mole fraction of (gaseous) species  $i$ , where

$$y_i = n_i / n_{\text{total, gas.prod.}} \quad (9)$$

and

$$n_{\text{total, gas.prod.}} = \sum_{i=\text{gas. products}} n_i \quad (10)$$

Using equations (7) and (8), equation (6) can be written as

$$\bar{G} = \sum_{i=\text{species}} n_i (\Delta\bar{G}_{f,i}^0 + RT \ln y_i) \quad (11)$$

$\bar{G}$  is to be minimized under the constraints that

$$0 \leq n_i \leq n_{\text{total}} \quad (12)$$

and that the  $n_i$  fulfill the conservation of mass for the elements. This can be written as



$$\sum_{i=\text{species}} a_{ij}n_i = A_j \quad j = 1,2,3, \dots \quad (13)$$

where  $a_{ij}$  is the number of atoms of element  $j$  in a mole of product species  $i$  while  $A_j$  is the total number of atoms of element  $j$  among the reactants [28].

In order to find the minimum value of  $\bar{G}$ , the  $n_i$  are varied by the  $fmincon()$ -function, which is part of the optimization toolbox in MATLAB® (version 2016a (9.0.0.341360), The MathWorks, Natick, MA, USA), under the mentioned constraints. The necessary  $\Delta\bar{G}_{f,i}^0$  values of the product species are calculated as follows [28]

$$\Delta\bar{G}_{f,i}^0 = \Delta\bar{H}_{f,i}^0 - T\Delta\bar{S}_{f,i}^0 \quad (14)$$

where

$$\Delta\bar{H}_{f,i}^0 = \bar{H}_{\text{compound},i}^0(T) - \sum_{k=\text{elements}} \nu_k \bar{H}_k^0(T) \quad (15)$$

and

$$\Delta\bar{S}_{f,i}^0 = \bar{S}_{\text{compound},i}^0(T) - \sum_{k=\text{elements}} \nu_k \bar{S}_k^0(T) \quad (16)$$

The  $\nu_k$  are the stoichiometric coefficients of stable element  $k$  that go into the formation of compound  $i$ . Enthalpy  $\bar{H}^0(T)$  and entropy  $\bar{S}^0(T)$  are for both compounds and elements calculated by

$$\bar{H}^0(T) = \bar{H}_f^0(T_0) + \int_{T_0}^T \bar{c}_p dT \quad (17)$$

and

$$\bar{S}^0(T) = \bar{S}_f^0(T_0) + \int_{T_0}^T \frac{\bar{c}_p}{T} dT \quad (18)$$

$T_0$  is the temperature of the reactants at the inlet and set to 25 °C. The molar heat capacity at constant pressure,  $\bar{c}_p$ , is essentially a function of temperature only for gasses that behave like an ideal gas.

Values for both  $\bar{H}_f^0(T_0)$  and  $\bar{S}_f^0(T_0)$  and a polynomial approximation to  $\bar{c}_p$  along with the necessary coefficients in

$$\bar{c}_p = R(a_1 + a_2T + a_3T^2 + a_4T^3 + a_5T^4) \quad (19)$$

were taken from the NASA Technical Memorandum 4513 [49]. Instead of using fixed  $\bar{c}_p$ -values at a given temperature, the expression for  $\bar{c}_p$  was substituted into equations (17) and (18) and the integration carried out to give the following expression in case of  $\bar{H}^0(T)$

$$\begin{aligned} \bar{H}^0(T) = & \bar{H}_f^0(T_0) \\ & + R \left( a_1(T - T_0) + \frac{a_2}{2}(T^2 - T_0^2) + \frac{a_3}{3}(T^3 - T_0^3) + \frac{a_4}{4}(T^4 - T_0^4) \right. \\ & \left. + \frac{a_5}{5}(T^5 - T_0^5) \right) \end{aligned} \quad (20)$$

$\bar{S}^0(T)$  was calculated following the same procedure.

The energy balance of the steady process in the gasifier is an important part of the chosen method. It is used to obtain the actual equilibrium temperature of the process at a given set of  $n_i$  and values of  $r$  and  $w$ . It can be written as follows

$$\sum_{r=\text{reactants}} n_r \bar{H}_r^o(T_0) = \sum_{p=\text{products}} n_p \bar{H}_p^o(T) + \bar{Q}_{\text{loss}} \quad (21)$$

In case of incomplete carbon conversion, graphite is part of the products.  $\bar{Q}_{\text{loss}}$  is the heat loss from the surface of the control volume due to imperfect thermal insulation.  $\bar{H}_r^o(T_0)$  and  $\bar{H}_p^o(T)$  are the enthalpies of the reactants and products at their respective temperatures.

The enthalpy of the biomass (bm) at inlet temperature  $T_0$  is calculated by [28]

$$\bar{H}_{f,\text{bm}}^o = \overline{\text{LHV}} + \sum_{p'=\text{products of bm}} n_{p'} \bar{H}_{p'}^o \quad (22)$$

where the products  $p'$  are in this case the products of stoichiometric combustion of the biomass with dry air. Based on the composition of the biomass ( $\text{CH}_y\text{O}_z\text{N}_a\text{S}_b$ ) this can be written as

$$\bar{H}_{f,\text{bm}}^o = \overline{\text{LHV}} + \Delta \bar{H}_{f,\text{CO}_2}^o + \frac{y}{2} \Delta \bar{H}_{f,\text{H}_2\text{O}}^o + \frac{a}{2} \Delta \bar{H}_{f,\text{N}_2}^o + b \Delta \bar{H}_{f,\text{SO}_2}^o + \frac{z}{2} \Delta \bar{H}_{f,\text{O}_2}^o \quad (23)$$

The molar lower heating value ( $\overline{\text{LHV}}$ ) is calculated by

$$\overline{\text{LHV}} = M [\text{HHV} - 8.936 \cdot (\text{wt}\% \text{H}_{\text{db}}) \cdot h_{f,\text{g},\text{H}_2\text{O}}(T_0)] \quad (24)$$

where  $M$  is the molar mass of the biomass and  $\text{wt}\% \text{H}_{\text{db}}$  the weight percent of hydrogen in the biomass on dry basis. The last factor in the second term in the parentheses is the enthalpy of vaporisation  $h_{f,\text{g},\text{H}_2\text{O}}$  of water at temperature  $T_0$ . HHV is the specific higher heating value of the biomass in kJ/kg. Two different equations have been implemented in the code. The first equation is for the case  $b = 0$  when there is either no sulphur content in the biomass or where no sulphur content is given (eqn. 14 in table 1 in [34])

$$\text{HHV} = 10^3 (0.341C + 1.323H + 0.0685 - 0.0153A - 0.1194(O + N)) \frac{\text{kJ}}{\text{kg}} \quad (25)$$

where  $C$ ,  $H$ ,  $O$ ,  $N$ ,  $S$ , and  $A$  are the weight fractions of carbon, hydrogen, oxygen, nitrogen, sulphur and ash on dry basis. For biomass with given sulphur content ( $b > 0$ ), Channiwala and Parikh's own correlation is employed [34]

$$\text{HHV} = 10^3 (0.3491C + 1.1783H + 0.1005S - 0.1034O - 0.0151N - 0.0211A) \frac{\text{kJ}}{\text{kg}} \quad (26)$$

