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Co-Production of Electricity and Hydrogen from Coal and Biomass Gasification

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This work addresses the techno-economic and environmental analysis of an Integrated Gasification Combined Cycle power plant (IGCC) of 308 MW_e of gross power, giving particular attention to co-gasification and co-production of electricity and H_2. Products, sub-products and effluents distributions are estimated by means of an ad-hoc developed superstructure for conceptual design of syngas generation and treatment, delivering preliminary flowsheets targeted to co-production. The resulting multi-objective optimization problem evaluates the trade-off between the cost of energy (COE), the total energy efficiency of the plant and the environmental impact evaluated through Impact 2002+ indicator. Sixteen scenarios are considered: 4 different feedstock's combined with 4 alternative plant topologies; electricity generation from syngas, electricity generation from H_2, and purified H_2 production from flue gas in a Pressure Swing Adsorption (PSA) unit in the Combined Cycle (CC). The case studies environmental boundary has been drawn from cradle to gate. The Pareto Frontiers (PF) for the Key Performance Indicators (KPIs) trade-off evaluation reveals that the scenario with petcoke as feedstock and H_2 production with PSA flue gas profit is the best one in terms of efficiency maximization and COE minimization. Scenario with residual biomass without PSA flue gas profit is the best in terms of environmental impact.

1. Introduction

Regarding the construction of a gasification plant as an investment project which has to be environmental friendly, it is necessary to ascertain where the trade-offs of this type of plant lay, and which would be the optimal solution to be materialized in a working project. The optimal combination of gasification with the downstream cleaning train is a main design challenge. Several works have already tried to measure the global performance of this type of plants. For instance, the work by Chiesa et al. (2005) considers the production of H_2 and electricity from coal. They evaluate different scenarios, considering CO_2 venting or CO_2 capture; electricity production from syngas and H_2, and with or without steam cycle, and pure H_2 production. The authors propose different analyses considering performance and emissions through simulation. In the economic analysis performed by Kreutz et al. (2005), it is interesting to appreciate that the barriers found for a wide H_2 economy are a lack of both, cost effective storage and large interested market. Also the CO_2 storage capacity and CO_2 transportation have to be addressed in an efficient way to promote such solution. Inayat at al. (2010)

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investigate the operation of a gasifier working with 100% biomass and steam as gasifying agent to optimize the production of H_2. Carbon Capture and Storage (CCS) processes aim at liquefying the CO_2 stream before its release, with the subsequent storage. Such a technology in power plants decreases the global efficiency due to the extra energy requirement. CCS in a gasification plant integrated with a combined cycle (IGCC) is an alternative to diminish global CO_2 emissions. Implementing the CCS train of units leads to the possibility of co-production of H_2 and electricity. In this work, an IGCC power plant model with CCS technology has been developed in Aspen Plus to evaluate co-gasification matched with co-production. The trade-off between the selected criteria has been evaluated by means of Pareto Frontiers (PF).

2. Gasification plant: an integrated approach

The integrated gasification superstructure developed is shown in Figure 1. This diagram includes every possible unit configuration from pre-treatment of raw materials to final product use. Raw materials can be of different origins, and biomass pre-treatment options contemplate energy and matter densification. Feedstock size adaptation is needed to accommodate the raw material structure to the chosen gasification technology. The syngas from the gasifier should be cooled down before cleaning. However, the so-called hot gas cleaning options do not require syngas cooling. Finally syngas usage contemplates electricity, H_2, chemicals, liquid fuels, synthetic natural gas and/or heat generation. Regarding Figure 1, among all the possibilities that the gasification plant offers, in this specific work: *Dashed lines* show the design choices considered: raw material share and syngas use selection. This last point involves topological changes represented by feeding the syngas to the CC or the CCS train, considering in this second case the possibility of pure H_2 production to be used in the Gas Turbine (GT) or to be sold on the market after further purification. *Bold lines* identify the units modeled in Aspen Plus. The raw material that enters the system is firstly dried and crushed. The obtained feedstock dust is transformed into syngas in a Pressurized Entrained Flow (PRENFLO) gasifier. Before entering the gas purification step and after quench gas cooling, syngas is further cooled down in a Waste Heat Boiler (WHB) that allows for heat profit in the Steam Turbine (ST) cycle. Syngas is cleaned by removing solids, basic and acid trace components; and liquid sulfur is obtained as a byproduct. The units used are a ceramic filter, then a venturi scrubber (consequently water used is required to be cleaned in a sour water stripper). Acid species removal concerns a COS hydrolysis reactor, followed by a MDEA absorber and a Claus plant for sulfur recovery. The clean gas is finally sent to a CC. Firstly, the syngas power is used in a GT cycle. The flue gas is cooled down before its release in a Heat Recovery Steam Generator (HRSG) which benefits from the heat in the ST cycle. If the syngas is sent to the carbon capture technology, a WGS reactor, a Rectisol process and a Pressure Swing Adsorption (PSA) process are of concern. Modeling and validation strategies are further explained in Pérez-Fortes et al., (2009). *Dotted lines* indicate the main integration flows: oxygen consumption, N_2 use and steam network. The oxygen that is required by the gasifier comes from the Air Separation Unit (ASU), which is fed by a flow of air that is firstly compressed in the GT system. After the ASU process, two N_2 streams are obtained: one with relatively pure N_2 and the other called waste nitrogen. The first one can be used in the feeding system to transport and pressurize the feedstock dust, as well act as a temperature moderator in the gasifier. The second one is usually used in the GT combustor to control NO_x formation. Finally, a net consumption of steam is usually counted for the gasifier, for the venturi scrubber and for the GT combustor. These consumptions are met using portions of the produced steam in the plant within the ST cycle. Moreover, heat from the gas cooling is profited to produce steam in the CC, through the WHB and the HRSG.

