ENHANCING THE LIFE-CYCLE ENVIRONMENTAL PERFORMANCE OF AN ENERGY SYSTEM FOR THE COPRODUCTION OF SYNTHETIC BIOFUELS AND ELECTRICITY

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ABSTRACT

Fischer-Tropsch (FT) synthesis coupled with combined-cycle strategies could be a sustainable pathway for biofuel and power generation. The present work deals with the life cycle assessment of four alternative FT-based systems to identify the best option in terms of global warming and cumulative energy demand. All systems involve poplar biomass gasification, biosyngas conditioning, Fischer-Tropsch synthesis, refining, and power generation. Different configurations are defined by taking into account further electricity production using clean syngas or further processing of the FT tail gas via autothermal reforming (ATR) or membrane separation. Key inventory data are provided through process simulation. The ATR system potentially arises as the most favorable option. The products from this system show significant benefits when compared to equivalent conventional products.

INTRODUCTION

The shortage of fossil fuels and the growing energy demand have led to increasing energy prices. This situation, along with environmental concerns (e.g., global warming), has motivated the search for energy systems which result in a clean and sustainable energy sector.

The Fischer-Tropsch (FT) synthesis is a well-known chemical process for the production of liquid hydrocarbons from syngas. There is a growing interest in this process as it could be a sustainable pathway for biofuel generation, having the potential of being coupled with combined-cycle strategies to coproduce electricity from renewable resources (Iribarren et al., 2013). Since multiple FT-based configurations are possible, the present work uses the life cycle assessment (LCA) methodology to evaluate the global warming impact and the cumulative energy demand of a set of relevant alternatives.

METHODS

The goal of this study is to evaluate and contrast the life-cycle global warming and energy performance of four alternative FT-based systems for the coproduction of synthetic biofuels and electricity. The functional unit (FU) for the LCA of each system was defined as 1,000 t of wet biomass to be processed in the FT plant. All systems cover from biomass cultivation to the supply of the products at plant (cradle-to-gate approach). Hybrid poplar (50% moisture) was selected as the biomass feedstock since it is a short-rotation plantation, i.e. it can be grown with little input and in relatively small areas (Gasol et al., 2009).

Figure 1 shows a simplified diagram of the four FT-based systems under evaluation. For all these systems, the common processes that take place in the FT plant include biomass pretreatment, syngas production via poplar biomass gasification, biosyngas conditioning, hydrocarbon production through FT synthesis, refining, and power generation. The present work considers a base case for the coproduction of synthetic biofuels and electricity, as well as three potential modifications of this base case that define three alternative systems.

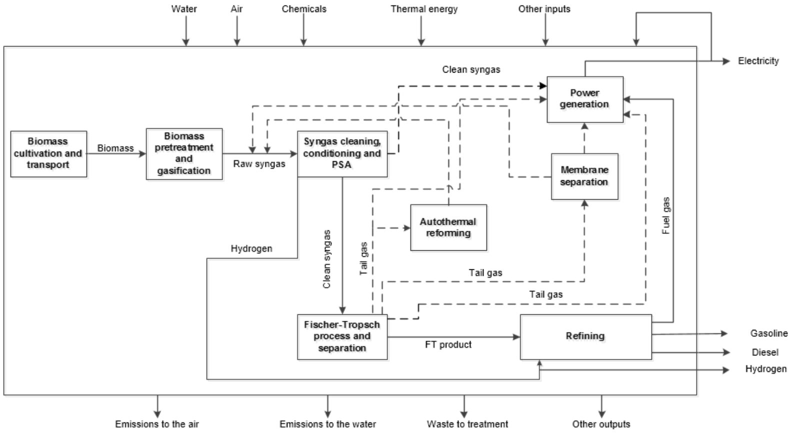

Figure 1. Simplified diagram of the four FT-based systems. Dotted arrows represent flows that are not common for all systems.

