ECONOMICS OF HYDROTHERMAL CARBONIZATION OF BIOGAS DIGESTATE IN A HYBRID AD-HTC PLANT

Kay Suwelack[1,2]*, Nadim Dostert[1], Dominik Wüst[1], Andrea Kruse[1]

[1] Hohenheim University, Institute of Agricultural Engineering, Conversion Technology and LCA of Renewable Resources, Stuttgart, Germany.
[2] Fraunhofer Institute for Technological Trend Analysis INT, Euskirchen, Germany.

Contact: t: +49-2251-18-340, f: +49-2251-18-38-340, kay.uwe.suwelack@int.fraunhofer.de

ABSTRACT: In the recent years hydrothermal carbonization (HTC) has become subject to research again and therefore to numerous scientific publications. To date most of this research revolves around the chemical and technical optimization of the HTC process itself, HTC of different biomasses, and the entire spectrum of hydrochar application. A current search reveals, that only very little has been published on the economics of HTC. This is mostly due to the fact, that reliable economic assessments need to be done on the basis of well-defined technical processes and erecting of larger scaled research/commercial plants has even begun within the last couple of years. In this sense the paper at hand analyses the economic viability of hybrid anaerobic digestion (AD) and HTC plants taking into account that there are a number of interesting synergies that can be realized by combining these different types of bioenergy plants.

1 INTRODUCTION

In the process of hydrothermal carbonization (HTC) biomass is heated for 1 to 12 hours in hot pressurized water at temperatures between 180 °C and 250 °C to produce a lignite-like product usually called biochar or hydrochar. Due to its aqueous reaction conditions, HTC is particularly suitable for biomass with high water content. Therefore a prior energy-intensive drying can be abandoned. In the last years numerous types of biomass, like microalgae [1], wheat straw [2], biogas digestate [3, 4], municipal waste [5] and sewage sludge [6] have been examined for their properties in the HTC-process. Although the detailed reaction mechanism is highly complex, it was found that dehydration and decarboxylation are the most influential reactions in the process [7]. Through the release of water and CO_2 the produced hydrochar has, in comparison to the initial feedstock, increased carbon content and higher heating value (HHV). Moreover the product has a higher hydrophobicity, which improves its mechanical dewatering qualities [8]. The possible applications of the hydrochar are very diverse. It can be used as alternative to conventional char in power plants [9], basic substance for synthetic fuel [10] or activated carbon [11], electrode material in fuel cells and supercapacitors [12, 13] and lastly as a soil amender [14]. Most of the existing literature is focused on the process itself and possible other feedstocks. In comparison very little research has been published regarding the economics of HTC. Wirth et al. showed that the production of HTC hydrochar from regionally grown straw and wood in Brandenburg (Germany) is not profitable under their supposed conditions [15]. Given the fact that there is a high regional availability of the feedstock, it was also found that larger centralized plants are more viable, due to economy-of-scale effects concerning investment- and operating costs. Furthermore, Erlach et al. showed that hydrochar from biodegradable waste can be produced at a cost of 9.8 €/GJ_{HHV} which is comparable to the costs of wood pellets (9.7 €/GJ_{HHV}) [16]. Moreover Wirth et al. found that the anaerobic treatment of the process water can be economically feasible in an industrial HTC plant. For this purpose the organic loading rates have to be at least 1.5 kg_{COD} m^{-3} d^{-1} [17]. Nevertheless it is crucial to further strengthen the data base in this field, to analyze if HTC can become an economically and competitively viable process.

The basic idea to combine HTC with AD plants is not new [17–19]. The combination of HTC and AD has potential for a number of interesting synergies which are not limited to heat supply from the combined heat and power plants (CHPP) of an AD plant. There is also potential for cheap feedstock supply in the form of digestate and for anaerobic treatment of HTC waste water in AD. All three aspects should enhance the economic viability of HTC. Especially Germany with roughly 9,000 agricultural biogas plants currently in operation, offers large potential for the realization of such a HTC-AD hybrid plant concept [20].

