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Optimal coupling of a biomass based polygeneration system with a concentrated solar power facility for the constant production of electricity over a year

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ABSTRACT

In this paper we address the integration of a polygeneration system based on biomass with a concentrated solar power facility for the constant production of electricity over a year long. The process is modelled as a superstructure embedding two different gasification technologies, direct and indirect, and two reforming modes, partial oxidation or steam reforming followed by gas cleaning and three alternatives for the syngas use, water gas shift reactor (WGSR) to produce hydrogen, a furnace for thermal energy production and an open Brayton cycle. We couple this system with a concentrated solar plant that uses tower technology, molten salts and a regenerative Rankine cycle. The problem is formulated as a multi-period mixed-integer non linear programming problem (MINLP). The optimal integration involves the use of indirect gasification, steam reforming and a Brayton cycle to produce 340 MW of electricity at 0.073 €/kWh and 97 kt/yr of hydrogen as a credit.

1. Introduction

The transition from the current fossil-based economy into a more sustainable one faces a number of important challenges. Most of the sustainable sources of energy, namely biomass, wind and solar, present a variable availability over time which results in the fact that storage systems, supplementary sources of energy or a combination of some of them are needed to maintain the production capacity of commodities like electricity that cannot be stored. Weekman (2010) and Yuan and Chen (2012) presented overviews regarding the integration possibilities as a perspective for the future combination of different sources of energy in order to address this issue. In particular, Hertwich and Zhang (2009) focused on the concept of integrating biomass and solar for the production of third generation of biofuels following a scenario based approach using process simulation. However, in that study the variability in sun reception and operating conditions was not considered. Magnusson (2011) combined the biochemical production route for ethanol with the production of heat and power using a process simulation approach for the year long operation resulting in a maximum production of ethanol over summer time. For that the combination of biomass with solar energy is becoming a reality at the level of pilot plant with the use of biomass to provide the energy when solar is not available (Sanz, 2012).

In this work we consider the integration between a concentrated solar plant and a polygeneration system. On the one hand we have the concentrated solar power facility. Martín and Martín (2013) evaluated the optimal production of electricity over a year long operation. The fluctuation on the electricity production from winter to summer time in a favourable allocation is important, up to 2.5 times higher during summer. Furthermore, the range in solar availability results in the fact that the system is not operating at its full capacity more than a month or two in a year. Therefore, the use of solar energy on its own is rather limited to provide energy. On the other hand, polygeneration (Gao, Jin, Liu, & Zheng, 2004; Liu, Gerogiorgis, & Pistikopoulos, 2007; Liu, Pistikopoulos, & Li, 2009; Baliban, Elia, Weekman, & Floudas, 2012; Ghanbari, Saxen, & Grossmann, 2013; Baliban et al., 2013a, 2013b) allows the use of different raw materials, fossil and renewables including biomasss, capable of simultaneously producing electricity and chemicals. The basic building block is syngas, a mixture of CO and hydrogen that can be used for the production of methanol, ethanol, dimethyl ether (DME), Fischer–Tropsch (FT) liquids and hydrogen. For a sustainable production we focus on biomass as a source of energy and chemicals. Thus, the polygeneration system consists of biomass gasification, followed by gas clean up to remove hydrocarbons, solids, NH_3 and H_2S, similar to thermal production of bioethanol or FT fuels (Martín & Grossmann, 2011a, 2011b). Next, syngas is used to produce chemicals, thermal energy and/or electricity.

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Nomenclature

C_i	cost €/kg of species *i*
$fc(i)$	flow of component *i* (kg/s)
k_p	equilibrium constant
n_i	flow of component *i* (kmol/s)
P_i	partial pressure of species i (Pa)
Q	thermal energy (kW)
T	temperature (K) unless otherwise specified
X	ratio of moles of oxygen fed to the gasifier and the moles of carbon in the biomass
Y	ratio of moles of steam fed to the gasifier and the moles of carbon in the biomass
W	electrical energy (kW)
Z	objective function (€/s)

Units

Compress	compressor
Expan	turbine
Furnace	furnace
HX	heat exchanger
MS	molecular sieve
Spl	splitter
Src	source
Snk	sink

Subindexes

C	carbon
CO	carbon monoxide
CO_2	carbon dioxide
H_2	hydrogen
H_2O	water
Steam	Steam
Electr	electricity

