THERMOECONOMIC ANALYSIS OF THREE BIOMASS UPGRADING PROCESSES INTEGRATED WITH A MUNICIPAL CHP PLANT

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RESUMO –*This work assess the exergoeconomic performance of three biomass upgrading processes, namely wood pellets, torrefied wood pellets and pyrolysis slurry (a mixture of pyrolysis char and oil), integrated with a municipal combined heat and power plant. Economic data of the assessed processes has been obtained from the literature and has been combined with the exergy data following the specific exergy costing approach in order to perform the exergoeconomic analysis. The systems' exergetic efficiency can be improved by 22%, 26% and 31% for the integration with pyrolysis slurry, torrefied wood pellets and wood pellets, respectively, making wood pellets the most efficient integration option. However, the integration of pyrolysis slurry production yields the highest profit under the projected price scenario.*

1. INTRODUCTION

Environmental and economic concerns boost the search for potential pathways for municipal CHP plants to mitigate the adjunct district heating (DH) network's CO_2 emissions and, at the same time, add a new product to the company's portfolio. Recent research shows the growing interest in the mentioned upgrading processes and their integration with CHP plants. As shown in previous work (Kohl *et al*., 2013), the integration of upgrading processes has the potential to increase operation hours considerably and also revealed benefits regarding primary energy consumption and CO_2 emissions. However, the economic feasibility remained unproven and the gained results favoured integration of wood pellets regarding the energetic efficiency. This work presents an exergoeconomic analysis based on the very same simulation models as described previously (Kohl *et al*., 2013). By comparing the production costs with the potential income that can be realised on the product market, the overall economic feasibility of the integration concepts can be assessed. In addition the results of the exergoeconomic analysis is compared to the results of the energetic-environmental analysis. As a novelty, the exergetic analyses of the three biomass upgrading processes (pelletising, torrefaction and fast pyrolysis) are presented and compared to each other.

2. METHODS AND MATERIALS

2.1. Evaluated Process

Stand-alone CHP plant (CHP): Figure 1 shows the stand-alone CHP plant, consisting of a fluidised bed boiler (B) and superheater (D). The hot flue gases leaving at 850 °C exchange heat within the first superheater (C), the economiser (E) and the air pre-heater (A) before they are emitted. Design data from literature was used and all load points have been calculated based on the simulation software's implemented data bases as explained by Kohl *et al*. (2014). The live steam is expanded in a turbine (F) to the feedwater tank (H) and enters the DH exchanger (G) for condensation at load-dependent temperatures.