Figure 1 shows the algorithm that is used to find the minimal value of  $\bar{G}$  of the products for a certain input of biomass, moisture and gasification temperature  $T$ . The necessary amount of air to obtain the desired gasification (or equilibrium) temperature  $T$  is adjusted in the outer loop by means of changing  $\lambda$ , starting from an initial guess for the air-fuel-ratio  $\lambda_{\text{start}}$  given by the user. The actual equilibrium temperature  $T$  is found by the inner loop. Also starting from an initial guess ( $T_{\text{start}}$ ), the value of  $T$  is adjusted until the energy balance at the current value of  $r$  is satisfied. The relative error  $\epsilon_E$  between the right and the left side of the energy balance (equation (21)) is calculated and has to be smaller than  $\epsilon_{E,\text{max}} = 10^{-3}$ .

$$\epsilon_E = \left| \frac{\sum_{r=\text{reactants}} n_r \bar{H}_r^0(T_0) - (\sum_{p=\text{products}} n_p \bar{H}_p^0(T) + \bar{Q}_{\text{loss}})}{\sum_{r=\text{reactants}} n_r \bar{H}_r^0(T_0)} \right| \leq 10^{-3} = \epsilon_{E,\text{max}} \quad (27)$$

In the outer loop,  $\lambda$  is adjusted until the equilibrium temperature  $T$  is within a given error range  $\epsilon_{T,\text{max}}$  of the desired gasification temperature  $T_{\text{exp}}$ . The temperature deviation is calculated by  $\epsilon_T = |(T - T_{\text{exp}})/T_{\text{exp}}|$  and has to be smaller than  $\epsilon_{T,\text{max}} = 10^{-4}$ .

In case the moisture content of the gasifying agent is to be accounted for,  $w_{\text{ga}}$  has to be recalculated each time  $\lambda$  is assigned a new value. This has to be done because  $w_{\text{ga}}$  is in units of kmol H<sub>2</sub>O per kmol dry biomass and therefore dependent on the actual amount of air entering the reaction volume.

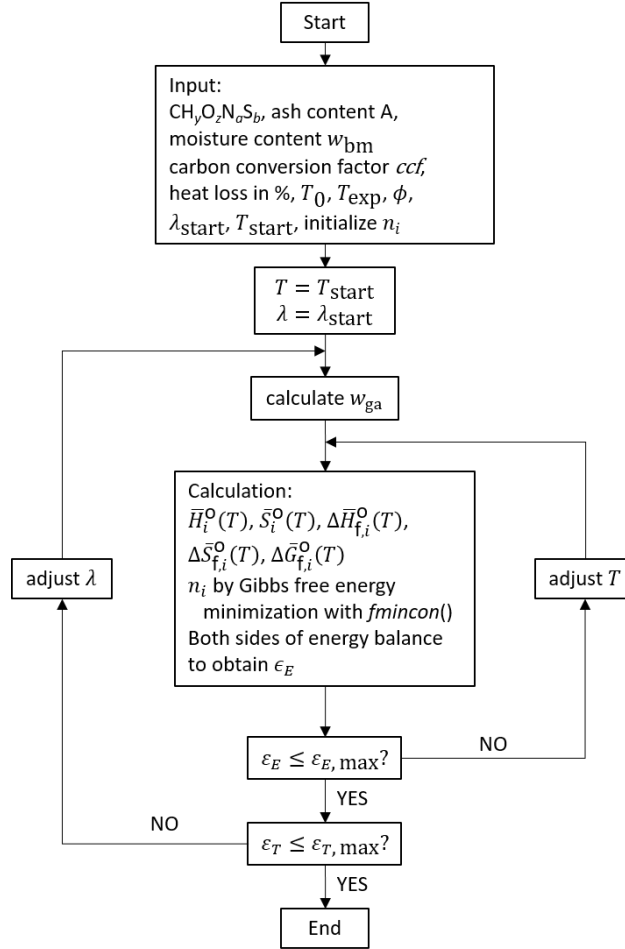


Figure 1: Algorithm for finding the set of  $n_i$ , that minimize the Gibbs free energy of the gaseous products that can be formed from the biomass, moisture and air input for a specified gasification temperature  $T$ .

In the analysis of the results from the Gibbs free energy minimization, a number of properties of the process have been analysed.

The mass of H<sub>2</sub> produced per kg biomass at specified conditions is the main result of this study. It is calculated by

$$m_{\text{H}_2} = \frac{n_{\text{H}_2} M_{\text{H}_2}}{M_{\text{bm,dry}}} \quad (28)$$

and given in kg H<sub>2</sub> per kg dry biomass. Multiplied with the mass of the respective waste fraction available per year, the annual hydrogen production potential from that waste fraction can be

calculated. These annual production potentials can then be set in relation to the consumption of various hydrogen vehicles. The number of existing fossil-fuel vehicles of each type, which could potentially be replaced by a corresponding hydrogen-fuelled vehicle can be calculated. Vehicle types, their annual consumption and their current number in the Hordaland region in Western Norway are given in *Table 3*.

By means of the water-gas-shift-reaction (WGS), one kilomol hydrogen can be produced for each kilomol carbon monoxide in the product gas. High conversion efficiencies are possible. The H<sub>2</sub> production potential of gasification only and the maximum possible potential for gasification plus water-gas-shift-reaction are therefore compared with each other. The equation for the hydrogen production potential can therefore be written as

$$m_{\text{H}_2, \text{WGS}} = \frac{(n_{\text{H}_2} + n_{\text{CO}})M_{\text{H}_2}}{M_{\text{bm, dry}}} \quad (29)$$

The cold gas efficiency (CGE) is a measure of the efficiency of the gasification process based on the first law of thermodynamics. In essence, the heating value of the products is related to the heating value of the biomass. The CGE thus shows how much of the initial heating value is retained in the products per amount of dry biomass input. The definition used in this work is based on the definition given by Melgar et al. [25]

$$\text{CGE} = \frac{n_{\text{CO}}\overline{\text{LHV}}_{\text{CO}} + n_{\text{H}_2}\overline{\text{LHV}}_{\text{H}_2} + n_{\text{CH}_4}\overline{\text{LHV}}_{\text{CH}_4}}{\overline{\text{LHV}}_{\text{bm, dry}}} \quad (30)$$

The second law efficiency of the gasification process can be calculated by the ratio of the sum of the thermal exergy  $\bar{X}_{p, \text{therm}}$  and chemical exergy  $\bar{X}_{p, \text{chem}}$  of the product gas to the chemical exergy of the input biomass  $\bar{X}_{\text{bm, chem}}$  without the exergy of the moisture and gasifying agent. As the input biomass is assumed to be at the surroundings temperature and pressure, its thermal exergy is zero.

$$\eta_{\text{II}} = \frac{\sum_{p=\text{gas, prod.}} (\bar{X}_{p, \text{therm}}(T) + \bar{X}_{p, \text{chem}}(T_0))}{\bar{X}_{\text{bm, chem}}(T_0)} \quad (31)$$

where [50, 51]

$$\bar{X}_{p, \text{therm}}(T) = n_p \left( \bar{H}_p(T) - \bar{H}_p(T_0) - T_0(S_p(T) - \bar{S}_p(T_0) - R \ln y_p) \right) \quad (32)$$

and [50, 51]

$$\bar{X}_{p, \text{chem}}(T_0) = n_p (\bar{x}_{p, \text{chem}}(T_0) - RT_0 \ln y_p) \quad (33)$$

As an alternative, the second law efficiency of the gasification process can be calculated based on the changes in chemical exergy between biomass and products. This can be done by leaving out the thermal exergy term in (31).

$$\eta_{\text{II, chem}} = \frac{\sum_{p=\text{gas, prod.}} \bar{X}_{p, \text{chem}}(T_0)}{\bar{X}_{\text{bm, chem}}(T_0)} \quad (34)$$

At  $T_0$ , some of the water in the products may be in the liquid phase if  $T_0$  is below the dew point temperature of the product gas. Its chemical exergy is then  $\bar{X}_{\text{H}_2\text{O}(l), \text{chem}}(T_0) = n_{\text{H}_2\text{O}(l)} \bar{x}_{\text{H}_2\text{O}(l)}$ . In this case, the amount of water in the liquid phase is subtracted from the amount of water in the gas phase

before the respective exergies for the water vapour are calculated. The values for the molar chemical exergy of the relevant compounds are given in *Table 4*. The chemical exergy of the solid carbon in the case of incomplete carbon conversion is not accounted for here, as the focus is on the gaseous products.

