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Selection of Fuel Cell Combined Cycles for Cost-Effective Reduction of Carbon Emissions: P-Graph

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To increase the efficiency of energy conversion, building on the concept of the traditional combined cycle, fuel cells are currently under extensive investigation due to the higher efficiencies they offer. Two kinds of High-Temperature Fuel Cells (HTFC) have been identified as best candidates for Fuel Cell Combined Cycles (FCCC) – Molten Carbonate Fuel Cells (MCFC) and Solid Oxide Fuel Cells (SOFC) due to the possibility to integrate them with bottoming power cycles. The paper presents a procedure for the evaluation of energy conversion systems involving FCCC subsystems, which utilise biomass in competition/combination with fossil fuels. This features significant combinatorial complexity due to the many possible device combinations and processing paths. They can be efficiently handled by the P-graph methodology (Friedler et al., 1995) which is successfully applied for the optimal choice of FCCC. Several promising system components as MCFC, SOFC, steam turbines (ST) and gas turbines (GT) are evaluated using the P-Graph framework and a methodology for the synthesis of cost-optimal FCCC configurations is developed. The results show that such systems can be economically viable for wide range of economic conditions.

1. Introduction

The continuously increasing world demand for energy results in Greenhouse Gas Emissions (GHG) escalation. The current state-of-the-art covers mainly the traditional combined cycles (GTCC, IGCC) with efficiencies around 55-60%, employing only heat-based engines such as GT and ST. To increase the efficiency, new technologies have to be applied and HTFC are potentially part of them because of their inherently high electrical efficiency. Present results on integrating HTFC with ST and GT indicate possibility to achieve both high efficiencies (Massardo and Bosio, 2002) and economic viability (Varbanov et al., 2006). The use of biomass-derived fuels offers reduction of the CO_2 emissions. Biomass can be utilised in two main ways by FCCC systems – oxygen-deficient gasification and biogas digestion. Both routes have their advantages and limitations, varying between different regions. Reducing significantly the CO_2 emissions at reasonable cost levels is a priority. New technologies such as FCCC are expensive to develop and resources should be economised. The presented novel tool for optimising the performance and economy of FCCC systems is a step in this direction.

Systems for FCCC-based CHP and biomass processing are complex to model. They present a large number of alternative routes, introducing an additional layer of combinatorial complexity. An initial approach for solving these problems employed Mathematical Programming (MP). It represents the selection of the operating units by integer variables. For larger size problems it becomes exponentially difficult:

- The size of the algebraic optimisation problems grows, where the solver needs to examine clearly infeasible combinations of integer variable values.
- The huge number of operating unit options makes it rather difficult to build the necessary problem superstructures heuristically and even automatically.
- When a superstructure is created heuristically, certain low-cost options would be missed together with the opportunities for optimal solutions.

For handling process synthesis problems of a practical complexity the Process Network Synthesis methodology based on the P-Graph (Process Graph) could be applied. This is the core of the suggested novel methodology. P-Graph is a rigorous mathematical tool for unambiguous representation of processing networks. The combinatorial instruments associated with it – the axioms ensuring representation unambiguity (Friedler et al., 1992), the algorithms generating the maximal network structure (Friedler et al., 1993) and for generation of all possible solution structures (Friedler et al., 1995), have several important properties making the approach superior to MP in solving network/process synthesis problems:

- It is algorithmic, meaning it is capable of performing the task of superstructure construction automatically, following the rules and options specified by the operators. This helps in minimising subjectivity during synthesis.
- It skips infeasible combinations of process units
- P-graph PNS drastically reduces the combinatorial search space and is orders of magnitude more efficient than pure mathematical programming (Friedler et al., 1996).

The presented evaluation procedure identifies FCCC systems and conditions favourable for CO_2 reduction. The objective function is Total Annualised Cost.

