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Integration of torrefaction and CHP plant: Operational and economic analysis

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HIGHLIGHTS

- Three scenarios of torrefaction integration into CHP plant are evaluated.
- Annual operation of integrated plants with part-load periods are considered.
- Economic performance is evaluated with NPV, IRR and PBP metrics.
- Sensitivity analysis of IRR is performed with several economic factors.

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ABSTRACT

Biomass torrefaction is a pre-treatment technology with high potential to convert biomass into a valuable commodity. The heat integration of torrefaction and combined heat and power (CHP) plant was investigated in previous work (Sermyagina et al., 2015). The aim of the present study is to assess possible economic benefits from integration. Three most promising integration concepts from the previous work were studied in terms of seasonal operational changes of district heating demand and varying ambient conditions. The performance of two integration concepts were evaluated together with stand-alone and co-located plants. The integration leads to a higher utilization of the CHP boiler capacity during part-load operation, possible increase of the operation time and growth of electricity generation as a result. The total efficiencies of the integrated cases (around 72% in higher heating value terms) are slightly higher than the stand-alone CHP plant (69%) or the co-located option (71%). The integration requires 40% more capital investments than the stand-alone CHP. On the other hand, the total capital investments of the integration cases are 20% lower than in co-located plants, and a profitability evaluation shows that lower investment costs may make integration schemes advantageous over the non-integrated plants. Feedstock price and investment costs are the main economic drivers affecting the profitability of the integrated options. An integration case which uses back pressure steam to account for the torrefaction heat demand showed the highest profitability due to a longer annual operating time, resulting in a growth of electricity and DH production over the stand-alone CHP plant.

1. Introduction

Modern society depends on materials and products that have been historically produced from fossil fuels. At the same time, the concept of sustainability in various industrial spheres is attracting increasing attention, especially considering the growing environmental concerns associated with fossil fuel combustion. Under these circumstances, the demand for efficient utilization of renewable sources is increasing. Biomass can be efficiently used for the production of various commodities, such as vehicle fuels (e.g. bioethanol and biodiesel), chemicals and plastics, fertilizers and pharmaceuticals as well as for energy generation [1,2]. The complete recovery of different by-products and wastes from agriculture and industry along with the utilization of other biomass sources has a significant potential for substituting traditional fossil fuels.

Biomass-based combined heat and power (CHP) production or co-generation is a proven technology that can be effectively applied for local biomass feedstocks. Simultaneously, despite the positive environmental and potential economic benefits, the untreated woody biomass as a fuel is associated with certain problems: heterogeneous nature, poor grindability, relatively high

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Nomenclature

c	energy price [€/MW h]
E	energy [MJ]
HHV	higher heating value [MJ/kg]
i	interest rate [%]
LHV	lower heating value [MJ/kg]
MC	biomass moisture content [%]
n	plant economic lifetime [y]
Q	heat [MJ]
r	ratio of annual operation and maintenance cost to total capital investment [–]
t	time [h]

Greek letters

α	scaling factor [–]
η	efficiency [%]
Σ	sum

Abbreviations

CBM	bare module cost
CEPCI	Chemical Engineering Plant Cost Index
CHP	combined heat and power
DH	district heat
EU	European Union
EY	energy yield
FCI	fixed capital investment
GHG	greenhouse gas
IRR	internal rate of return
MY	mass yield
NPV	net present value
PBP	payback period
PEC	purchased equipment cost
TCI	total capital investment
USD	United States dollar

Subscripts

b	boiler
bc	biocoal
chips	total fuel input
dry	dry basis
el	electricity
f	boiler fuel
feed	torrefaction feedstock
net	net
O&M	operation and maintenance
p	purchased
s	sold
wet	wet basis

moisture content and low bulk density [3,4]. Torrefaction is a thermal pre-treatment process to convert raw biomass into more homogeneous and with subsequent pelletizing energy-dense product. In torrefaction, the feedstock is heated slowly (<50 °C/min) to the reaction temperature, typically 200–300 °C, under atmospheric pressure in the absence of oxygen [4–6].

The torrefied biomass (biocoal) with improved properties can be then co-fired with pulverized coal. Torrefaction thus makes it possible to increase the use of biomass in coal-fired boilers, reducing greenhouse gas (GHG) emissions and making the energy production more sustainable [7–9]. Even though there is still limited amount of available related data from industrial applications, the research in this area shows that co-firing of torrefied biomass with coal allows a significant reduction of CO_2 emissions without a major penalty in boiler efficiency [7,10]. Torrefied pellets also have certain advantages in comparison with traditional wood pellets considering not only their physical properties and energy content but also the gas emissions from combustion. McNamee et al. [11] evaluated the life-cycle GHG emissions of several supply chains for torrefied pine and reported that torrefaction could allow to produce lower GHG emissions per output energy content, compared to conventional wood pellets. In another study [12], the gas emissions from the combustion of a range of fuels (torrefied spruce, peat, biomass/coal blend and two coals) were investigated. The results indicated the lowest levels of NO_x and CO emissions for the torrefied wood briquettes among all the studied fuel samples and a significant reduction (approx. 40%) of particulate emissions from combustion of torrefied wood compared to the source material.

The integration of biomass pre-treatment processes with industrial systems can lead to benefits through more efficient utilization of the available mass and energy streams. Various integration possibilities of biomass conversion processes with CHP plants or other industrial processes have been evaluated recently. Technical, economic and environmental benefits of integration of the biomass gasification into CHP based district heating (DH) system have been reported in [13,14]. The combination of cellulosic bioethanol production and a CHP plant may help to increase the operating hours, resulting in an increased power generation and improved overall system efficiency [15]. Opportunities for integrating pellet production and a CHP plant have been also intensively studied in [16–18] with the main outcomes of annual power production growth, significant reduction of CO_2 emissions and additional economic benefits from pellets trade obtained. The integration of torrefaction within a CHP plant can potentially cover the energy requirements of the torrefaction process and simultaneously increase the power generation and annual operating hours of plant as well as generate the valuable product for sale. Starfelt et al. [19] investigated the advantages of a combined system of torrefaction and CHP that covers the energy demand of the torrefaction reactor and keeps the heat and power generation at required levels. Possibilities of co-location of torrefaction facilities with coal-fired power plants and corn ethanol plants were evaluated in [20]. Kohl et al. [21] compared the energetic and environmental performance of the retrofit-integration schemes of a CHP plant and three biomass pre-treatment processes (fast pyrolysis, torrefied pellets and wood pellets production).

Typically, the annual operation of a CHP plant follows the pattern of seasonally varying district heat demand [21]. In addition to quantitative changes in the DH demand, the required DH supply temperature, temperature of combustion air, and the moisture and temperature of the boiler fuel vary during the year. Despite the aforementioned issues, the CHP plant operating parameters are often calculated only at design point to evaluate the possibilities of integration [14,17,20,22]. Some researchers investigated the effect of part-load operation on the performance of integration schemes [16,21,23,24]. At the same time, the comprehensive evaluation of the integration scheme is only possible when all the seasonal changes of operational conditions along with the characteristic features of the CHP plant at part load are taken into account.