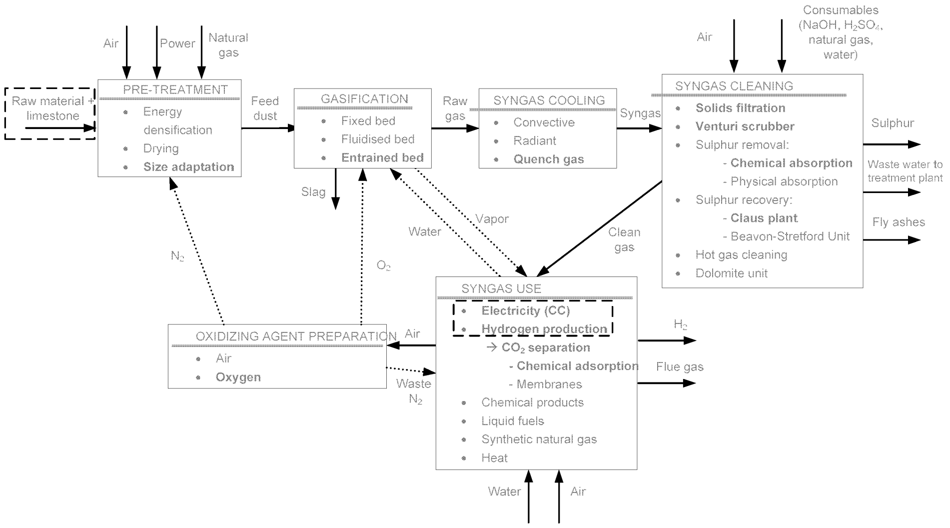

Figure 1: Gasification plant superstructure: dashed lines indicate the options considered. The modeled flowsheet is in bold. Integration flowrates are in dotted lines.

3. Key performance indicators (KPIs)

KPI is the name given to the metrics used for optimization. The metrics considered here include economical, plant performance and environmental indicators. For the first KPI, the COE is of concern, while the efficiency in terms of energy is considered for plant performance measurement. The environmental point of view is valued through a Life Cycle Assessment (LCA) based metric. The COE is defined as the energy price (in terms of electricity combined with H_2 production) that should be used to pay back the power plant investment during the estimated project life span. The investment calculation methodology follows the work of Hamelinck and Faaij (2002) and van Vliet et al. (2009). The total co-production energy efficiency calculation takes into account both electricity and H_2 production, considering the net power produced, and the raw materials Lower Heating Value (LHV), and the mass flow of the H_2 and feedstock streams. For the environmental metric, this work follows the methodology detailed in Bojarski et al. (2009). For each environmental intervention from each case study, Impact 2002+ evaluation (in pts) is considered.

4. Results

Co-gasification and co-production share election is based on multi-objective optimization through scenarios. The simulated scenarios use the following naming convention: C_{ij}, where the *i*-th value represents the fuel used: 1 coal/petcoke blend, 2 coal, 3 petcoke and 4 residual biomass (olive pomace in this case); and *j* represents the different topological options (thus, the final product). The topological changes considered are: in *option 1*, all syngas produced is sent to CC for electricity production. In *option 2*, all syngas is sent to produce H_2 which is burnt at a CC. In *option 3*, all syngas is sent to produce H_2, further purified and delivered to market. *Option 4* is the same than option 3, with the difference that PSA purge gas is sent to the CC. Therefore, for instance C_{34}, corresponds to a scenario that gasifies petcoke and all syngas is sent to produce purified H_2. Sixteen scenarios are simulated performing all possible combination options between inputs and outputs. Each one of the scenarios is analyzed using the KPIs described in section 3. The development of Pareto Frontiers (PF) is the methodology elected here to help in the decision-making task. This action allows for focusing on a lower number of scenarios from where a decision can be made. In the case of COE two considerations were done (a) one where the feedstock input is fixed disregarding the amount of power produced, while in the second case (b) the feedstock amount is modified to attain a certain amount of total power produced. Given that there is no coincidence between the selected best scenarios for each metric, a given decision rule has to be applied. One possibility is to apply a multicriteria decision-making assessment (MCDA) method: Technique for Order by Similarity to Ideal Solution (TOPSIS). This technique uses the euclidean distances from each scenario to the "*utopian*" and "*nadir*" solutions to select better solutions; two possibilities can be selected: the solution from the PF which is closest to the utopian point or the one farthest from the nadir point. Please note that the utopian and nadir points are defined considering the values of the solutions only pertaining to the PF. Regarding the utopian solution it would be formed by a hypothetical scenario that would achieve the best possible value for all criteria considered. The analysis of efficient solutions in terms of efficiency and environmental impact can be seen in Figure 2. Circles show dominated scenarios, dots show dominating solutions, stars denote utopian and nadir points. The cross shows scenarios farthest from nadir and the big circle shows scenarios closest to utopian point (the same convention is maintained in Figures 3 and 4). The Pareto front for the case of efficiency and environmental impact considers scenarios: C_{43}, C_{44}, C_{14} and C_{34}, clearly showing that from these points of view option 4 for blends, petcoke and biomass dominates all other scenarios. The closest scenario to utopian point is C_{44}, while the farthest from nadir is C_{43}, showing that biomass is the fuel to use when considering these two objectives. In the case of efficiency and COE, two Pareto analyses can be performed; one considering each COE, shown in Figure 3. In this case, scenario C_{34} dominates all others showing that petcoke use for producing H_2 if the most efficient and more profitable in terms of COE. In the case of comparing COE and environmental impact, the tradeoffs are shown in Figure 4. The Pareto front scenarios: C_{43}, C_{44}, C_{14} and C_{34}, which coincides with the one found for the case of efficiency and environmental impact. Note that in the case of the calculation of COE based on the same amount of energy scenario C_{44} is not included in the PF. In both cases the solution that TOPSIS selects is C_{43}, which is closest to utopian point and also is farthest from nadir.