The base case study is herein detailed, as it is the basis for the definition of the remaining systems. In the plant, the poplar feedstock is milled and dried before entering the low-pressure indirect gasifier, in which raw biosyngas is generated. The produced syngas undergoes conditioning, which includes tar reforming, scrubbing, acid gas removal through absorption with amines, and a LO-CAT® process (Spath et al., 2005; Susmozas et al., 2013). Clean biosyngas presents an H_2/CO molar ratio of 2.5. Since the FT reaction needs an H_2/CO molar ratio of approximately 2, a small amount of H_2 is separated in a pressure swing adsorption (PSA) unit with 85% efficiency before entering the FT reactor. Part of the separated H_2 is used in the refining area. The syngas stream is fed to the FT reactor, in which CO and H_2 react to produce a hydrocarbon mixture. An FT slurry reactor with 80% CO conversion was considered. This reactor uses a Co catalyst and operates at 200 ºC and 25 bar. At the exit of the FT reactor, two streams are obtained: wax (C_{20+}) and a stream made up of C_1-C_{20} hydrocarbons and unconverted syngas. The latter is cooled down in order to separate the tail gas (C_1-C_4 and unconverted syngas) from the C_{5+} fraction. The C_{5+} stream is then processed in the refining area along with the wax stream, producing diesel, gasoline, and fuel gas (C_1-C_4). The tail gas and the fuel gas are used in the power generation section, which consists of a combined cycle with a gas turbine and a steam turbine with three pressure levels (87/31/2.4 bar). This combined cycle makes the plant energetically self-sufficient (Liu et al., 2011).

The remaining three systems under examination are similar to the “base case”, but they take into account relevant modifications in its configuration. The “syngas power case” considers that part of the conditioned syngas (20%) is sent directly to power generation in order to increase the electricity output. In the “ATR case”, part of the produced tail gas (30%) undergoes autothermal reforming (ATR) so that hydrocarbons react with O_2 and steam producing syngas (Zahedi Nezhad et al., 2009), which (after being conditioned) is recycled to the FT rector in order to increase the fuel output. Finally, in the “membrane case”, the produced tail gas undergoes membrane separation, thus obtaining a hydrogen-rich stream (90 vol% purity) suitable for the FT process (after conditioning) and a hydrocarbon-rich stream which is fed to the power generation section.

Key inventory data for the operations carried out in the FT plants were obtained through process simulation in Aspen Plus®. The poplar feedstock was defined as a non-conventional component by specifying its proximate and ultimate analyses. The gasification section was modeled according to Susmozas et al. (2013). The product from the FT reactor was assumed to consist only of paraffins. The refining area was simulated based on literature data (Swanson et al., 2010; Iribarren et al., 2013). Inventory data for background processes were taken from the ecoinvent database, while data for poplar cultivation were based on Gasol et al. (2009).

RESULTS

The global warming impact potential (GWP) and the cumulative non-renewable (fossil and nuclear) energy demand (CED) of each FT-based system were calculated. Table 1 presents the GWP results and the life-cycle energy balances (estimated as the difference between the potential energy output and the CED indicator) of the evaluated systems. Based on these results, the ATR and membrane cases were found to be the best configurations. In particular, the ATR case study was selected as best option since it represents a more well-established configuration with reduced GWP.

Table 1. GWP and life-cycle energy balance of each case study (values per FU)

	Base case	**Syngas power case**	**ATR case**	**Membrane case**
GWP (kg CO_2 eq)	70,327.25	93,980.93	14,703.73	17,237.54
Energy balance (MJ)	2,078,126.77	1,697,408.83	2,195,995.74	2,427,665.64

DISCUSSION

The GWP and CED indicators of the energy products from the best-performing system (i.e., the “ATR case”) were compared with those of their conventional equivalent products: fossil gasoline, fossil diesel, grid electricity, and steam-methane-reforming hydrogen (Dones et al., 2007; Susmozas et al., 2013). As can be observed in Figure 2, energy products from the FT system were found to involve much more favorable results.

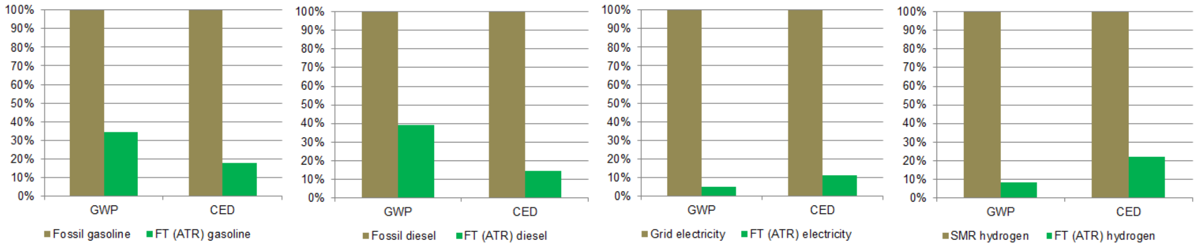

Figure 2. GWP and CED results of FT products (based on the ATR case study) relative to their conventional equivalent products

CONCLUSIONS

FT-based systems proved to have the potential of supplying energy products with a promising life-cycle performance in terms of global warming and energy balance. Therefore, fuels and electricity from this type of bioenergy systems could contribute favorably to the future energy sector.

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