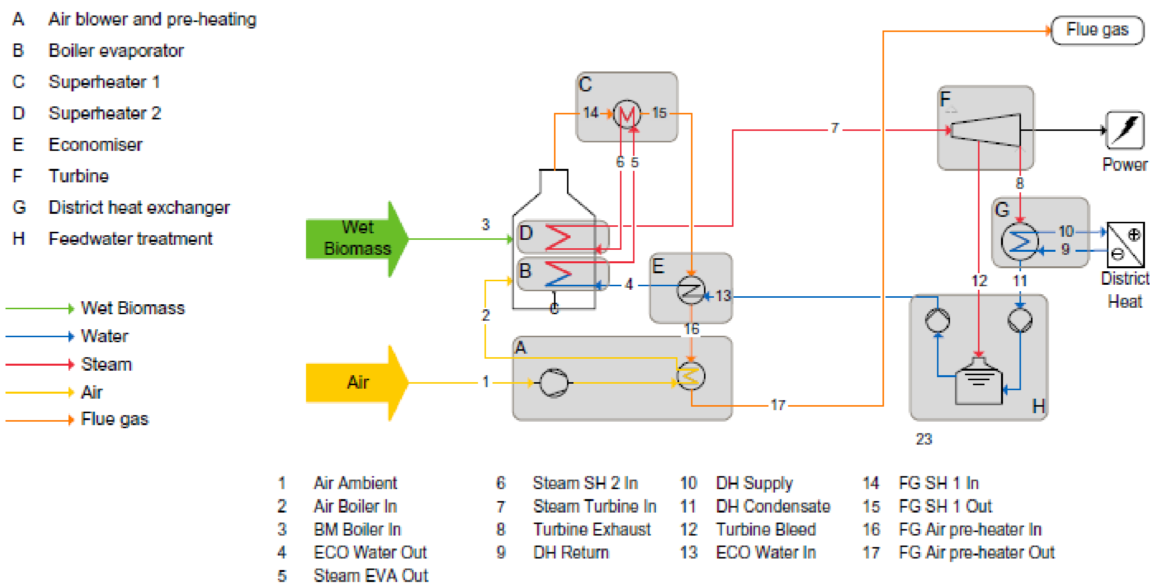

Figure 1 –Process flowsheet of the stand-alone CHP plant.

CHP plant integrated with wood pellets (WP): Figure 2 shows the integration of WP production. WP production requires drying to about 10% moisture content. Therefore, live steam is supplied to an indirect steam dryer (I, the heat consumption was set to 3000 kJ/kg water evaporated). The amount of steam available for drying is defined by the required DH load. The boiler operates on higher loads than required by the stand-alone CHP plant and the heat generated in excess is shifted to the steam dryer. The flue gases leaving the air pre-heater (A) are used as carrying medium in the dryer. The dried biomass is milled, pressed and cooled (section K). The power consumption of the added equipments was estimated to 119Wel/kWch of the chemical energy contained in the wet wood that enters the process. This power consumption is subtracted from the net power generation.

CHP plant integrated with torrefied wood pellets (TWP): Figure 3 shows the integration of TWP production. The production of TWP requires a torrefaction reactor operating at 300 °C (K). The heat required was estimated to 714 kJ/kg dried biomass (Bergman *et al*., 2005).

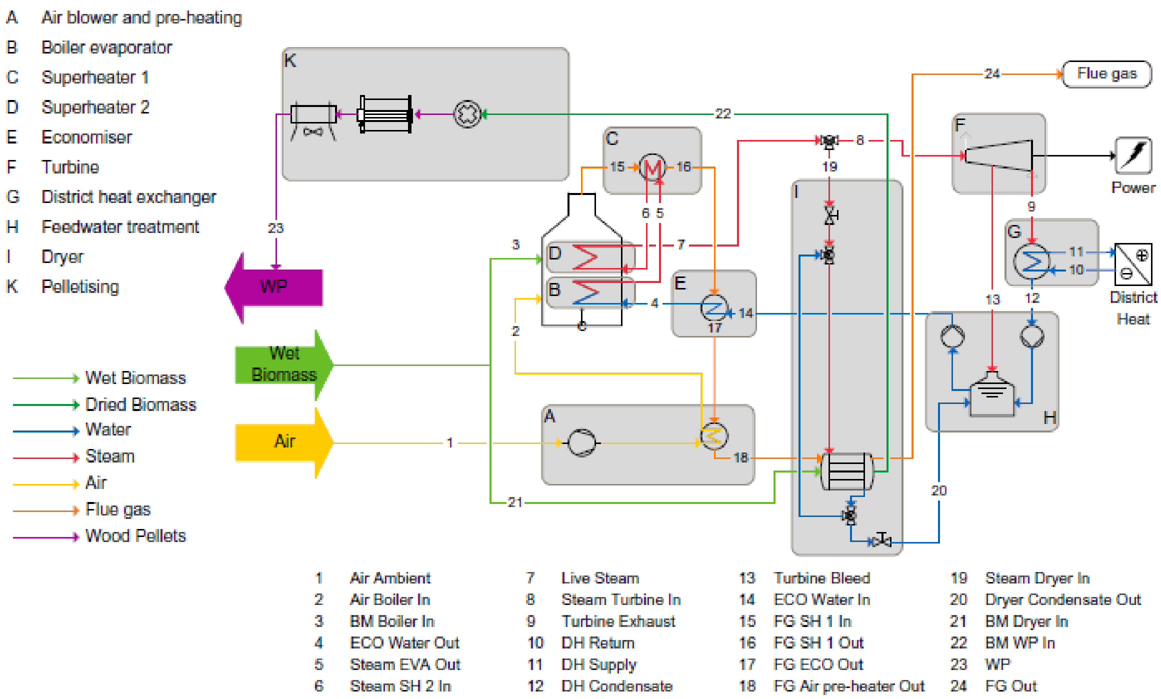

Figure 2 –Process flowsheet of the CHP plant integrated with WP production.

