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Integration of hydrothermal carbonization and a CHP plant: Part 2 —operational and economic analysis

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ABSTRACT

Wood-fired combined heat and power (CHP) plants are a proven technology for producing domestic, carbon-neutral heat and power in Nordic countries. One drawback of CHP plants is the low capacity factors due to varying heat loads. In the current economic environment, uncertainty over energy prices creates also uncertainty over investment profitability. Hydrothermal carbonization (HTC) is a promising thermochemical conversion technology for producing an improved, more versatile wood-based fuel. Integrating HTC with a CHP plant allows simplifying the HTC process and extending the CHP plant operating time. An integrated polygeneration plant producing three energy products is also less sensitive to price changes in any one product. This study compares three integration cases chosen from the previous paper, and the case of separate stand-alone plants. The best economic performance is obtained using pressurized hot water from the CHP plant boiler drum as HTC process water. This has the poorest efficiency, but allows the greatest cost reduction in the HTC process and longest CHP plant operating time. The result demonstrates the suitability of CHP plants for integration with a HTC process, and the importance of economic and operational analysis considering annual load variations in sufficient detail.

1. Introduction

Biomass-fired combined heat and power (CHP) production using local wood sources is a strategy that combines carbon-neutral energy source with supply security and dispatchability. The main weaknesses with wood-based heat and power production are related to the limitations of untreated wood as fuel - low energy density, degradation in storage, and infeasibility for replacing fossil fuels in many existing plants. Often the low capacity factor of a CHP plant due to the significant annual variation of heat demand also has a detrimental effect on profitability.

Several technologies exist for converting raw biomass to better-quality fuels that can be more easily transported and stored. These high value bioproducts are more versatile fuels for various combustion technologies, including liquid fuels for traffic use. Depending on the biofuel and the scenario, the economic profitability of many of the biomass conversion technologies may currently depend on public subsidies. As the conversion processes typically require additional heat input and produce waste heat streams, process integration can sometimes yield benefits either by improving the overall energy efficiency or reducing the investment cost.

Numerous studies have investigated the integration of biomass conversion with power generation, CHP and other processes. Starfelt et al. showed that integrating ethanol production with a heat and power plant yields a clear improvement of efficiency, with less biomass used for a given amount of district heat (DH), power and ethanol in comparison to stand-alone plants [1]. In a later study the economic benefits of integration, attributed mainly to increased power production and extended operating time, were shown [2].

Co-generation of sugar, ethanol and electricity was shown to improve thermodynamic performance over stand-alone plants through decreasing the exergy destruction [3], and by heat integration of the processes, water and process steam consumption can be reduced [4]. Fahlen and Ahlgren [5] found integration of gasification with natural gas combined cycle CHP production economical under some scenarios. Integration of pelletization [6] and torrefaction [7] with CHP production have also been shown to yield energy efficiency benefits. Efficiency benefits were shown also in the integration of torrefaction with a large coal-fired CHP plant for the purpose of partial or complete fossil coal replacement in the

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boiler [8].

In northern European context, CHP plants are often backpressure steam plants. As heat load varies seasonally over the year, the annual operating time and power production of such plants is limited. Integration with a biomass conversion process has been shown to yield benefits in terms of increased operating time and higher power production during this period. Extending the annual operating time increases the capacity factors and incoming cash flow, thus increasing the value of the investment. This was found to be the case with ethanol production [1], pelletization and torrefaction [9], and biomass fast pyrolysis [10].

In this study the integration of hydrothermal carbonization (HTC) and a small-scale biomass-fired backpressure CHP plant is studied. HTC is a mild pyrolysis process similar to torrefaction. The biomass is typically mixed with liquid water to form a slurry, and heated to a temperature of 180–250 °C at saturated-state pressure. Compared to torrefaction, HTC achieves similar pyrolysis severity at a lower temperature. Using vapour instead of liquid water has also been studied, resulting in less severe carbonization than with liquid water when using otherwise similar parameters and the feedstock [11]. Possible feedstocks include various waste streams such as municipal and paper industry sludges [12], bark [13], corn husks [11] or weed plants [14] as well as woody biomass [15].

The published studies of HTC and CHP integration have so far been limited. An integration concept aiming at simplifying the HTC process was published by Erlach et al. first in [16]. This was later compared with two additional ones in [17]: a minimum-change integration where the only change to the stand-alone HTC process was using extraction steam from the CHP plant as a heat source, and one where the simplified process was further improved with a superheated steam drier for improved efficiency. While these integration studies did not reveal possibilities for significant efficiency improvements, they did show a potential for significant reduction in complexity, translating to reduced investment costs and likely improved operability as well. A wider variety of integration schemes were studied and compared on technical merits at full and low load in Part 1 of this study [18], yielding similar conclusions: while simplification of the HTC process is possible by integrating it with a CHP plant, a significant efficiency improvement is not.

