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Energy efficient thermochemical conversion of very wet biomass to biofuels by integration of steam drying, steam electrolysis and gasification

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ABSTRACT

A novel system concept is presented for the thermochemical conversion of very wet biomasses such as sewage sludge and manure. The system integrates steam drying, solid oxide electrolysis cells (SOEC) and gasification for the production of synthetic natural gas (SNG). The system is analyzed by thermodynamic modelling and the analysis shows that the system can handle mechanically dried biomasses with a water content of 70 wt% and an ash content of up to 50 wt% (dry basis). A high tolerable ash content is an advantage because very wet biomasses, such as sewage sludge and manure, have a high ash content. The analysis shows that the total efficiency of the novel system is 69–70% depending on the biomass ash content, while the biomass to SNG energy ratio is 165%, which is near the theoretical maximum because electrolytic hydrogen is supplied to the synthesis gas. It is proposed to combine the novel system with an anaerobic digester for conversion of biomasses with high nitrogen content, such as sewage sludge. The organic nitrogen in the sewage sludge will be mineralized in the digester instead of ending up as N_2 in the SNG product.

1. Introduction

Very wet biomasses, such as sewage sludge and manure, are typically converted by anaerobic digestion to produce biogas. An issue with anaerobic digestion is however the low conversion efficiency, meaning that a significant amount of the chemical energy stored in the biomass is still available in the digested biomass. Thermochemical processes such as gasification can have a much higher conversion efficiency, leaving very little carbon in the gasification ash. To use very wet biomasses (water content above 70 wt %) for gasification, a drying process is required. This drying process has a high energy demand and can therefore have high operational cost. However, if waste heat is available in the downstream processing of the biomass, the drying may not be a significant issue. This paper shows how very wet biomasses can be used for production of biofuels through gasification by using a steam dryer integrated with solid oxide electrolysis cells (SOEC). This novel concept is shown in Fig. 1 and can be compared with a more "conventional" system in Fig. 2. The novelty of the concept is the use of excess steam from the steam dryer in the SOEC, whereas the "conventional" system would have a separate boiler for raising steam to the SOEC.

In the novel concept, more waste heat will therefore be available for the steam dryer and the system can therefore tolerate biomasses with a much higher water content. Previous work within this field of integrating gasification and electrolysis for synthesis of fuels or chemicals include [1–8]. The biofuels produced in these references are: methanol [1,4–7], Fischer-Tropsch fuels [2], synthetic natural gas (SNG) [3], and dimethyl ether (DME) [8]. Liquid water electrolysis is used in these studies, except for [2,8], in which steam electrolysis is used instead. None has considered using these systems for conversion of very wet biomasses, and none has considered supplying steam to the SOEC from a steam dryer. The use of wet biomasses for gasification has been studied before. In Ref. [9], gasification of dried sewage sludge is compared to pyrolysis of dried sewage sludge with subsequent gasification of the pyrolysis char. The energy demand of the drying and pyrolysis is found and compared with the available energy in the output gas and bio-oil. In Ref. [10], a process for bio-char production from sewage sludge is evaluated. In this study, the sewage sludge is first dried

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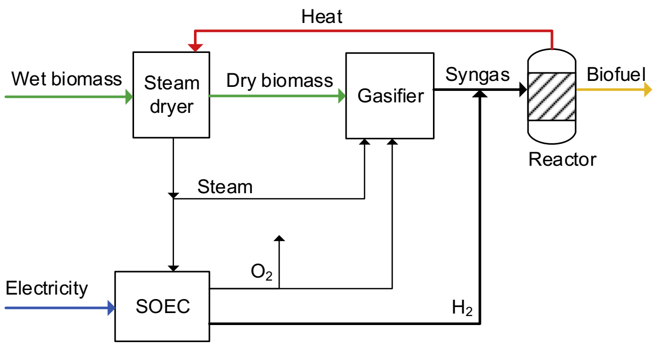

Fig. 1. Simplified flowsheet of the proposed system for utilization of wet biomass and electricity for biofuel production. Color description: green = biomass, blue = electricity, yellow = biofuel, red = heat. (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)

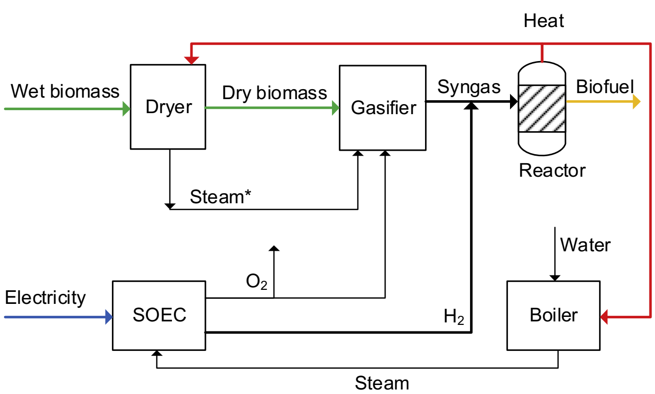

Fig. 2. Simplified flowsheet of a "conventional" system for integration of steam electrolysis and biomass gasification for biofuel production. *only if a steam dryer is used. Color description: green = biomass, blue = electricity, yellow = biofuel, red = heat. (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)