During the torrefaction, the biomass is decomposed into char and gas. The gas is combusted in the biomass boiler and thus its energy content is subtracted from the boiler input. The reaction heat is extracted from the hot flue gases. After the reactor, the biomass is milled, pelletized and cooled to finally form TWP (K). The power consumption of the added equipments was estimated to 155Wel/kWch of the chemical energy contained in the wet wood. This power is subtracted from the net power generation. The DH load is controlled in the same way as for the WP case, with the addition that heat for drying is also extracted from the flue gases. The steam and heat extraction from the flue gas have been iterated in a way that there is just enough heat available for both, the drying and the torrefaction reaction of the dried biomass.

<u>CHP plant integrated with pyrolysis slurry (PS)</u> : Figure 4 shows the integration of pyrolysis slurry. For PS production, the biomass is dried to a moisture content of 10 wt.%, milled (I) and fed to the fast pyrolysis reactor where it is decomposed at 500 °C in an inert atmosphere to form liquid, char and gas. Heat is supplied by hot flue gases leaving the boiler at 850 °C which are cooled to 480 °C. The heat for the pyrolysis reaction was estimated as 1830 kJ/kg dried wood. The gas is co-combusted in the biomass boiler and thus its energy content is subtracted from the boiler input. The power consumption of the added equipments was estimated to 123Wel/kWch of the chemical energy contained in the wet wood that enters the process. This power consumption is subtracted from the net power generation. Char and gas are separated with a hot cyclone and the liquid fraction is condensed with a spray cooler applying cooled pyrolysis oil (K).