None of the aforementioned studies investigated the plant operation throughout the annual variation of load and operating conditions in detail. As load variation is significant for CHP plants producing district heat (DH) in Nordic countries, this is an important topic for proper economic evaluation of plant configurations. In this study a discretized multi-period model of the annual variation of the DH load, fuel quality and ambient conditions is used. Multiperiod DH load approximation has been used in a number of earlier studies investigating CHP plants [19] or their integration with pelletization and torrefaction [9] or fast pyrolysis [10]. Of the seven concepts introduced in Part 1 of this study [18] – six integrated concepts and the case of separate stand-alone plants – three were ruled out as problematic or clearly inferior. The remaining four are evaluated here in terms of operability and economic performance.

A particular concern for the profitability of any energy sector investment in the current situation is the significant uncertainty over future energy prices, emission trading, as well as subsidies and taxes. As such, without subsidies or significantly increased CO_2 emission cost through taxation or emission trading, biochar is currently not a competitive alternative to coal. Electricity markets in the Northern Europe are at a period of change where uncertainty over renewable power subsidies and the future of nuclear power create serious doubts about the price of electricity. Using different scenarios for investment cost and electricity prices, the four different plant concepts are compared in terms of net present value (NPV), internal rate of return (IRR), and payback period (PBP). A sensitivity analysis is performed.

Preliminary studies often evaluate plant concepts at few loads. Then they are compared and using some criteria the promising ones are chosen for further study. In this paper this kind of ranking is compared to full economic ranking where operational characteristics at a large enough number of load points for good coverage are taken into account.

2. Studied cases

The economics of integrating a small-scale CHP plant and HTC process, and operation under different loads and conditions are considered. The CHP plant, as described in Part 1 of the study [18] and summarized in Table 1, is a wood chip fired back pressure plant with minimum and maximum district heat (DH) loads of 8 MW–20 MW, and a net electrical output of 8 MW_{el} at full load. The main characteristics of the plant are listed in Table 1.

Four different HTC and CHP plant concepts were considered, all of which are designed for hydrochar production of 5 tons per hour, or 1.39 kg/s. Case 0 is the reference case where both plants operate separately in stand-alone mode. The feed slurry is pressurized and pre-heated in stages before the HTC reactor with flash vapour from product slurry depressurization. For final heating to reactor temperature the stand-alone HTC plant has a grate-fired boiler of 5 MW design-point output, producing 30 bar steam at approximately 350 °C temperature. The LHV-based boiler efficiency at design point is 82%.

Before thermal dryer the product slurry is mechanically dewatered. The liquid from dewatering is mostly recirculated back to the process feed. The dryer is operated with low-pressure flash vapour from the product slurry cooling and depressurization, and hot waste water from the mechanical dewatering.

Three integration concepts were considered; Case 1, Case 5 and Case 6 of Part 1 of the study. Case 1 is the minimum-change variant from the basic stand-alone HTC process. The only difference between this and Case 0 is the replacement of the stoker boiler with the use of live steam from the BFB boiler of the CHP plant, throttled to 30 bar and cooled to 350 °C with feedwater injection.

Cases 5 and 6 are similar processes, representing more significant simplifications of the HTC process. Case 5 utilizes a mixture of feedwater and drum water to supply the water and heat necessary to reach the desired HTC reactor state. This eliminates the need for feed slurry heating, but also the sink where most heat from product slurry cooling is recovered in Case 0 and Case 1. In Case 5 the available heat is recovered by using the flash vapour in an additional low-pressure feedwater heater in the CHP plant, and cooling the hot water from dewatering by heating the process makeup water in a heat recovery heat exchanger. Case 5 is an entirely once-through process without water recirculation, which increases the waste water and makeup water flows significantly. The energy efficiency is also somewhat inferior to Case 0 and Case 1. Case 6 is similar to Case 5, but with limited HTC process water recirculation, allowing both more efficient heat recovery and reduced waste

Table 1
CHP plant main characteristics at full and minimum load.

Parameter	Full load	Minimum load
Net power output	8.0 MW	2.0 MW
District heat output	20.0 MW	8.0 MW
Total (CHP) Efficiency	85%	83%
Live steam parameters	90 bar/500 °C	90 bar/450 °C
Furnace temperature	900 °C	700 °C