*Table 4: Molar chemical exergy at 25 °C for product gas compounds in kJ/kmol. All values were taken from table A-26, model 2 in the book of Moran et al. [52]*

Compound	$\bar{x}_{\text{chem}}$ (kJ/kmol)
H <sub>2</sub> O (g)	9 500
H <sub>2</sub> O (l)	900
N <sub>2</sub>	720
H <sub>2</sub>	23 610
CH <sub>4</sub>	831 650
CO	275 100
CO <sub>2</sub>	19 870
SO <sub>2</sub>	313 400

## Results

After implementation of the model in MATLAB®, it was validated against results published by Fournel et al. [28] for the gasification of both saw dust (carried out experimentally by Altafini et al. [21]) and rubber wood (experimental data published by Jayah et al. [26]).

The MATLAB® calculations for saw dust were carried out for the chemical composition given in Table 2 in reference [28] at the temperature of 1073 K. Dry air ( $w_{\text{ga}} = 0$ ) was used as the gasifying agent, inlet temperatures were set to 298.15 K, the pressure to 1 atm absolute. The carbon conversion factor was set to 100 %, the heat loss to 1% of the HHV of the biomass.

A comparison of the results is shown in *Table 5*. There is very good agreement with respect to the root mean square error (RMSE) between the results for the current implementation and the experimental values listed in [28]. The RMSE is calculated with

$$\text{RMSE} = \sqrt{\frac{\sum_{i=\text{species}} (\text{Exp}_i - \text{Mod}_i)^2}{N_d}} \quad (35)$$

where  $N_d$  is the number of data points,  $\text{Exp}_i$  is the experimental results for species  $i$  and  $\text{Mod}_i$  the results from the model.

The reason for the small differences in the numbers between the model as implemented by the authors of this work and the other studies lies in the detail of the implementation of some of the equations in the model. One difference may be the implementation of the expressions for the enthalpy and entropy of the chemical compounds, for example. There, either a fixed value for the molar heat capacity  $\bar{c}_p$  for a certain temperature can be used or the integral of the heat capacity-containing terms is carried out before the evaluation of  $\bar{c}_p$ . Another reason may be that the code chooses between two different equations for the HHV based on the sulphur-content of the biomass being zero or not.

Table 5: Volume-% of the 5 main gaseous products of the gasification of saw dust at 1073 K. The composition of the sawdust is given in both ref. a [21] and [28]. The difference between the ‘simple’ and the ‘modified’ model is, that the volume fraction of methane is fixed to 1.66 vol% in the modified model, which gave improvements compared with the simple model without constraint on the methane amount in the work of Jarungthammachote and Dutta [23]. RMSE stands for root mean square error. The results from the implementation of the method in this work are in good agreement and slightly better for the simple model than those of Fournel et al. [28]

Saw dust	Altafini et al. [21]		Fournel et al. [28]		This work	
	Exp.	Model	Simple	Modified	Simple	Modified
H <sub>2</sub>	14.0	20.06	21.69	18.83	20.39	18.64
CO	20.14	19.7	23.46	21.47	21.78	21.72
CH <sub>4</sub>	2.31	0.0	0.03	1.66	0.02	1.66
CO <sub>2</sub>	12.06	10.25	9.57	11.14	10.38	10.96
N <sub>2</sub>	50.79	50.1	45.26	46.9	47.44	47.02
RMSE		3.03	4.74	2.88	3.54	2.82

The comparison with the experimental results for gasification of rubber wood at 1273 K and different moisture contents by Jayah et al. [26] and numerical results obtained by Fournel et al. [28] in Table 6 shows also good agreement. It is therefore assumed that the implementation of the method is correct and can be used for the biomass of interest in this investigation.

Table 6: Volume-% of the 5 main gaseous products of the gasification of rubber wood at 1273 K. The composition of the rubber wood is given in both ref. [26] and [28]. The difference between the ‘simple’ and the ‘modified’ model is, that the volume fraction of methane is fixed to 1.1 % in the modified model, which gave improvements compared with the simple model without constraint on the methane amount in ref. [28]. RMSE stands for root mean square error.

Rubber wood		Jayah [26]	Fournel et al. [28]		This work	
		Experiment	Simple	Modified	Simple	Modified
Moisture	RMSE		4.23	3.51	3.66	3.40
14 wt%	H <sub>2</sub>	12.5	17.9	16.0	17.1	15.8
	CO	18.9	19.4	18.1	18.6	18.7
	CH <sub>4</sub>	1.1	0.0	1.1	0.0	1.1
	CO <sub>2</sub>	8.5	10.9	11.9	11.2	11.5
	N <sub>2</sub>	59.1	51.8	53.0	53.0	53.0
Moisture	RMSE		1.2	0.73	1.62	0.37
14.7 wt%	H <sub>2</sub>	15.5	17.8	15.8	17.1	15.7
	CO	19.1	19.1	17.7	16.4	18.4
	CH <sub>4</sub>	1.1	0.0	1.1	0.0	1.1
	CO <sub>2</sub>	11.4	11.0	12.1	10.1	11.7
	N <sub>2</sub>	52.9	52.0	53.3	53.1	53.1
Moisture	RMSE		0.8	1.12	0.82	0.91
16 wt%	H <sub>2</sub>	17	17.7	15.8	17.1	15.7
	CO	18.4	18.5	17.2	17.9	17.9
	CH <sub>4</sub>	1.3	0.0	1.1	0.0	1.1
	CO <sub>2</sub>	10.6	11.4	12.4	11.6	11.9
	N <sub>2</sub>	52.7	52.4	53.0	53.3	53.3

The analysis of the hydrogen production potential from the wet organic waste fractions in municipal solid waste was carried out for different values of moisture content (0-40%, as received), carbon conversion (70 %, 85 % and 100 %) and heat loss (1 %, 5 % and 10 % of the biomass's HHV) for five temperatures between 1073 K and 1273 K.

Figure 2 shows the hydrogen production potential in kg H<sub>2</sub> per kg dry biomass for the three different wet organic waste fractions 'household', 'industrial', and 'combined'. The calculations were carried out at the inherent moisture content of the waste fractions (see Table 1), 100 % carbon conversion and 1 % heat loss in the temperature interval between 1073 K and 1273 K. The hydrogen yield is the largest at the lower end of the temperature interval and among the three waste fractions and the largest amount of hydrogen is obtained from the industrial wet organic fraction with 56.2 g H<sub>2</sub>/kg biomass (dry). The household wet organic waste with its higher inherent moisture content has a maximum hydrogen yield of 35.9 g H<sub>2</sub>/kg biomass (dry) at the same conditions. Figure 3 shows the amount of H<sub>2</sub>, CO and CO<sub>2</sub> in the product gas (volume percent on dry basis) for the industrial wet organic fraction as a function of temperature at the waste fraction's inherent moisture content 31.9 wt% (dry). While the amount of CO<sub>2</sub> and CO are almost constant, the hydrogen content decreases with increasing temperature, while more water is formed. In general, the largest hydrogen yield was obtained at 1073 K in all simulations, which is why this temperature was chosen for all further calculations.