2 METHODS

2.1 Technology Design Assessment

For the analyses undertaken in this paper the basic concept of AD and HTC combination is described in the following. With it, the rules for a so called technology design assessment, as it has been defined in literature with respect to a unified appraisal framework for biomass conversion systems, are followed [21]. Within the concept at hand it is assumed, that the HTC plant is located on-site a biogas plant with an installed electrical capacity of 2 MW and that it needs additional digestate supply from four to eight external biogas plants with an average electrical capacity installed of 500 kW each. The real number of plants depends on the initial dry mass content of the external digestate and on the size of the external plants in range.

For transportation purposes the external digestate must undergo solid-liquid separation to make transport economically feasible. For both, liquid-solid separation and transport we included costs in the assessment. The total dry matter content of the feedstock is round about 18,500 Mg per year (with 15 wt-% DM content in the feedstock entering the core HTC process – flow 201 compare Fig. 2), which leads to a hydrochar output of round about 10,000 Mg per year (with 85 wt-% DM content after pellet drying – flow 307 in Fig. 2). A more detailed mass balance is depicted in Fig. 1. The flow numbers in Fig. 1 refer to the numbers in the flow chart (compare Fig. 2). Within detailed thermodynamic calculations it was found, that heat and steam supply from the CHPP of the AD plant counts for nearly 25 % of the total energy demand of the HTC plant. Further, it is assumed that the local biogas plant is able to handle a major fraction (80 %) of HTC waste water properly. The remaining waste water will be transported back to the remote plants in return to digestate delivery.

Mass balances for the core HTC process have been calculated with the help of the model equations from literature [4]. The assumed process parameters have been 245 °C process temperature, 120 minutes retention time and pH 7.

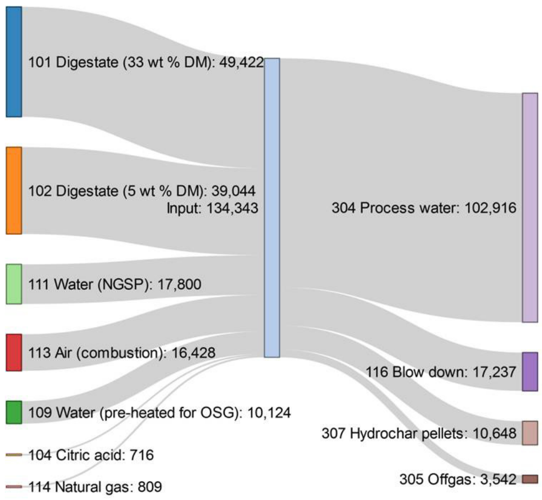

Figure 1: Mass balance for the HTC plant based on biogas digestate in Mg per year (flow numbers refer to Fig. 2).

2.2 HTC process

The HTC plant concept has been modeled diligently not only in terms of the flow chart, but also with respect to mass and energy balances. The process is based on semi-continuous batch operation, which has been modeled by the example of AVA-CO_2 (Karlsruhe, Germany) The company runs a similar process already for a couple of years on an industrial pilot scale.

The total process can be split up into five sub-systems (see Fig. 2) whereas subsystem 2 represents the core HTC part, consisting out of 8 batch reactors with a metric operation volume of 15 m³ each. Subsystem 1 represents the feeding system, consisting out of a hammer mill, push floor, conveyor belt and bio-filter. Subsystem 3 represents the internal heat recovery system, made out of a flash tank (for direct steam recovery) and a heat exchanger to recover thermal energy from the process water.

The external heat supply is marked as subsystem 4. A steam generator, fueled with natural gas and an off-gas steam generator (to recover heat from the CHPP off-gas of the AD plant) are used for thermal energy supply. The total energy supply can roughly be split up in 25 % from biogas CHPP, 40 % from internal heat recovery, and 35 % from natural gas. Finally, subsystem 5 represents the product handling unit, consisting out of buffer tank, filter press, briquetting unit, and belt dryer. The process is designed to produce hydrochar pellets for energy or material use purposes.