and pyrolyzed, and then some of the produced bio-char is gasified, and finally co-combusted with the volatiles from pyrolysis to cover the energy demand for pyrolysis and drying. Neither of these two references utilize waste heat for the drying of the wet biomass before gasification. In this paper, the novel system concept (Fig. 1) is analyzed by thermodynamic modelling and compared with the more "conventional" system (Fig. 2). Focus is on determining the maximum water content of the biomass that the system can tolerate, and show how this maximum depends on the biomass ash content, since these very wet biomasses can have a very high ash content.

1.1. Steam quality required by the SOEC

The concept of using steam from a steam dryer in an SOEC has not been tested, and will only work if the steam is free of unwanted species. The unwanted species include particles, sulfur compounds, alkali compounds and halides [11]. The required cleaning could be limited to a bag house filter for particle removal, but if sulfur or alkali compounds or halides are released at these very low temperatures, which is considered unlikely, a guard bed would also be needed [11]. When drying biomass in steam at up to 200 °C, some organic compounds will be released according to [12]. In Fig. 3, the release of organic material vs. temperature is shown.

In the temperature range of approx. 100–150 °C, acetic acid, formic acid, and formaldehyde are released, in the temperature range of approx. 150–230 °C, monoterpenes, fatty acids, and resin acids are released [12]. These compounds consists of C, H, O in various ratios. Because of the high temperature and the high catalytic activity of an SOEC, compounds consisting of C, H and O are not considered a problem at very low concentrations as would be the case here [11]. In the unlikely situation that the compounds needs to be removed, an active carbon filter could be used [13].

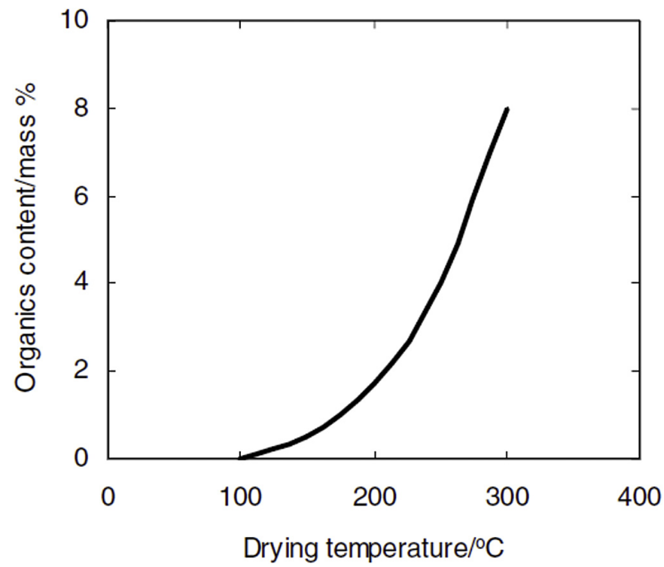

Fig. 3. Schematic dependence of total amount (wt%, dry basis) of organic compounds released in atmospheric drying of biomass on temperature. From Ref. [12].

1.2. Choice of biofuel to produce

The novel concept (Fig. 1) could, in principal, be used for production of many different types of biofuels, but the synthesis of methane for production of synthetic natural gas (SNG) is especially interesting because the methane synthesis is highly exothermic. This can be seen from eqs. (1)–(4), where the methane synthesis reactions are shown together with the methanol synthesis reactions. The heat of reaction (change in standard enthalpy of formation) is given for each reaction. It can be seen that the methane synthesis releases more than double the amount of heat per converted CO or CO_2 molecule compared with methanol synthesis.

Methane synthesis reactions:

$$CO + 3H_2 \leftrightarrow CH_4 + H_2O \qquad -206\ \text{kJ} \tag{1}$$

$$CO_2 + 4H_2 \leftrightarrow CH_4 + 2H_2O \qquad -165\ \text{kJ} \tag{2}$$

Methanol synthesis reactions:

$$CO + 2H_2 \leftrightarrow CH_3OH \qquad -91\ \text{kJ} \tag{3}$$

$$CO_2 + 3H_2 \leftrightarrow CH_3OH + H_2O \qquad -50\ \text{kJ} \tag{4}$$

A higher heat release in the synthesis will mean that more waste heat is available for the biomass drying and the system will therefore be able to handle biomasses with higher water content. In the following calculations on the system, the produced biofuel is therefore SNG.

2. Design of the biomass based SNG plant

The designed system consists of four parts as seen on Fig. 1 and