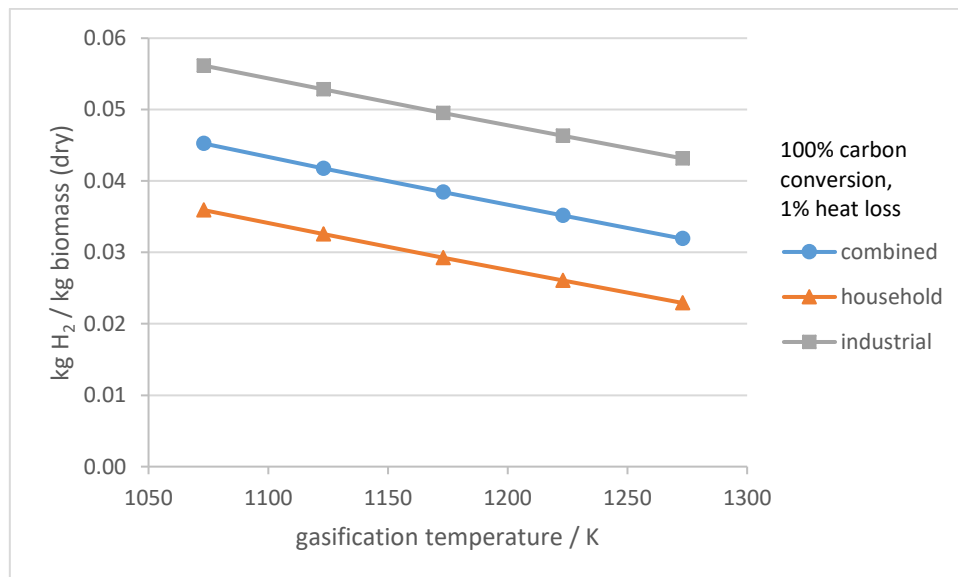


Figure 2: The hydrogen production potential per kg dry biomass is shown for the three wet organic waste fractions 'household', 'industrial' and 'combined'. The hydrogen yield is largest at the lowest temperature used in the calculations, which were carried out for complete carbon conversion and 1% heat loss.

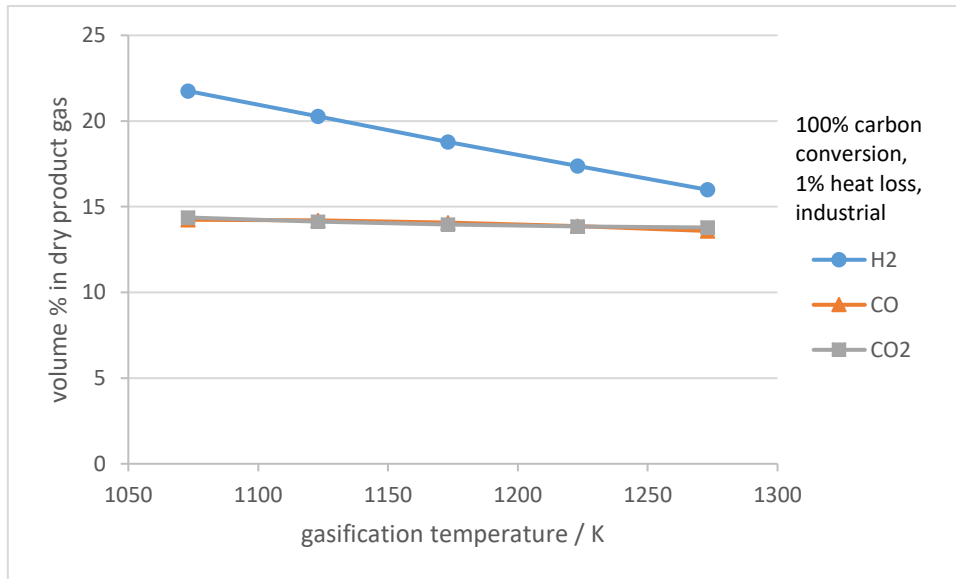


Figure 3: Volume % of H<sub>2</sub>, CO and CO<sub>2</sub> in the dry product gas from gasification of the industrial wet organic fraction complete carbon conversion and 1 % heat loss. The volume percent of CO and CO<sub>2</sub> is almost identical in this case.

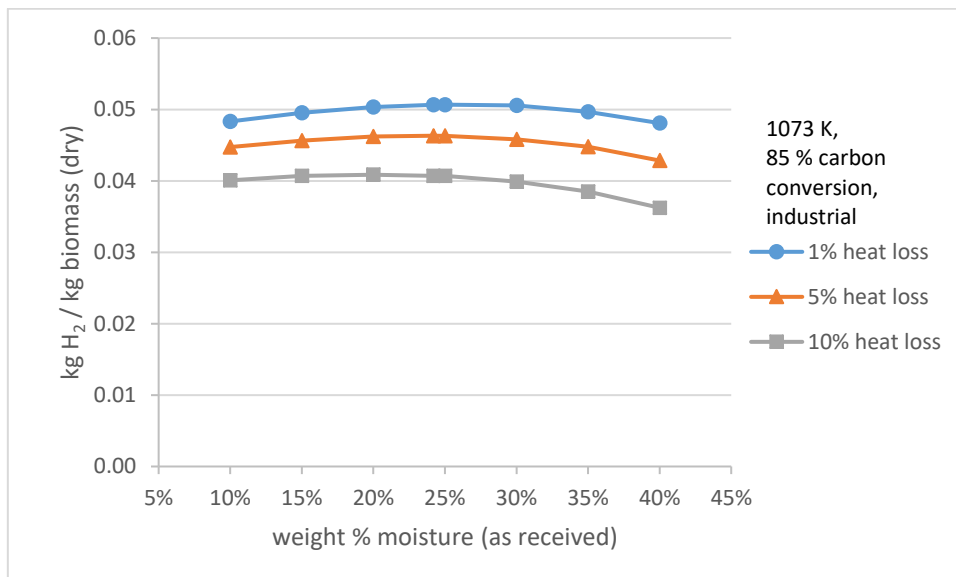


Figure 4: Hydrogen yield per kg dry biomass as function of the moisture content (as received) and heat loss percentage at 85% carbon conversion during gasification of the industrial wet organic fraction. The inherent moisture of the industrial wet organic fraction is 31.9 wt% on dry basis or 24.2 wt% as received.

The moisture content of the biomass has an important impact on the actual combustions process when incinerated by lowering the combustion temperature, as a lot of energy is necessary to evaporate it. As the actual moisture content in the collected waste is much higher due to the very humid climate and high annual precipitation on the Norwegian west coast, the analysis has also been carried out for moisture content up to 40 wt% (as received), which is not unusual during periods with heavy rain. Results are shown for the industrial wet organic waste at varying moisture content. As a further approximation to realistic conditions, the carbon conversion factor has been set to of 85 % in this case as all three waste fractions have a fixed carbon content of ca. 15 % [31]. The results are shown in Figure 4. The first thing to be noted is that the hydrogen yield at the inherent moisture (24.2 wt% as received)



drops from 56.2 g H<sub>2</sub>/kg biomass (dry) to 50.6 g H<sub>2</sub>/kg biomass (dry), a decrease by 10 %, due to the lower carbon conversion factor (ccf). It drops further with increasing heat loss to 40.7 g H<sub>2</sub>/kg biomass (dry). At the lowest heat loss from the process, the hydrogen yield varies only little around the maximum close to the inherent moisture content value. The curvature gets stronger with increasing heat loss, and is more pronounced towards increasing moisture content. The location of the maximum hydrogen yield shifts towards smaller moisture content with increasing heat loss. With further decreasing carbon conversion, the maximum hydrogen yield shifts further to the left and for the intermediate and largest heat loss investigated some of the curves go over to monotonically decreasing curves in the investigated moisture content interval. The same trends have been found for the other two waste fractions.