2.3 CAPEX estimation

In the first step the purchased equipment costs (PEC) were obtained based on the flow chart through vendors' quotations. The process parameters of the required components included a safety (overdesign) addition of 20 %. In Tab. 1 the component type and its net price are shown.

Table 1: System components and prices from vendors' quotations.

Component	Net Price [kEUR]
Hammer mill	23.5
Push floor & Screw conveyor	97.0
Mixing tank	37.5
Buffer tank	22.1
HTC-Batch reactors	1,879.6
Flash tank	113.9
Bio-filter	12.5
Slurry pump P200. P300	78.3
Slurry pump P100. 101. 102. 301	33.6
Steam generator	314.8
Off-gas steam generator (CHPP)	89.6
Filter press	604.5
Pellet press	155.3
Belt dryer	318.1
Purchased Equipment Costs (PEC)	**3,780.3**

In the next step the total capital investment (TCI), synonymously for the capital expenditures (CAPEX), was obtained through a factorial method according to Bejan et al. [22]. In this case the particular cost positions of the TCI are calculated as a percentage of the PEC. Only the costs for contingencies were determined as a percentage of the fixed capital investment (FCI). All of the applied factors are average literature values recommended in the above-mentioned reference.

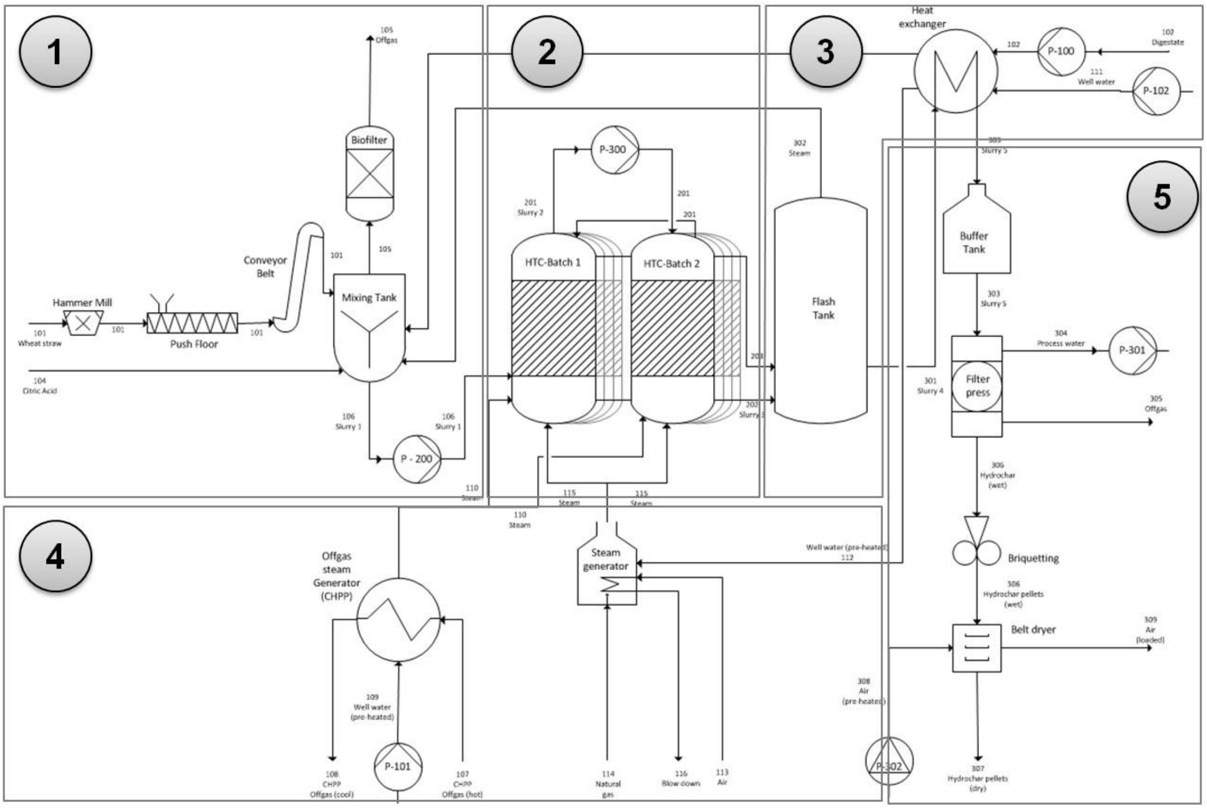

Figure 2: Process flow chart for the HTC batch process concept.