2. Efficiency of FC and combined cycles

FCCC system efficiencies vary with the FC operating temperature, the type of the bottoming cycle and with the degree of cycles integration (Varbanov et al., 2007). HTFCs can be combined with different turbines - FC+GT and FC+ST or both: FC+GT+ST. The last combination results in only marginal improvements. Regarding the FC+GT option, the GT can be directly integrated (very efficient, cheaper to build, less flexibility) or indirectly heated (more flexible, high-cost indirect heat exchanger). The procedure for evaluating FCCC + biofuel systems needs to distinguish between the main options trading-off electrical efficiency vs. capital costs.

3. Process representation with P-graph

P-graph is a directed bipartite graph, having two types of vertices – one for operating units and another for the objects representing material or energy flows/quantities, which are connected by directed arcs (Friedler et al., 1992, Nagy et al., 2001). Operating units and process streams are modelled by separate sets (***O*** and ***M*** respectively) and the arcs are expressed as ordered pairs. E.g., if an operation $o_1 \in O$ consumes material $m_1 \in M$, then the arc representing this relationship is (m_1, o_1). Fig 1 illustrates the FCCC system representation using conventional block-style diagram and P-graph fragment.

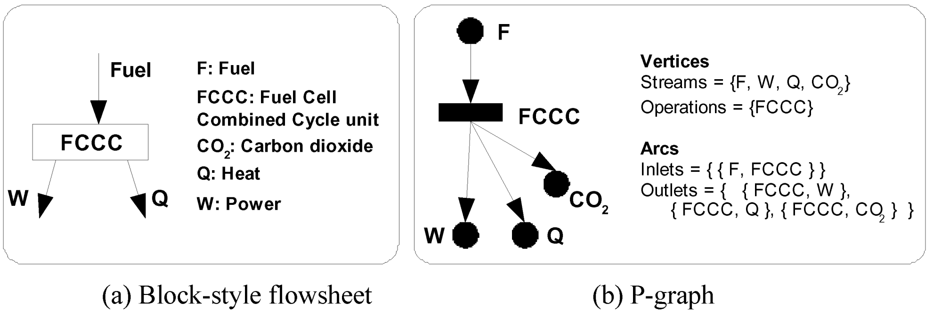

Fig 1. FCCC representations

4. Context definition: balance between biomass and fossil fuels

4.1. Utilisation of dedicated and waste-stream biomass

The renewable energy production competes for primary resources with food production. Food and other industries need to manage large volumes of organic solid and liquid waste – e.g. manure, vegetable residues, black liquor, etc. FCCC systems can be integrated into combined energy-food-waste supply chains with other processes, (Beamon, 1999). The benefit for FC-based systems can come from:

- Cost sharing between the biofuel and the other biomass-based products;
- In selected cases waste streams can be used as fuel raw materials which cannot be released directly into the environment. Using them for FC fuel generation would result in negative fuel prices due to the fees to be charged for the waste treatment.

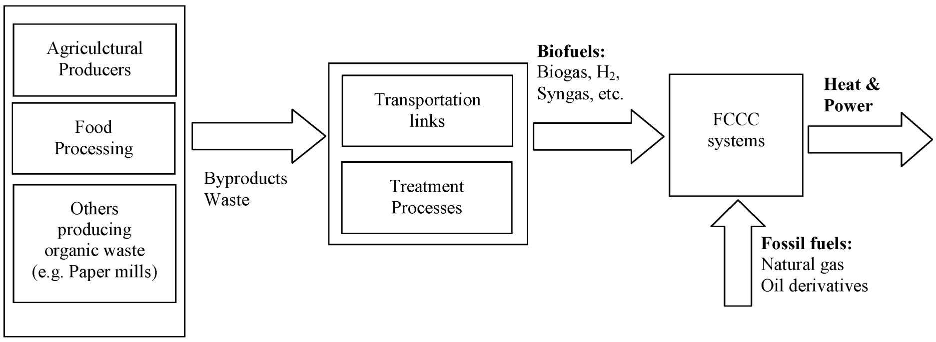

Fig 2. Combining different sources for energy generation

4.2. Options defined: fossil fuels and biomass

Although biomass is nominally carbon-neutral its harvesting and transportation contribute to the carbon footprint (Bulatov et al., 2007). But compared with fossil fuels, biomass is a promising options to reduce CO_2 emissions. It is generally needed to combine (Fig 2) the energy (CHP) generation with the production of other commodities (mostly food) as well as using primary energy sources other than biomass– some of them renewable. In the case study presented below, natural gas was a fossil fuel option for its immediate suitability for FCCC systems and as it is the least-polluting fossil fuel.