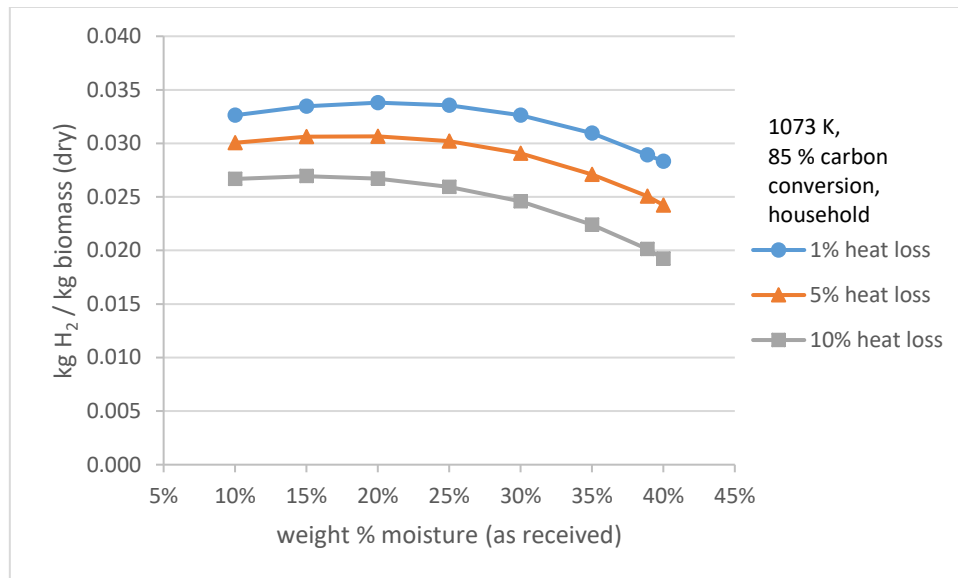


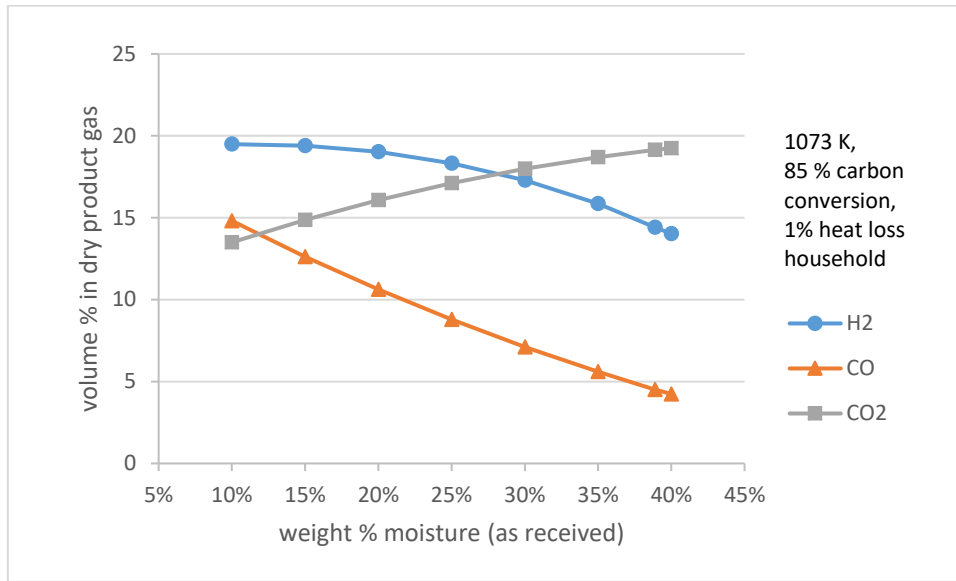
Figure 5: Hydrogen yield per kg dry biomass as function of the moisture content (as received) and heat loss percentage at 85% carbon conversion during gasification of the household wet organic fraction. The inherent moisture of the industrial wet organic fraction is 63.6 wt% on dry basis or 38.9 wt% as received.

For comparison, the same graph as in Figure 4 is shown for the household wet organic waste in Figure 5. The household wet organic waste has a much higher inherent moisture content (63.6 wt% on dry basis or 38.9 wt% as received) than the industrial wet organic fraction. Due to differences in chemical composition, the maximum hydrogen yield lies further to the right and is lower in general. In the scenarios shown in Figure 5, the maximum hydrogen yield is 33.8 g H<sub>2</sub>/kg biomass (dry) at 1% heat loss and 20 wt% moisture (ar), while the lowest hydrogen yield in this overview is 19.3 g H<sub>2</sub>/kg biomass (dry) at 10% heat loss and 40 wt% moisture (ar).

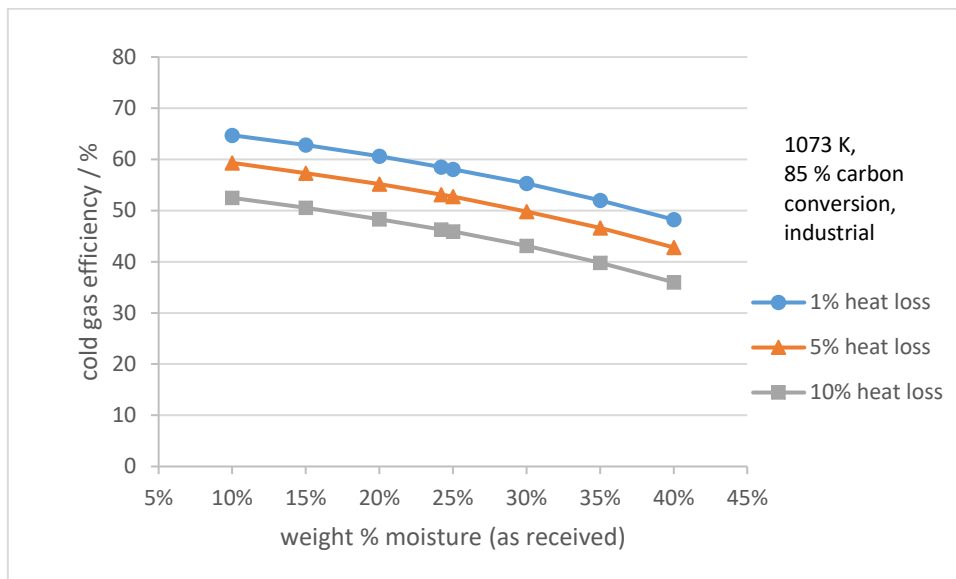
Figure 6 shows the changes in composition of the products of gasification of household wet organic waste at 1073 K, 85 % carbon conversion and 1 % heat loss as function of weight percent moisture (ar). The trend is the same for all waste fractions and combinations of heat loss and carbon conversion factor: hydrogen and carbon monoxide decrease with increasing moisture content, while the carbon dioxide amount increases.

Figure 7 shows the cold gas efficiency as defined in equation (30) for all three waste fractions at 1073 K and 85 % carbon conversion as function of the moisture content and heat loss. Figure 8 shows the second law efficiency as defined in equation (34) (based on chemical exergy only) for the same set of calculations. In both cases, the efficiencies are monotonously decreasing functions of the moisture

content. Increasing heat loss also contributes to lower efficiencies. Inclusion of the thermal exergy into the second law efficiency would enhance the values by 7-8 % as shown in *Figure 8*.