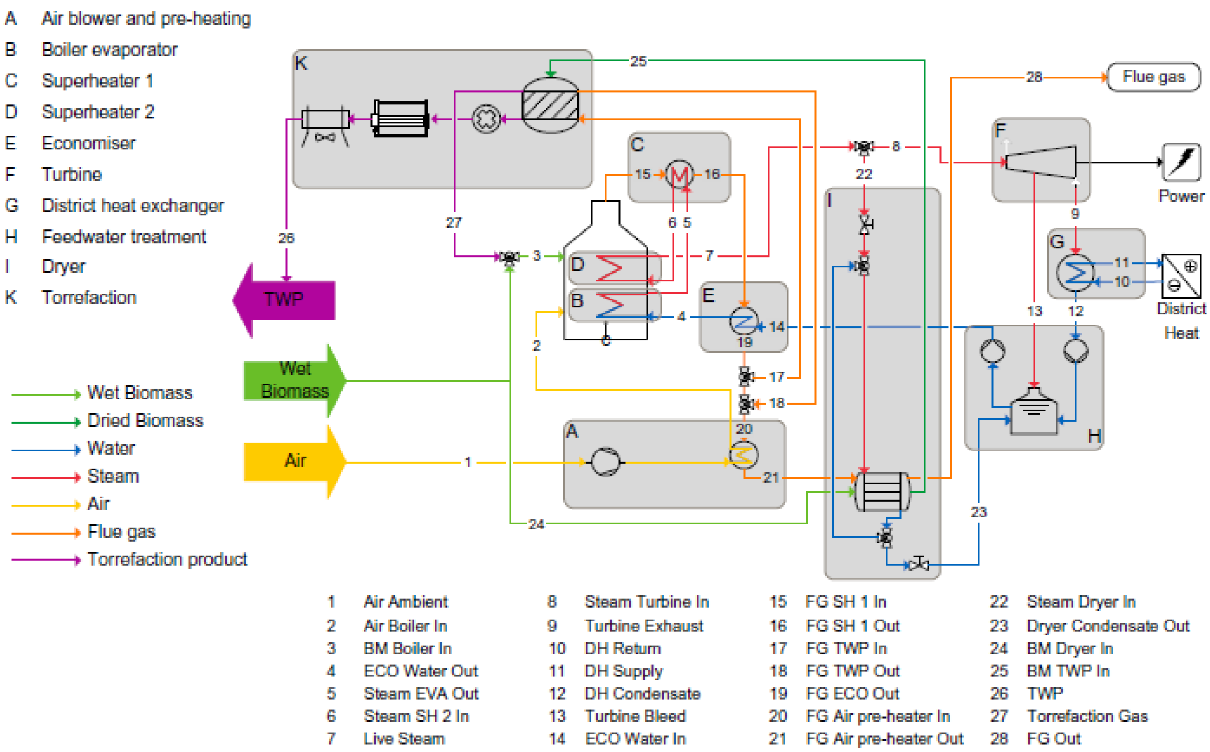

Figure 3 –Process flowsheet of the CHP plant integrated with TWP production.

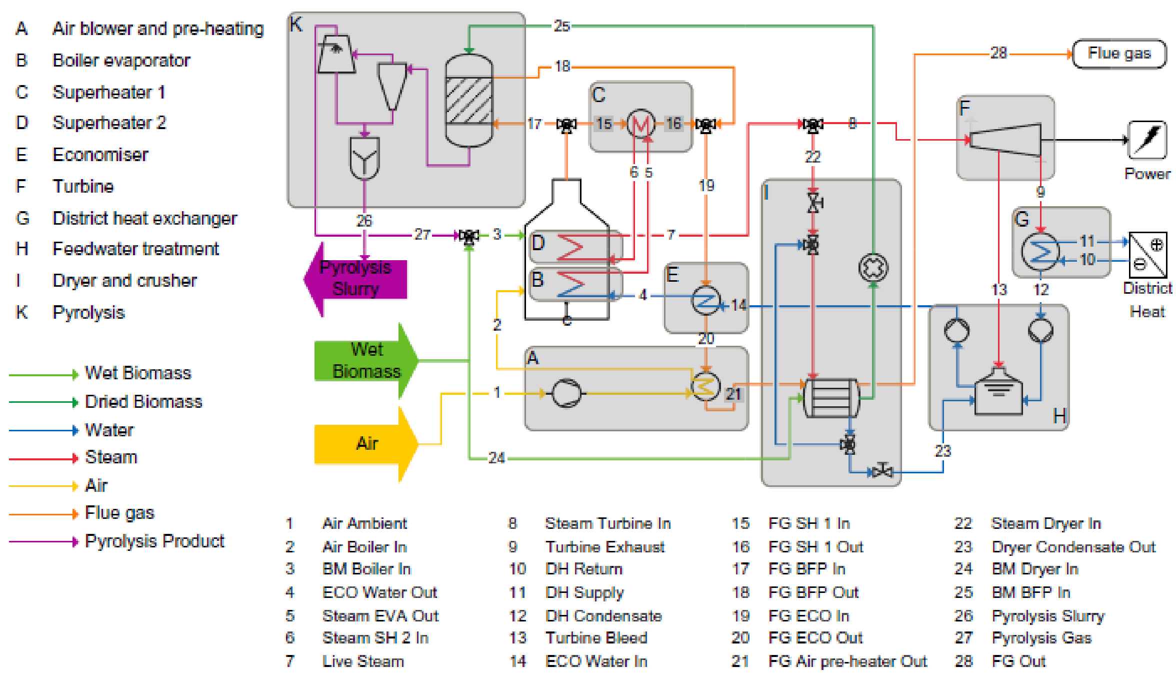

Figure 4 –Process flowsheet of the CHP plant integrated with PS production.

2.2. Exergy Analysis

Exergy analysis can reveal the margin available to design more efficient energy conversion systems. Although the maximum efficiency in energy conversion systems corresponds to an ideal process (no entropy generation and reversibility), all real processes are, to some extent, entropy generators. Exergy analysis was performed by calculating the chemical and physical exergy of all material and energy stream of the process according to the methodology of Kotas (1995). Then, an exergy balance for each subsystem (A, B, C etc) reveals the amount of exergy destroyed.