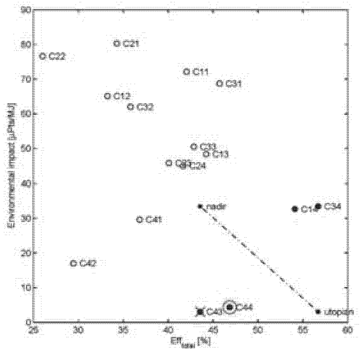

Figure 2: PF considering efficiency and environmental impact.

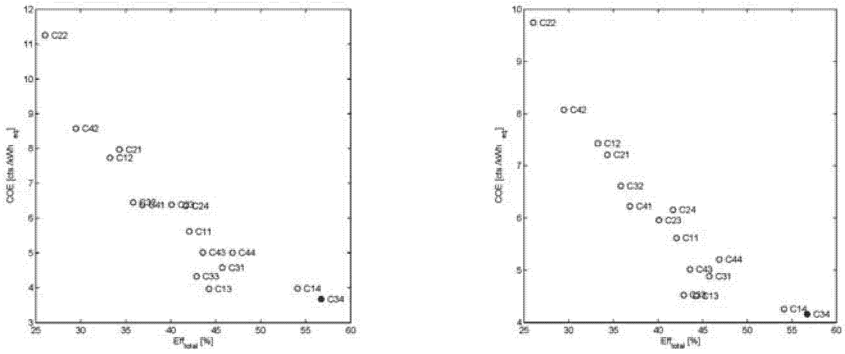

Figure 3: PF considering the efficiency and COE. Left figure shows COE based on fixed feedstock input, while right shows COE based on fixed amount of energy.

5. Conclusion

A gasification plant superstructure has been developed in Aspen Plus. Sixteen scenarios are considered encompassing four different feedstocks' combined with four different plant topologies encompassing electricity and H_2 generation. This work discusses the selection of processing options in terms of techno-economic and environmental metrics. The approach used considers all objectives to be equally important, but this can be easily modified if different tradeoffs are required and if other MCDA techniques are suited. The PF for the KPIs trade-off evaluation reveals that the scenario with petcoke as feedstock and H_2 production with PSA flue gas profit is the best one in terms of efficiency maximization and COE minimization. Scenario with residual biomass without PSA flue gas profit is the best in terms of environmental impact.

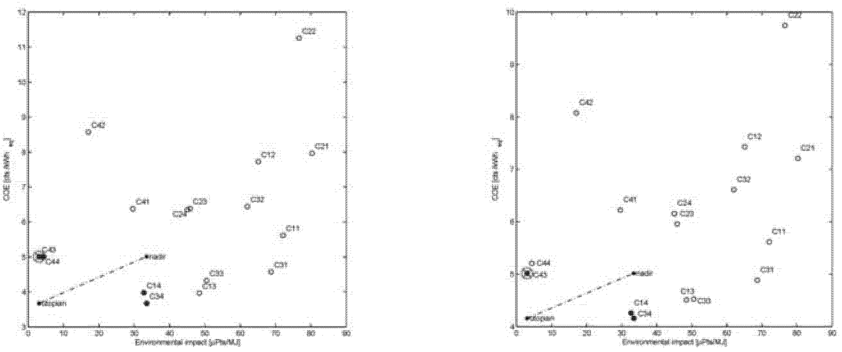

Figure 4: PF considering environmental impact and COE. Left figure shows COE based on fixed feedstock input, while right shows COE based on fixed amount of energy.

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