*Figure 6: Volume % of H<sub>2</sub>, CO and CO<sub>2</sub> in the dry product gas for household wet organic waste gasified at 1073 K, 85 % carbon conversion factor and 1 % heat loss.*



*Figure 7: Cold gas efficiency of the gasification of the industrial wet organic waste at 1073 K, 85 % carbon conversion and different heat losses as function of moisture content.*

Three different cases are studied in order to estimate the mass of hydrogen that could be produced annually from the given waste fractions. The best case has 100 % carbon conversion, 1 % heat loss and the waste has been pre-dried with available process heat to 25 wt% moisture (ar) from the typical 35 wt%. The average case has 85 % carbon conversion, 1 % heat loss and 35 wt% moisture (ar). As a worst case, a combination of only 70 % carbon conversion, 10 % heat loss and 40 wt% moisture (ar) is used. Results for these different cases are given in *Table 7* in tonne H<sub>2</sub> per year.

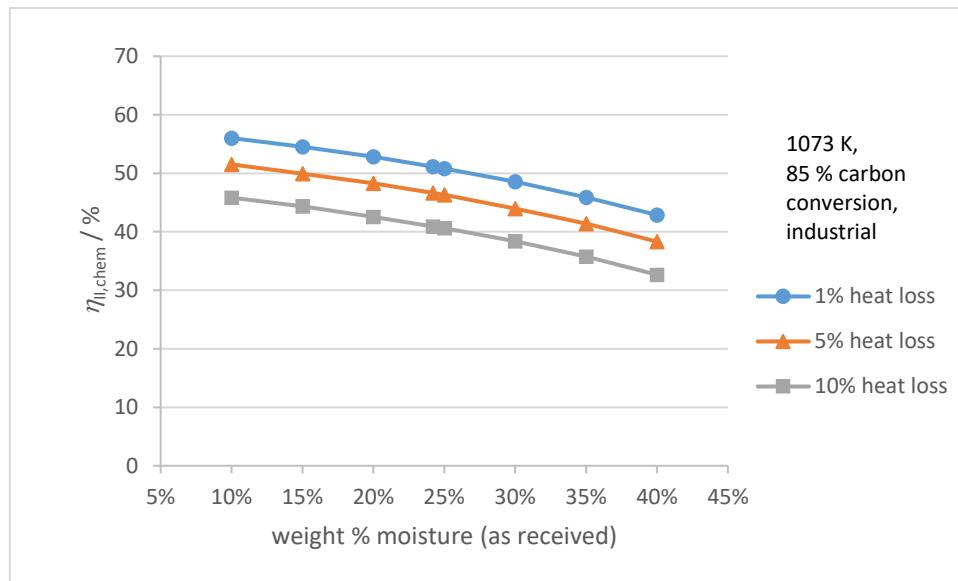


Figure 8: Second-law-efficiency of the gasification process of the industrial wet organic waste at the same conditions as in Figure 7 based on the chemical exergy of the dry product gas in relation to the exergy of the dry biomass input.

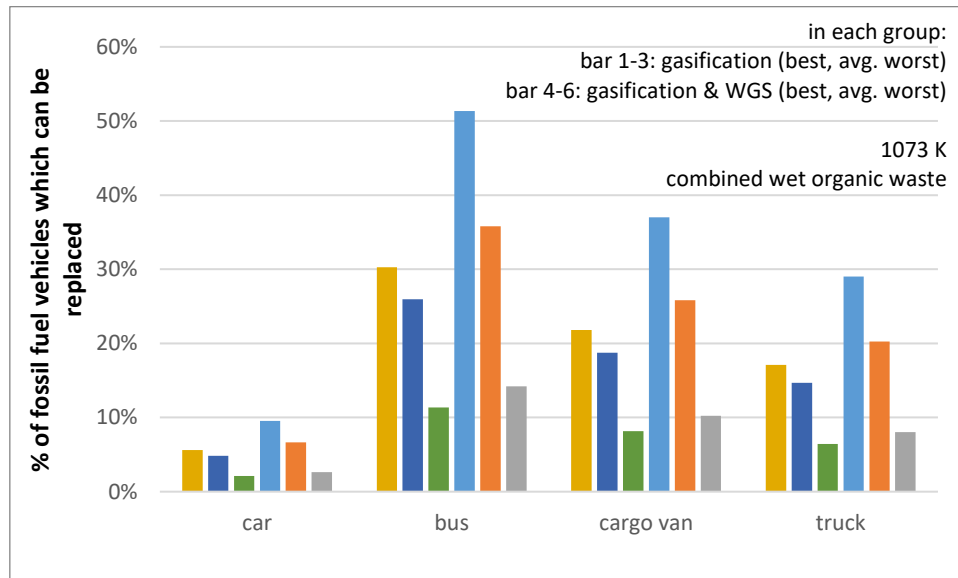
Table 7: Annual hydrogen production potential for the different wet organic waste fractions in the three different cases defined in the text at 1073 K. Results for simple gasification and gasification followed by water-gas-shift-reaction (WGS) are shown. The water gas-shift-reaction has the potential to increase the hydrogen yield by more than 35% in the average cases.

		gasification		gasification and WGS		
Waste fraction and case	dry mass / kg	kg H <sub>2</sub> / kg bm (dry)	m <sub>H<sub>2</sub></sub> / tonne/yr	kg H <sub>2</sub> / kg bm (dry)	m <sub>H<sub>2</sub></sub> / tonne/yr	increase / %
<b>combined wet organic waste</b>						
best case	35 843 485	0.0448	1604	0.0759	2721	69.6 %
average	35 843 485	0.0384	1376	0.0529	1896	37.8 %
worst case	35 843 485	0.0168	601	0.0210	754	25.4 %
<b>industrial wet organic waste</b>						
best case	13 837 435	0.0563	778	0.0923	1278	64.1 %
average	13 837 435	0.0497	687	0.0701	970	41.2 %
worst case	13 837 435	0.0261	361	0.0334	462	27.9 %
<b>household wet organic waste</b>						
best case	22 006 051	0.0385	847	0.0608	1337	57.8 %
average	22 006 051	0.0309	681	0.0419	922	35.3 %
worst case	22 006 051	0.0107	235	0.0132	290	23.6 %

The results for the number of road vehicles, ferries and passenger boats are made for the combined wet organic waste only, as this fraction yields the largest total amount of hydrogen.

Results for the percentage of fossil driven road vehicles registered in the Hordaland region that could potentially be replaced by hydrogen driven ones are shown in Figure 9. Due to the large number of cars registered in Hordaland (see Table 3), the fraction that could be replaced by hydrogen driven vehicles is very low; even though the absolute numbers exceed several thousand cars. The lower bound

is at 4958 cars in the worst case with gasification only and the upper bound at 22453 cars in the best case with gasification and WGS. A special case are taxis, which are not shown in *Figure 9*. They have a much larger annual driving distance compared with the average car. Between 938 cars in the worst case and 4249 cars in the best case could be supplied with hydrogen. That means that even in the worst case, all taxis in Hordaland could be run with hydrogen produced from waste.