Table 1: Break-down of the TCI components (MEUR).

I. Fixed-capital investment (FCI= DC + IC)	**11,47**
A. Direct costs (DC=ONSC + OFSC)	8.84
1. Onsite costs (ONSC)	*7.82*
Purchased-equipment cost (PEC)	3.78
Purchased-equipment installation	1.70
Piping	1.17
Instrumentation and controls	0.76
Electrical equipment and materials	0.42
2. Offsite costs (OFSC)	*1.02*
Land	0.19
Civil, structural, and architectural work	0.83
Service facilities	-
B. Indirect costs (IC)	2.63
1. Engineering and supervision	1.13
2. Construction costs (included in B.1)	-
3. Contingencies	1.50
II. Other outlays	**0.64**
A. Start-up costs	0.05
B. Working capital	0.44
C. Costs of licensing, research and development	-
D. Allowance for funds used during construction (AFDUC)	0.15
Total capital investment (TCI)	**12.11**

2.4 Calculation concept

The total revenue requirement (TRR) is an income which has to be collected annually through the sale of all products (notably the hydrochar) to cover all expenses, which are necessary for a sound system operation on the one hand, and to recover the invested capital in the plant on the other hand. Taken all together it represents the total product costs. According to Fig. 3 the TRR can be divided into six parts.

The three positions TCR, ROI and ITX represent the financial expenditures (FINEX). OTX, FC and OMC can be expressed as the operational expenditures (OPEX). The sum of the two major parts is equal to the TRR. The calculation of the TRR was done under the assumption that the real escalation rate (r_r) for the digestate was 0.3 % and for natural gas and electricity 0.5 %. For the remaining positions r_r was set to be 0 % and the average inflation rate (r_i) 2.0 %.

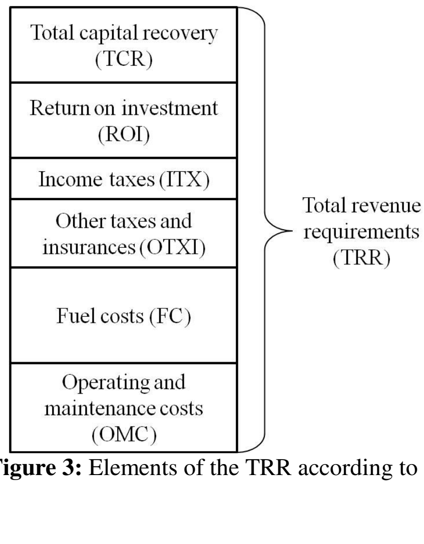

Figure 3: Elements of the TRR according to [22].

The annual levelized costs were calculated with the constant-escalation-levelization-factor (CELF) according to Bejan et al. [22].

2.5 OPEX and FINEX assumptions

The assumption with respect to operational (OPEX) and financial expenditures (FINEX) are summarized in Tab. 3.

Table 3: Break-down of OPEX and FINEX assumptions.