5. A Case study: FCCC/CHP, competing biomass and natural gas

5.1 Case study description

A case study is considered, with CHP generation from agricultural residues and natural gas, using a number of potential operating units for the fuel pre-processing and a number of FCCC options. It has been assumed that the residues are suitable for both gasification and anaerobic digestion. Power and heat needs have been set to 10 MW and 15 MW respectively. The energy prices are projections slightly higher than the current ones: 100 *€/MWh* for power, 30 *€/MWh* for heat and 30 *€/MWh* (~ 300 *€/(1000 m^3)*) for natural gas. The price of the fertiliser by-product from biogas digestion is assumed 50 *€/t*. Several partial cases have been explored (Tab 1). The plant life time is 10 years.

Tab 1. Cases investigated

Parameters	Case 1	Case 2	Case 3	Case 4	Case 5	Case 6
$Price_{AR}$, *€/MWh*	1	10	10	18	20	10
$Yield_{FRT}$, *t/(MWh AR)*	0.077	0.077	0.005	0.077	0.077	0.077
Profit, *MM€/y*	10.05	6.48	6.23	3.66	3.45	5.51

The fuel pre-processing units are shown in Fig 3 using P-graph notation. The FCCC options (Fig 4) reflect combinations of fuels, FC types and steam pressure levels.

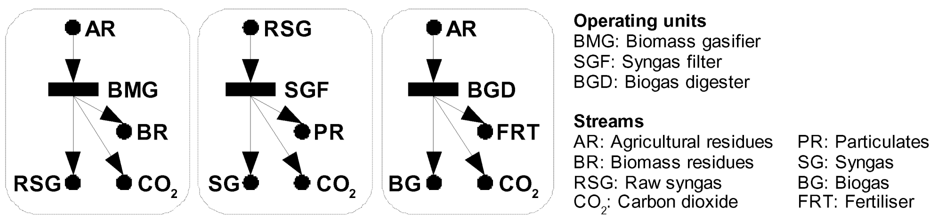

Fig 3. Fuel preparation operating units

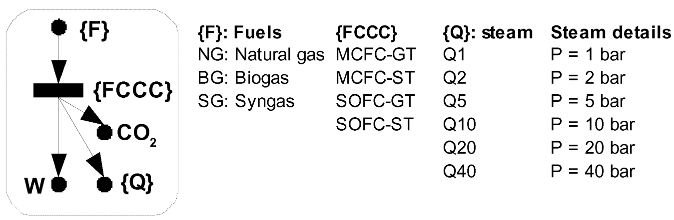

Fig 4. Definition of the FCCC options

5.2 Results and discussion

CHP networks have been synthesised for the options in Figs. 3, 4 using the P-graph algorithms developed by Friedler et al. (1992, 1993, 1995, 1996). The resulting topologies are presented in Fig 5 and the corresponding annual profit is in the last row of Tab 1. Starting from a low price of agricultural residues and gradually increasing it, the resulting energy network topology remains the same (Cases 1-2, Fig 5(a)). In Case 3, the sensitivity of the system design towards the fertiliser yield from the anaerobic biogas digester has been evaluated and have some marginal significance (see Tab 1). The main factor is the competition between natural gas and agricultural residues prices. When the estimate of the latter reaches 18 *€/MWh*, the optimal design switches to Fig 5(b). This is a hybrid between biomass utilisation and natural gas top-up. Fig 5(c) shows the complete switch to natural gas with the agricultural residues reaching 20 *€/MWh*. An availability limit 30 *MW* was imposed on the agricultural residues. The resulting flowsheet Fig 5(d) illustrates that for the particular economic conditions the biomass utilisation is so profitable that it justifies investing in two parallel gas boilers.