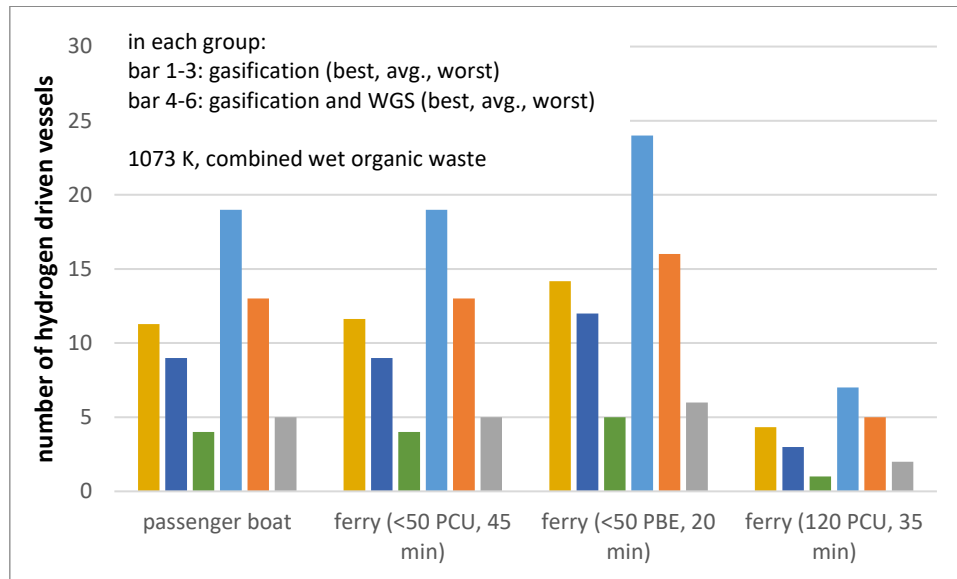
*Figure 9: Percentage of four different types of fossil fuel driven vehicles that could be replaced in each of the three cases (best, average and worst) and the two scenarios with gasification only and gasification followed by water-gas-shift-reaction (WGS).*

The fraction of buses, which can be replaced, are about 25 % and 35% respectively in the average case for gasification and gasification combined with WGS. Another application of hydrogen in this case would be existing gas-driven buses. Blending the natural gas with hydrogen can improve the thermal efficiency of gas engines [53]. The resulting increase in NO<sub>x</sub> emissions has to be dealt with by applying appropriate exhaust gas cleaning techniques. As the hydrogen is just a fraction of the fuel in such a natural gas-hydrogen blend, a much larger number of busses could be supplied with environmentally friendly fuel. Verma et al. [53] studied the effect of adding and varying the proportion of hydrogen in natural gas. Up to 40 vol% (hydrogen) were investigated, with 20 vol% giving the best thermal efficiency.

The fraction of fossil fuel driven cargo vans, which could potentially be replaced, is slightly smaller than those of the buses. The numbers are 18.7 % and 25.8 % for the average cases with gasification only and gasification with WGS respectively. The lower limit is at 8.2 % in the worst case with gasification only and the maximum is 37 % with gasification in combination with WGS. Even though the numbers are not large nor could the hydrogen fuel supply the majority of vehicles of this type, the contribution to a reduction of the amount of fossil fuel consumed could be considerable.

Heavy trucks are the type of vehicle with the largest hydrogen consumption in this comparison (5 kg H<sub>2</sub>/100 km). Based on the consumption of the model chosen for comparison, the amount of hydrogen driven heavy trucks is just 2-8 % lower than the amount of cargo vans, with the largest deviation in the best cases for gasification only and gasification with WGS (17.1 % and 29 % compared with 21.8 % and 37 % for cargo vans).

While only a partial amount of the road vehicles in Hordaland could be replaced with hydrogen driven types, the picture is different as *Figure 10* shows together with the numbers of different types of vessels in *Table 3*.



*Figure 10: Number of hydrogen driven vessels that could be supplied in each of the three cases (best, average and worst) and the two scenarios with gasification only and gasification followed by water-gas-shift-reaction (WGS).*

In the average and best cases all small (< 50 passenger car units) ferries with both short and long crossing times in Hordaland could be supplied with hydrogen. There would be enough hydrogen left to operate at least one fast passenger boat (average case, gasification only) and a maximum of 11 vessels of this type. This would cover all 10 fast passenger boat connections currently in operation in the region under the assumption that the hydrogen consumption is equal on all routes. As an alternative to the passenger boats, a number of larger ferries (> 50 passenger car units) could be run on hydrogen as well in case hydrogen is produced by gasification combined with WGS. Either two (average case) or four larger ferries (best case) with an annual H<sub>2</sub> consumption of 370 tonne could be operated in addition to the nine smaller ferry connections.

In the two worst-case scenarios, at least all the small (< 50 passenger car units) short distance passenger car ferries in Hordaland could be driven by hydrogen from local waste.

If the goal was to supply only the largest ferries with hydrogen, then between one (worst case, gasification only) to seven (best case, gasification and WGS) of the 15 connections with this type of vessel could be supplied with hydrogen from waste.

Separation of the wet organic fraction from the collected waste would be beneficial for the fraction that is to be incinerated, as *Table 8* shows. Removal of the moisture rich wet organic fractions lowers the moisture content of the remaining waste and this increases its heating value. Removing the industrial wet organic fraction alone has only negligible effect (about 2.5 %) on the heating value of the remaining waste, which is to be incinerated. Separating the household wet organic fraction (HHV increase by 8.4 %) or both household and industrial wet organic fraction combined (HHV increase by 12.6 %) has a more pronounced effect.

Table 8: Properties of the remaining waste for incineration once the wet organic (w.o.) fractions are removed. Weight percent moisture and HHV are given on dry basis. The additional necessary capacity for achieving the same energy output as in 2013 is given in tonne of waste (as received, ar) and as percent of the annual capacity of the plant.

Waste fraction	dry mass (tonne)	wt% moist.	change in moisture content	HHV <sub>Phyllis</sub> (MJ/kg)	change in HHV	additional capacity (tonne, ar)	% of annual capacity
without combined w.o.	103 963	11.2 %	-47.9 %	26.55	+12.6 %	22 473	10.2 %
without industrial w.o.	125 969	20.3 %	-5.36 %	24.13	+2.53 %	12 506	5.7 %
without household w.o.	117 800	13.6 %	-36.5 %	25.62	+8.41 %	11 811	5.4 %

## Discussion

The technique employed is an equilibrium method, which does not take dimensions of the reaction zone and the kinetics of chemical reactions into account. The results obtained are therefore an upper limit on the achievable hydrogen yield based on the assumption that the gasifier is large enough so that the products are in chemical equilibrium before they leave the process.

The right hand side of the applied chemical reaction equation contains only six compounds. Other investigations have allowed for a larger number of product species; for example the one conducted by Baratieri et al. [22]. When, for example, nitrous compounds such as NO, NO<sub>2</sub>, N<sub>2</sub>O and NH<sub>3</sub> were added to the right hand side in the employed model, the mole fractions of NO<sub>x</sub> and N<sub>2</sub>O were several orders of magnitude smaller than the smallest mole fraction of the standard products. Even NH<sub>3</sub> only appeared in negligible amounts.

The formation of liquid tars has been neglected in the model used with only gaseous and solid (in case of incomplete carbon conversion only) products having been taken into account. The latter approach has also been used by Baratieri et al. [22]. Altafini et al. [21] reported only 0.57 % vol% (dry basis) of C<sub>2</sub>H<sub>4</sub> and 0.14 vol% C<sub>2</sub>H<sub>6</sub> in their experiments of saw dust gasification, but did not find either C<sub>2</sub>H<sub>4</sub> or C<sub>2</sub>H<sub>6</sub> and virtually no methane in the calculations they made for comparison. In retrospect, the implementation of the most important tar species like C<sub>2</sub>H<sub>2</sub> and C<sub>2</sub>H<sub>4</sub> [50] could have given more detailed results and would have involved little additional work. However, the goal was to keep the model close to the one it is based on and leave such extensions for further work and refinement. It is planned to incorporate tar-relevant species into the model in the future.

