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Impact of retrofitting existing combined heat and power plant with polygeneration of biomethane: A comparative techno-economic analysis of integrating different gasifiers

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ABSTRACT

It is vital to identify and evaluate the optimal gasifier configuration that could be integrated with existing or new combined heat and power (CHP) plants to maximize the utilization of boiler operating capacity during off-peak hours with minimal effect on the boiler performance. This study aims to identify technically and economically most suitable gasification configuration and the reasonable operational limits of a CHP plant when integrated with different types of gasifiers. The selected gasifiers for the study are, (i) indirectly heated dual fluidized bed gasifier (DFBG), (ii) directly heated circulating fluidized bed gasifier (CFBG), and (iii) entrained flow gasifier (EFG). The gasifiers are selected on their ability to produce high-quality syngas from waste refused derived fuel (RDF). The syngas from the gasifiers is utilized to produce biomethane, whereas the heat and power from the CHP plant are consumed to run the gasification process. A detailed techno-economic analysis is performed using both flexible capacity and fixed capacity gasifiers and integrated with the CHP plant at full load. The results reveal that the integration leads to increase in operating time of the boiler for all gasifier configurations. The indirectly heated DFBG shows the largest biomethane production with less impact on the district heat and power production. Extra heat is available for biomethane production when the district heat and biomethane are prioritized, and the electric power is considered as a secondary product. Furthermore, the economic indicators reflect considerable dependency of integrated gasification performance on variable prices of waste biomass and biomethane.

1. Introduction

The number of waste and biomass-based incineration combined heat and power (CHP) plants are expected to increase especially in Northern Europe due to strict regulations on landfilling of the organic waste also known as refuse derived fuel (RDF) [1]. RDF is an organic waste which constitutes of non-recyclable combustible waste collected from various sources such as municipal solid waste, commercial and industrial organic waste, and agricultural waste. In Europe, the waste management directives 2006/12/EC put the legislation on landfilling and state that the RDF must primarily use for energy production. In Europe, the total volume of RDF derived municipal solid waste alone is expected to reach 338 million tonnes by 2020 [2]. According to a report from the Confederation of European Waste to energy plants (CEWEP), the number of waste to energy (WtE) plants in Europe increased from 448 plants by 2010 to 502 by mid-2013 [3]. In Europe, the WtE plants treated about 95 million tons of organic waste in 2014 mainly in CHP plants [4]. In most CHP plants, district heat is the main product with power considered as a secondary output. Variation of seasonal heat demand in district heating networks also affects the operation time of a CHP plant [5]. Some CHP plants also deliver heat to industries which also result in the variation of heat demand due to production changes of consumer industries. Moreover, the heat demand too gets affected by plant shut-down for maintenance, etc. [1]. Besides, the rise of energy efficient buildings is reducing the district heating demand, especially in developed countries. Kohl et al. [6] reported that a typical CHP plant only operates for 70 days a year at a full load capacity and operates at a part-load for 145 days. Consequently, a CHP plant would not operate at full capacity for approximately 150 days a year. The heat production and annual operating hours of combined heat and power plants depend largely on the district heating demand that varies considerably for the whole year. The seasonal variations in the heat demand from CHP plants provide the heat sink that can form a basis for the integration of thermochemical processes such as gasification, pyrolysis, and

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Nomenclature

Abbreviations

AIC	annualized investment cost
ASU	air separation unit
CEWEP	Confederation of European waste to energy plants
CFBG	circulating fluidized bed gasifier
CHP	combined heat and power
CRF	capital recovery factor
DFBG	dual fluidized bed gasifier
EFG	entrained flow gasifier
FCI	fixed capital investment
HRSG	heat recovery steam generation
LHV	lower heating value
NAP	net annual profit
NPV	net present value
O&M	operating and maintenance
PBP	payback period
RDF	refuse derived fuel
ROROI	rate of return on investment
TCI	total capital investment
WCI	working capital investment
WGS	water gas shift
WtE	waste to energy

Symbols

A	capacity
C	cost (Euros)
E	activation energy (J/mol)
I	consumption (MWh)
i	interest rate (%)
k	kinetic constant
n	scaling factor
N	project life (years)
P	production (MWh)
R	gas constant (J/mol/K)
Rt	cash flow
T	temperature (K)
Y	yield (wt.%)

Subscripts

o	base capacity

torrefaction with CHP plants for the production of useful products. The operational analysis of CHP plants with thermo-chemical process integration needs to be investigated with possible opportunity for different fuel production, such as liquid or gaseous biofuels.

