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Exergy analysis of a polygeneration-enabled district heating and cooling system based on gasification of refuse derived fuel

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A B S T R A C T

District heating and cooling (DHC) systems, modified or retrofitted with integration of gasifiers and gas upgrading equipment, represent promising alternatives to traditional approaches since various scenarios of products complementary to heat, cold, and electricity can be realized, namely: char only; char and syngas; char, synthetic natural gas (SNG) and hydrogen (H_2); and char, syngas, SNG and H_2. This manuscript evaluates a polygeneration-enabled DHC system in detail (operation during a typical year) from exergetic and exergoeconomic perspectives. The base DHC system utilizes natural gas as fuel with a nominal capacity of 29 MW heat, 35 MW of cold, and 5 MW of electricity. The retrofit employs refuse derived fuel (RDF) as feedstock to an atmospheric gasifier with downstream gas clean-up, a gas turbine, and a heat recovery steam generator along with heat exchangers for integration with the base DHC system. The exergy analysis revealed that the polygeneration system presents adequate performance at all scenarios established. Among the sets of value-added products the combination of char and syngas is the most beneficial as the system efficiency reaches a value of ~72%. The outcomes of the exergoeconomic analysis support the exergy results. The lower production costs for value-added products are achieved for the maximum simultaneous char and syngas production, with each of these costs estimated to be 6.1 USD/GJ.

1. Introduction

Nowadays a traditional district heating and cooling (DHC) system has to confront two principal challenges. First of all, even though renewables provide a significant contribution to DHC, the majority of such systems (57.8%) still operate on fossil fuels (Key World Energy Statistics, 2014). Secondly, modern DHC systems face uncertain profitability owing to the slow, but steady, decrease in DHC demand along with electricity price fluctuations.

These obstacles can be addressed simultaneously by a shift to a polygeneration-enabled DHC system via retrofitting with new technologies. In this way the modified system can gain an advantage of the diversification of both system inputs and outputs (Serra et al., 2009; Ilic et al., 2012). In addition to the traditional DHC products – heat, cold and electricity – the system can supply some unconventional ones, bringing complementary profit to the system through value-added products. Also, the polygeneration system can operate flexibly by varying the output of products according to demand.

Fuel selection for the polygeneration DHC system is based on two main stipulations: feedstock availability and sustainable system development. One favorable energy source that satisfies both parameters is refuse derived fuel (RDF), i.e. products of municipal solid waste (MSW) plants processing. Presently the most commonly applied MSW management scheme involves landfilling with or without incineration. The introduction of the waste management Directives 2006/12/EC and 1999/31/EC promoted energy recovery from RDF, making it an ample resource that can be exploited in polygeneration DHC systems.

RDF energy can be converted via either biological (fermentation or digestion) or thermochemical processing (combustion,

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Nomenclature

$\dot{C}$	cost rate, USD/h
$\dot{c}$	exergoeconomic cost, USD/GJ
Cost	equipment/unit/system costs, USD
c_p	heat capacity, kJ/(kg•K)
e	specific exergy, kJ/kg
E	exergy, kW
f_{OM}	operation and maintenance coefficient
h	enthalpy, kJ/kg
IR	irreversibility, kW
m	mass flow, kg/s
n	discount rate, 7%
P	pressure, kPa
R	universal gas constant, 8.31 kJ/(kg•K)
s	entropy, kJ/(kg•K)
t	project lifetime, years
T	temperature, K
Q	thermal energy (heat, cold), kW
W	electricity output, kW
Z	fixed cost, USD/h
τ	plant annual operation time, 8760 h
ψ	efficiency
ω	mass fraction

Subscripts

C	carbon
ch	chemical
cold	cold
gas	gasification
i	enumeration index
in	inputs
H	hydrogen
heat	heat
N	nitrogen
o	reference environmental model parameters
O	oxygen
out	outputs
ph	physical
prod	product
ref	reference

Abbreviations

ABS CHILL	absorption chiller
CEPCI	chemical engineering plant cost index
CHP	combined heat and power plant
CO_2 UNIT	carbon dioxide removal unit
CO&H_2 UNIT	carbon monoxide and hydrogen removal unit
COMPR CHILL	compression chiller
COMPR	compressor
cooling season	days 122–304 of a year
CYCL	cyclone
DH	district heating
DHC	district heating and cooling
ER	equivalence ratio
GASIF	gasifier
GASIF HEX	gasifier heat exchanger
GT	gas turbine
heating season	days 1–121 and 305–366 of a year
HEX	heat exchanger
HRSG	heat recovery steam generator
IR	irreversibility, kW
LHV	lower heating value, kJ/kg
MAX	maximal
MET	methanation
MET COMPR	compressor for the methanation unit
MSW	municipal solid waste
N_2 UNIT	nitrogen removal unit
RDF	refuse derived fuel
$R_{SG\ to\ sell}$	ratio of syngas amount produced for selling to syngas consumed in the GT, %
$R_{SG\ to\ SNG}$	ratio of syngas amount produced for the SNG unit to syngas consumed in the GT, %
S/C	steam to carbon molar ratio
SNG	synthetic natural gas
SCRUB	scrubber
WGS	water gas shift
WSt	water-steam
WSt HEX	water-steam heat exchanger

gasification, pyrolysis or liquefaction) (Basu, 2013). Biological conversion technologies are not applicable for RDF conversion owing to slow process times. Combustion is an obvious option, however it is not possible to achieve value-added products beyond electricity and heat via this pathway. Liquefaction and pyrolysis are promising technologies but both need still to be realized commercially at a large scale. The remaining alternative, gasification, is judged to hold the most potential in exploring RDF conversion for polygeneration. First of all, gasification is a fairly established conversion technology with a number of working facilities fueled by biomass (Klinghoffer and Castaldi, 2013), with main outputs including syngas (H_2, CO, CO_2, N_2, H_2O, CH_4 and other hydrocarbons) and charcoal (char). Syngas can be used directly in a power cycle for electricity and heat production, or it could be sold or upgraded to other products (see below). Charcoal might be applied as a fuel (Hwang et al., 2007) or as a resource for cement production (Uson et al., 2013); so it is also considered as a value-added product.

Although syngas and char are finished products for sale, their demand and, consequently, their prices on the market are unforeseen. To enhance the DHC system flexibility towards the market situation as well to secure profitability, a polygeneration DHC system should fabricate an additional output apart from syngas and char. Among possible products synthetic SNG produced via syngas methanation is the most encouraging. First of all, it is a prospective substitution for natural gas, and, thus, SNG will have reliable demand. Secondly, there is no need to construct the distribution network specifically for SNG as it could be supplied directly through the natural gas distribution system (CBP 2005-001/02, 2005). Lastly, its production allows obtaining another by-product (hydrogen) ready for sale as well.

Despite these positive aspects, studies considering RDF applications in the context of a polygeneration DHC system including gasification could not be found in the literature. Moreover, the prospect to produce the selected value-added products assortment in DHC systems was not investigated thoroughly.

To evaluate the RDF energy potential recovery, a DHC system located in a residential area of Lisboa, Portugal, was selected for