The aim is to optimize the topology and the operating conditions for the minimum production cost to conceptually design a hybrid facility for the constant production of electricity over a year long and chemicals, hydrogen. To improve the design and energy efficiency of the integration of solar energy and biomass mathematical optimization techniques can be used (Grossmann, Caballero, & Yeomans, 1999). We propose a conceptual design based on the optimization of a superstructure embedding the various process units involving biomass gasification and syngas purification considering alternatives for some of the steps in the process to evaluate the trade-offs related to thermal energy vs. direct electricity production. The optimization of the superstructure is formulated as an MINLP problem, where the model involves a set of constraints representing mass and energy balances, design equations, chemical equilibrium, rules of thumb, etc. for all the units in the system. A sensitivity study and an economic evaluation are performed to determine the effect of the chemicals and raw materials costs on the design selection and on the production cost of the optimal conceptual design.

The paper is organized as follows. Section 2 describes the natural resources considered, biomass and solar energy, and the process. Section 3 presents the main modelling features of the different units. Section 4 discusses the solution procedure for this multiperiod MINLP problem. Finally, Section 5 presents the results, including a sensitivity study on the topology selection, the plant operation ending with an economic evaluation for estimating the electricity production cost.

2. Overall process description

2.1. Biomass and solar energy resources

In a previous work, Martín and Martín (2013) evaluated the operation of a concentrated solar plant located in Almería, Spain. The location was selected based on the high solar radiation available, as it can be seen in Fig. 1 (Sancho Ávila et al., 2013). We consider the same location for the hybrid facility that couples the concentrated solar plant with the biomass-based facility. In terms of the availability of lignocellulosic energy crops, Fig. 1 also presents the distribution of the yield of miscanthus as representative for lignocellulosic energy crops potential across Spain (http://www.usf.unikassel.de). Another source of biomass that can be considered is forest residues that are also available in the region (Gómez, Rodriguez, Montañés, Dopazo, & Fueyo, 2010). With the information and the design of the solar plant evaluated in Martín and Martín (2013), we can certify the availability of biomass for the operation of a combined facility sun-biomass to electricity and chemicals with a similar capacity of a typical group in a coal-based thermal plant, around 340 MW of electricity.

2.2. Process description

We divide this section in two to describe the biomass-based polygeneration system and the concentrated solar facility.

2.2.1. Polygeneration systems

Fig. 2 shows the superstructure proposed for the polygeneration system. The biomass is first preprocessed to eliminate solids and water. Later, gasification produces raw syngas from the biomass, considering the composition as that of switchgrass. Gasification can be atmospheric or pressurized, direct or indirect, resulting in very different gas compositions.

The Renugas gasifier, pressurized direct oxygen fired gasifier, produces a gas rich in CO_2, while the fraction of CH_4 can be further reformed to hydrogen. Gasification at high pressure allows large throughput per reactor volume, and reduces the need for pressurization downstream, so that less overall power is needed. However, the gasifier efficiency is lower and more steam is needed. Furthermore, the Renugas gasifier requires pure oxygen to reduce the equipment size, not to affect the catalysts downstream as well as to avoid diluting the syngas. The low pressure gasifier, Battelle Columbus (Ferco), is indirectly heated so that it is possible to use air to combust the char since two units, a combustor and a gasifier, are used. The gasifier produces a gas with low CO_2 content, but contains heavier hydrocarbons. The reactor is fast fluidized, allowing throughputs equal to the bubbling fluidized Renugas gasifier despite the nearly atmospheric operation (Phillips et al., 2007). Working at lower pressure decreases the operating cost.

The next step is syngas reforming to remove hydrocarbons. We consider either steam reforming, which is endothermic but generates higher yield to hydrogen, or partial oxidation, that is exothermic but whose yield to hydrogen is lower (Rand & Dell, 2008; Hamelinck & Faaij, 2002). Autoreforming or CO_2 reforming are not considered in this work.

Subsequently, the gas must be cleaned. We consider either cold or hot cleaning. Cold cleaning uses a water scrubber to remove solids and NH_3. Alternatively, hot gas cleaning uses ceramic filters at high temperature. In the case of high pressure operation the hot cleaning is selected, while for low pressure the cold cleaning process is considered. Finally, a multibed PSA system is used to remove the last traces of hydrocarbons, H_2S and CO_2 in that order.

Once the syngas is purified, we consider three alternatives. On the one hand, we can use a water gas shift reaction to produce hydrogen such as in Martín and Grossmann (2011c). The second

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