The thermo-chemical conversion of waste biomass can produce biomethane that has advantages over other fuels as discussed by Heyne et al. [7]. Integration of biomethane in the existing gas grid is also easy due to the existing established market for biomethane, with its utilization in the broad range of small to large vehicles. Also, biomethane can covert to other useful chemicals and products e.g. hydrogen, ammonia, methanol, etc. Syngas containing mainly CO and H_2 is a precursor for the production of biomethane. Among various thermo-chemical processes, biomass gasification could efficiently convert low-quality organic waste i.e. RDF to produce a substantial quantity of syngas to produce various liquid or gaseous biofuels [8]. Also, the methanation of syngas is a technically feasible option to generate biomethane. Due to reasons above, the integration of an existing CHP plant with waste biomass gasification is selected as a point of interest in this study.

The gasification process is an energy intensive process and requires external heat and electric power to run the process [8]. The required heat needs to be produced onsite for the standalone gasification. However, the integration of biomass gasification for polygeneration with the CHP plant can result in a high overall efficiency. Few studies focused on the techno-economic benefits of the polygeneration concept. The studies [7,9–14] analyzed the technical feasibility of integrating biomass gasification with CHP plants. Heyne et al. [7] evaluated the impact of integrating gasification in a steam cycle by using the DFBG reactor. Gustavsson et al. [14] studied the techno-economic potential of combining gasification and existing CHP plants for biofuels production. Fahlen et al. [15] investigated the integration of biomass gasification with natural gas CHP plant and found that the integrated approach is economically feasible. Difs et al. [16] also reported the economic benefits for all stakeholders when integrating biomass gasification with district heating systems. However, they also concluded that economic benefits depend largely on policy instruments. Wetterlund et al. [17] determined the effect of different economic policies on the feasibility of biomass gasification integration with district heating systems. In process integration with CHP plant different type of gasifiers may perform and affect the performance of CHP plant in a diverse manner. Gasification of biomass is carried out via different routes such as; fixed or fluidized bed gasifiers and entrained flow gasification (EFG) [18]. Previously, Heyne et al. [19] compared the stand-alone performance of an indirectly heated dual fluidized bed gasifier (DFBG) and a directly heated circulating fluidized bed gasifier (CFBG). They reported that the performance of both gasifiers is almost the same with similar exergy efficiency in the range of 79–81% and the only issue with the direct mode is incomplete carbon conversion. However, according to Meijden et al. [20], there is quite a large difference in the efficiencies of stand-alone CFBG (58%) and indirect mode DFBG gasifier (64%) and 54% for EFG for the production of biomethane. Gassner et al. [21] did the thermo-economic analysis of directly heated CFBG and indirectly heated DFBG gasifiers for the production of methane and reported their standalone efficiency lies within 63–69%. They further optimized the process and reported that efficiency of the gasification process could increase through polygeneration plants from 71 to 91% [22]. The biomass gasification process for biofuel production is a complex system even on the standalone basis [23]. The comparison of different gasifiers from reviewed literature shows that the competitiveness of all options with a range of efficiencies from 58 to 81%, there is still a lack of conclusive evidence to prefer one gasification technology over another to retrofit with CHP plant especially when considering heat demand variations [21–23].

For efficient integration of gasification with CHP plants, it is essential to highlight and address the uncertainties in the operation of CHP plant when retrofitting polygeneration system. There is a research challenge to investigate the impact of retrofitting different gasifiers and consider the CHP operational analysis to identify suitable gasification technology for the process integration. A detailed process analysis is vital to maximize the operating hours of boilers with minimal effect on the performance. Moreover, previous studies mainly consider wood derived biomass as a feedstock for the polygeneration process analysis instead RDF. The present study attempts to answer two main research questions: (i) what are the most reasonable operational limits of a CHP plant when integrated with different gasifiers? And (ii) what is the most economically viable option of gasification configuration integrated with new or existing CHP plants?

Fig. 1 shows a simplified schematic representation of the scope of this study. To analyze the process integration, three gasification systems: Indirectly heated dual fluidized bed gasifier (DFBG), directly