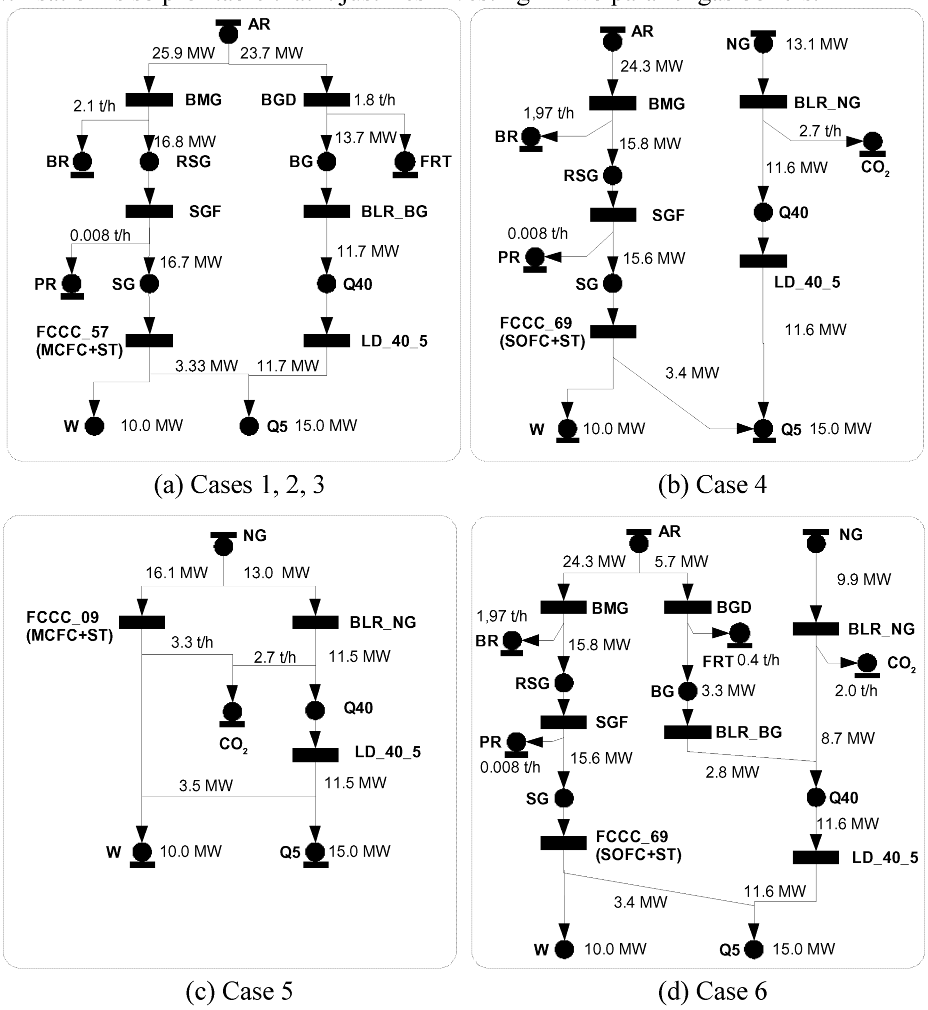

Fig 5. Resulting energy system flowsheets

6. Conclusions and future work

This contribution provides a tool based on a procedure for efficient evaluation of early-stage energy technologies, specifying a set of market conditions and then testing the resilience of the design against variations of key parameters. The task of designing a complete energy system involves significant combinatorial complexity. This cannot be efficiently handled by Integer Programming procedures. The P-graph framework and its associated algorithms are capable of efficiently handling exactly this type of complexity, inherent to network optimisation. The presented process synthesis procedure can be readily used for evaluating technologies in their early stages of development, such as FC / FCCC. The case study shows that FCCC systems can be economical over a wide range of economic conditions. The future work should concentrate on improving the integration of the unit process models with the network synthesis procedure, as well as evaluation of the dynamic and variability aspects of the concerned energy technologies and the associated biomass and fuel resources.

Acknowledgements

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