OPEX = FC + OMC + OTXI	**Amount**	**Price (€ unit^{-1})**
I. Raw materials and supplies		
A. Raw materials		
Digestate (separated)	49,422 t/a	5.0
Digestate	39,044 t/a	-
B. Operating supplies		
Citric acid	716 t/a	800.0
Water	27,925 t/a	1.0
Natural Gas (GJ/a)	40,103	11.1
Electricity (GJ/a)	1,399	33.3
Others		
II. Staff		
Engineer	1,760 h/a	45.0
Technician	8,760 h/a	30.0
III. O&M	**Factor ONSC**	**Factor**
High wear components	70%	10%
Low wear components	30%	2%
IV. Administration	**Factor TCI**	
Insurance	0.5%	
Accounting		10,000
Contingencies	0.5%	
FINEX=TCR+ROI+ITX		
Depreciation (TCR)	*EPL*	15 years
Return on investment (ROI)	i_{eff}	10 %
Taxes (ITX)	*Tax rate*	25 %

3 RESULTS

3.1 Total revenue requirements (TRR)

As can be seen from Fig. 3 the specific TRR for the hydrochar from digestate by HTC batch processing is high compared to previous calculations, which are in the range between 9 and 15 EUR per GJ [15, 16, 23]. In this case TRR is about 19.7 EUR per GJ, which is almost double the price of natural gas at the moment. The most relevant cost blocks are fuel costs (including feedstock and energy), return on investment and costs for operation and maintenance.

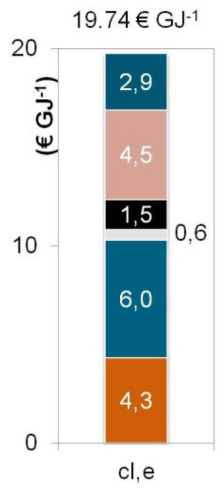

Figure 3: TRR break down (result).

3.2 Sensitivity analysis

When the different cost blocks from TRR are analyzed in more detail, it can be found that depreciation, maintenance of high wear components, acid and natural gas supply as well as staff costs for technician make-up the most relevant cost blocks.

The first two are by nature and assumptions directly depended on the CAPEX. Depreciation was found to be the most sensitive cost component, whereas the sensitivities of the other four cost categories are slightly similar with staff costs at the low end (compare Fig 4).

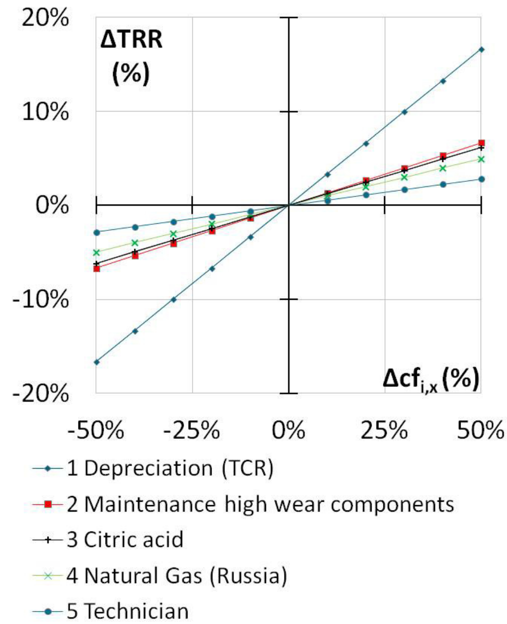

Figure 4: Sensitivity analysis (results).

3.3 Discussion

Compared to values from literature [15, 16, 23] the calculation presented here goes beyond cost ranges that have been published previously, although the concept presented here includes the specific technical advantages arising from the combination of HTC with an AD plant (especially in terms of energy supply). The reason for this might be, that previous studies just have made CAPEX estimates on knowledge about similar technical concepts, whereas CAPEX estimation here is based on vendors' quotations.

4 CONCLUSIONS

Hydrochar production from biogas digestate by the batch process described has almost double the price of natural gas, although the process is already based on energetic synergies with an AD plant and a low cost feedstock supply.

Costs could most likely be lowered by further energetic optimization of the plant concept. Natural gas demand should be further lowered. It should be investigated if continuous flow concepts are more efficient from energetic point of view.

The chemical and material use of the hydrochar should become a more dominant topic in research instead of energetic utilization. Higher priced materials e.g. like activated-carbon will make economic viability more likely, especially with respect to the batch process examined here.

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6 LOGOS

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