2.3. Investment Cost

For the CHP plant: The total capital investment (TCI) costs of the power plant were estimated based on a power plant recently built in Kerava (Finland). This plant has a thermal capacity of 81MWch and generates 21MWth, 10MWth and 48MWel of power, process steam and DH, respectively. The TCI of the Kerava plant was approximately 65 M€. The costs of the new plants are then estimated using scaling factors, according to Kohl *et al*. (2015).

For the WP, TWP and PS: TCI costs calculations were carried out by first sizing the equipments, designed for the maximum flow rate. After sizing the equipment, the purchased equipment cost (PEC) for each unit was extracted from references. All costing details can be found in Kohl *et al*. (2015). In order to determine the total onsite costs (TOC), installation cost factors have been estimated to range from 10% to 25% based on the PEC. As no detailed cost data for the processes described is available, it has been assumed that the TOC represent 35% of the TCI costs which is a typical value for chemical plant design (Peters and Timmerhaus, 1991). In order to consider start-up cost and the costs for connecting the CHP plant with the upgrading equipment 10% of the TCI costs were also added.

2.4. Exergoeconomic analysis

We applied the SPECO methodology, as described in Lazzaretto *et al*. (2006). It allows the allocation of cost and exergy destruction once the fuel and product of each considered process is defined. Exergoeconomic analysis divides process' total cost in costs of the process material stream and equipment cost (so-called Z-factors). The exergy cost balance of one process unit on an hourly basis can be written as:

$$\sum\left(c_{out}\dot{e}_{out}\right)_k + \left(c_W.W\right)_k = \left(c_{heat}.\dot{e}_{heat}\right)_k + \sum\left(c_{in}\dot{e}_{in}\right)_k + \dot{Z}_k \qquad (1)$$

All units as evaluated in the exergoeconomic analysis are highlighted in grey (Figures 1 – 4). Comparable to the energy balance, it describes that the sum of all (exergy) cost streams entering the unit k and the appropriate cost for unit operation Z_k (capital invest, operation and maintenance) equals the sum of all cost streams (material and work) leaving unit k. The annual equipment cost (Z-value) that is required for the exergoeconomic assessment was calculated by multiplying the annual operation cost of the plant (annuity, maintenance- and personnel cost) with the equipment cost share of each process unit. Further details and complete data can be found in Kohl *et al*. (2015).

3. RESULTS AND DISCUSSION

The exergoeconomic analysis yields production costs for all products allocated based on their exergy content; thus, it can be easily compared with the potential turnover that can be obtained on the product markets. These results are presented in Table 1. The results are based on the projected future average price. As a result of the increased operation hours, the operation costs of CHP plant increase by 15%, 17% and 22% for WP, TWP and PS, respectively. Also, as a result of the operation hours, the annual fuel costs increase. The cost for the upgrading equipment varies based on the investment cost, the linked operation cost and the throughput-dependent fuel cost. The overall annual values are roughly double for the integrated cases, but vary only by 4.6% and 11.4% between WP and PS and WP and TWP, respectively. Based on the TCI of the upgrading equipment, higher variations could have been expected, but the results undermine the high importance of the fuel costs, which is a common finding for biomass processing plants.

Table 1 – Cost and mass balance and plant profitability; annual values.