Jarungthammachote and Dutta investigated the effects of moisture content on the syngas composition at a fixed value of 40 % of the stoichiometric oxygen content [23]. The combustible fraction of municipal solid waste with an average composition of CH<sub>1.5932</sub>O<sub>0.5758</sub>N<sub>0.0444</sub> was the fuel for their combined experimental and numerical study. This led to a decreasing gasification temperature (from about 1375 K to ca. 1070 K) with increasing moisture content (from 0 % to 40 %). With decreasing temperature, a decrease in hydrogen yield from 20 vol% to 16 vol% was observed. The decrease in hydrogen yield was in the same range between 0% and 40% moisture content in the calculations in this study. However, as the temperature was fixed to 1073 K and thus  $\lambda$  was varied along with the moisture content, the results of this study and those in [23] are not fully comparable.

Jayah et al. reported that the moisture content of the biomass has a large impact on both composition of the product gas as well as conversion efficiency [26]. The latter is easy to understand because with increasing moisture content more thermal energy is needed to evaporate and superheat the liquid water content of the biomass to the equilibrium temperature. For the gasification of rubber wood chips in a downdraft gasifier, where a temperature profile along the length of gasification zone from

1600 K to 1000 K was taken into account, the cold gas efficiencies of between 53 % for 30 % moisture content (dry basis) to 58 % for completely dry material were calculated. The drop in cold gas efficiency was on a similar order of magnitude in the current investigation. A difference of 6-7 % CGE between 11% and 33% moisture (dry basis) were observed for the different waste fractions investigated at 1073 K.

The moisture content was, in this study, assumed to be bound water in the sense that it is adsorbed on the surface of the biological material. Peduzzi et al. [54] have taken one step further and distinguish between bound water in cell cavities and pores (so-called free-water), and bound water when the moisture content exceeds 30 % on dry basis. This bound water is then treated differently with respect to enthalpy and entropy values from the free water. However, the effect of this treatment on the results is not clear from their article and therefore it cannot be concluded if making this difference would have given results that are more reliable in the upper half of the moisture content interval in the current study.

The temperature of the inlet air was not found to have any significant impact on the first-law-efficiency in the study of Jayah et al. [26]. However, the heat loss from the gasification process through surfaces and non-gaseous products had a large impact. Efficiencies varied between 74 % for 5 % heat loss and 50 % for 15 % heat loss. The drop in cold gas efficiency observed by the authors of the current study was not as large. A difference of about 6-7 % CGE was found for calculations at 5 % and 10 % heat loss for all types of biomass at 1073 K at varying moisture content.

The effect of moisture on the cold gas efficiency on the gasification of saw dust at 1073 K was also studied by Altafini et al. [21]. The carbon conversion increased from 78% for completely dry material to 93 % for 30 % moisture content (wet basis). The cold gas efficiency varied between 66 % and 69 % with a maximum between 15 % and 20 % moisture on wet basis. The cold gas efficiencies in the current study were in a similar range of CGE values for complete or intermediate carbon conversion (85 %) and for the lowest of the investigated heat losses (1 %).

The observed product gas compositions are in good agreement with the results presented in a comparison in Table 6 in the article by Sues et al. [29], where the results of their model is compared with the results of three experimental studies. The agreement is best for incomplete carbon conversion (85 %) and heat loss in the order of 5% of the biomasses higher heating value. With regard to moisture, the interval between 10 % to 20 % (as received), which corresponds to 11 % to 25 % on dry basis, fits best with the product gas composition results by Li et al. [55] and Gil et al. (10-20 %) [56]; where moisture content on dry basis was between 9 % to 20 % [55] and 10 % to 20 % [56]. The formation of tars (hydrocarbons with two or more carbon atoms) was very small in these experimental studies whereas the amount of methane in the dry product gas could reach up to 6.2 vol% [56]. The gasification temperature in these studies was around 800 °C.

The negligible formation of methane is typical for the type of model employed and has been observed by several groups [22, 24, 28]. The methane levels observed in experiments are attributed to imperfections in the actual gasifiers, where inhomogeneous temperature distributions in the reaction volume, incomplete cracking of pyrolysis products and the use of piping materials catalysing the formation of methane ahead of the gas composition analysis can lead to the observed methane levels up to a few volume percent [22].

Mohammed et al. [57] reported hydrogen yields of 52 g H<sub>2</sub>/kg biomass in air gasification of empty fruit bunch in a fluidized bed reactor. This value fits very well into the range of values obtained from the current calculations for 85 % carbon conversion and low heat loss. Up to 72 g H<sub>2</sub>/kg biomass were reported by Zhang et al. [50] for air gasification of hinoki cypress saw dust at 1073 K. Such high values

(and up to about 100 g H<sub>2</sub>/kg biomass) could only be achieved if gasification would be followed by the water-gas-shift reaction. At high carbon conversion and low heat loss in the cases studied in this investigation.

The observed second law efficiencies based on the chemical exergy of product gas and fuel are in very good agreement with the level of irreversibilities calculated by Sues et al. [29] for the gasification of five different types of biomass with comparable composition to the biomass in this study. At 100 % carbon conversion and only 1 % heat loss, the second law efficiency for the gasification of the three different waste fractions in this study was about 65% for all three fractions, while the relative irreversibility of the gasification reaction in the whole biomass-to-hydrogen-process was given as ca. 36 % according to Sues et al. [29]

Of the different publications taken into account when implementing the current model and discussing the obtained results, only Jayah et al. [26] have reported the moisture content in the gasifying agent. It was slightly less than a third of the moisture content in the rubber wood chips and therefore a non-negligible contribution to the total moisture input. However, as the majority of reports the authors studied have not given specific values for moisture content of the air used as gasifying agent (for example its relative humidity), it was chosen to use dry air instead in the calculations. This was done even though the code allows for the input of a relative humidity of the input air because the authors' initial interest was in the results in the upper end of the moisture content interval, where moisture content of the gasifying agent is negligible compared with the moisture in the biomass.

In order to reach its energy output levels in the model year (2013) for both electricity and district heat, the waste incineration plant would actually need less waste when the wet organic fraction is removed compared with the composition of the complete waste. An increase in energy output is less likely to be achieved (by firing the incinerator with the same amount of waste with higher HHV) due to necessary modifications of the existing plant with components that allow for increased mass and volume flows of steam (especially heat exchangers and turbine).

The composition of municipal solid waste varies from year to year and throughout the year. Therefore, variations in hydrogen production rate and process parameters of the actual gasification process will vary with the seasons. Further waste analyses (both seasonal and for several years) are necessary in order to obtain upper and lower boundaries especially for the H and O content of the waste. Other further work that is planned is an estimate of the actual energy balance of a gasification plant with the described waste input in composition and amount. The differences between using atmospheric air and pure oxygen as gasification agent are also to be investigated. Another important problem to solve is how the waste needs to be pre-treated and homogenized to be able to have a stable and reliable gasification process with a predictable hydrogen output.

## **Conclusion**

Gasification of wet organic biomass fractions of municipal solid waste can make a considerable contribution to the transition from the use of fossil fuels in transportation on roads or waterways in Western Norway. Although not as environmentally friendly as electrolysis of water with electricity from renewable sources, the high energy and exergy efficiency of biomass gasification along with the possibility to capture CO<sub>2</sub> from the product gas make it an interesting candidate for hydrogen from a renewable resource compared with steam reformation of natural gas, for example. Gasification of biomass in municipal solid waste gives the local waste management operator a possibility to increase the capacity of waste that can be treated and a new product to be sold in addition to electricity and district heat. SO<sub>2</sub> and CO<sub>2</sub> emissions are local can be reduced by appropriate product gas treatment and carbon capture. The produced hydrogen can make a significant contribution to transportation in



the region, albeit in motor cars, larger vehicles and/or in ferries of various capacities in the Hordaland region in Western Norway. It will be needed if current plans for the transition from the use of fossil to renewable fuels are to be implemented in Western Norway in the near future.

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