	CHP	WP	TWP	PS
Payment CHP plant (M€)	1.54	1.54	1.54	1.54
Operation cost CHP (M€)	1.27	1.46	1.49	1.55
Fuel cost CHP (M€)	3.48	4.51	4.49	4.66
Fuel flow (kt)	48.7	63.1	62.9	65.2
Payment upgrading (M€)	-	1.04	2.24	1.38
Operation cost Upgrading (M€)	-	0.99	1.54	1.28
Fuel cost Upgrading (M€)	-	3.51	3.44	3.27
Fuel flow Upgrading (kt)	-	49.2	48.1	45.7
Overall production cost (M€)	6.30	13.05	14.73	13.68
Power production cost (€/MW h_{el})	178.57	173.67	184.36	178.22
DH production cost (€/MW h_{th})	31.26	28.35	29.30	29.39
Bio-product production cost (€/MW h_{ch})	-	57.66	73.25	70.55
Power generation (GW h_{el})	22.9	21.6	20.9	22.3
DH generation (GW h_{th})	70.8	79.6	80.6	82.8
Bio-product generation (energy) (GW h_{ch})	-	122.3	116.4	103.2
Bio-product flow (kt)	-	29.0	22.4	21.7
Wood chips market price (€/MW h)	32.60	32.60	32.60	32.60
Power market price (€/MW h_{el})	137.00	137.00	137.00	137.00
DH market price (€/MW h_{th})	89.30	89.30	89.30	89.30
Bio-product market price (€/MW h)	-	72.30	62.40	95.70
Power turnover (M€)	3.13	2.96	2.86	3.05
DH turnover (M€)	6.33	7.11	7.20	7.40
Bio-product turnover (M€)	-	8.84	7.26	9.88
Total turnover (M€)	9.46	18.90	17.32	20.32
Total profit (M€)	3.16	5.85	2.59	6.64
Total profit (M€) 30% of DH turnover for piping	1.26	3.72	0.43	4.42

Compared to the stand-alone CHP plant, the overall systems' exergetic efficiencies can be improved from 24% to 55%, 50% and 46% for WP, TWP and PS, respectively. This is well in line with results gained by a primary energy efficiency assessment carried out previously (Kohl *et al*., 2013).

4. CONCLUSIONS

Thermodynamic based concepts (entropy, exergy) and economic analysis can be coupled in order to get insights about cost allocation in a multiproduct process. An exergoeconomic analysis has been carried out for the integration of WP, TWP and PS with a CHP plant. The results are compared to the CHP stand-alone plant and among each other. The integration causes the annual cost to rise considerably. The highest investment is required for the TWP integration and is mainly caused by the large reactor volume required. Results also show that for all cases, the gross electricity generation can be increased by 10–13% due to longer operation hours, but that the net power output decreases by 2.6–8.7% due to the additionally installed equipment. Even though being the least efficient upgrading technology, due to the moderate investment cost and the high future potential at high bio-oil demand and price, PS integration constitutes the best option from an economical perspective. Based on the results, the integration of TWP production cannot be recommended.

5. REFERENCES

KOHL, T.; LAUKKANEN, T.; JÄRVINEN, M.; FOGELHOLM, C.J. Energetic and environmental performance of three biomass upgrading processes integrated with a CHP plant. *Appl Energy* , 107, p. 124–34, 2013.

KOHL, T.; LAUKKANEN, T.; JÄRVINEN, M. Integration of biomass fast pyrolysis and precedent feedstock steam drying with a municipal combined heat and power plant. *Biomass Bioenergy*, 71, p. 413–30, 2014.

KOHL, T.; TELES, M.; MELIN, K.; LAUKKANEN, T.; JÄRVINEN, M.; PARK, S. W.; GIUDICI, R. Exergoeconomic assessment of CHP-integrated biomass upgrading. *Applied Energy*, 156, p. 290-305, 2015.

BERGMAN, P.C.A.; BOERSMAN, A.R.; ZWART, R.W.R.; KIEL, J.H.A. Torrefaction for biomass cofiring in existing coal-fired power stations ''Biocoal''. Petten (NL), Energy Research Centre of the Netherlands (ECN), [Jul. Report No.: ECN-C-05-013], 2005.

KOTAS, T.J. The Exergy Method of Thermal Plants Analysis. Krieger, Melbourne, 1995.

PETERS, M.S.; TIMMERHAUS, K.D. Plant design and economics for chemical engineers. Fourth ed. New York, McGraw-Hill; 1991 [p. 525, 531, 570].

LAZZARETTO, A.; TSATSARONIS, G. SPECO: a systematic and general methodology for calculating efficiencies and costs in thermal systems. *Energy*, 31, p.1257–89, 2006.