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P-graph Methodology for Cost-Effective Reduction of Carbon Emissions Involving Fuel Cell Combined Cycles

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Abstract

Fuel cells are under extensive investigation for building combined energy cycles due to the higher efficiency potential 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). The paper presents a procedure for the evaluation of energy conversion systems involving FCCC subsystems, utilising biomass and/or fossil fuels. This involves significant combinatorial complexity, efficiently handled by the P-graph algorithms. Promising system components are evaluated using the P-graph framework and a methodology for the synthesis of cost-optimal FCCC configurations is developed, accounting for the carbon footprint of the various technology and fuel options. The results show that such systems employing renewable fuels can be economically viable for wide range of economic conditions.

Keywords: CO_2 minimisation; Combined Energy Cycles, Energy Efficiency, High-Temperature Fuel Cells

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 costs is a priority. New technologies 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 to solving these problems employed Mathematical Programming (MP). It represents the selection of the operating units by integer variables. For larger size problems its application becomes increasingly 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 without rigorous combinatorial tools.
- 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 efficiently applied. This is the core of a 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 (Process Network Synthesis) drastically reduces the combinatorial search space and is orders of magnitude more efficient than pure mathematical programming (Friedler et al., 1996).

Another important issue is the realistic evaluation of the CO_2 minimisation potential. Although biomass is nominally carbon-neutral, its harvesting, transportation and emissions treatment contribute to certain small carbon footprint (Bulatov et al., 2007), which is taken into account.

The presented procedure identifies FCCC systems and conditions favourable for CO_2 reduction. The objective function is Total Annualised Cost. In this context, the carbon footprint has been explicitly defined as the amount of CO_2 emissions per unit primary resource consumed. This applies to the biomass and the fossil fuels. Finally, a tax on the released CO_2 is also considered, which defines some additional operating cost.

2. Context definition: FCCC systems

2.1. Processing steps

Various complex energy systems and supply networks are possible. This study concentrates on evaluating the viability of using biomass as a primary resource. As a result, the processing architecture shown in Figure 1 is considered. It involves first pre-processing of the biomass to produce hydrogen-containing gas. Then, with all resources available as usable fuels, the energy conversion technologies are applied to generate power and heat.

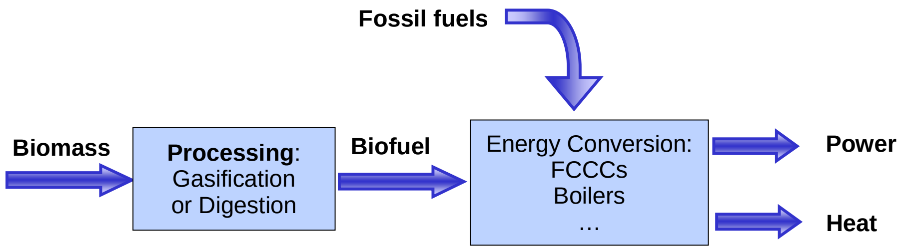


Figure 1. FCCC system boundary and processing steps

2.2. 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. The main reason is that the energy in the FC exhaust can only be shared by bottoming cycles and this energy generation potential can be almost fully utilised by ST or GT alone. Therefore, any involvement of more than one bottoming cycle cannot substantially increase the overall efficiency but rather can offer capital cost trade-offs.

Regarding the FC+GT option, the GT can be directly integrated (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.

There are several factors influencing the efficiency of the FCCC, from which the fuel cell operating temperature is the most important one. High-temperature fuel cells are net sources of waste heat at temperatures above 800 ºC. To utilise it efficiently, the cells should be the topping cycles. The choice of the bottoming cycles can be made between steam and gas turbines.

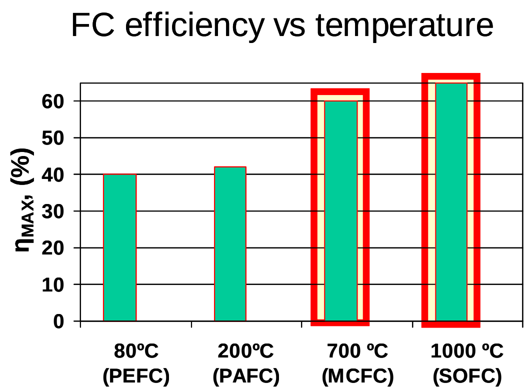


Figure 2. Variation of FC efficiency with operating temperature

There are two aspects how the fuel cell operating temperature affects the efficiency. The first is how the electrical efficiency of the cell alone varies. From the diagram in Figure 2 (Yamamoto, 2000) it is clear that the standalone efficiencies of the different fuel cell types are strongly correlated with the operating temperature, differing by more than 20% between the Proton-Exchange Fuel Cells and the Solid-Oxide Fuel Cells. The second aspect is the integration of the cell with the bottoming cycle. Higher temperatures favour higher potential for further power generation form the FC exhausts. Any drop in the temperature drastically decreases this potential.

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).

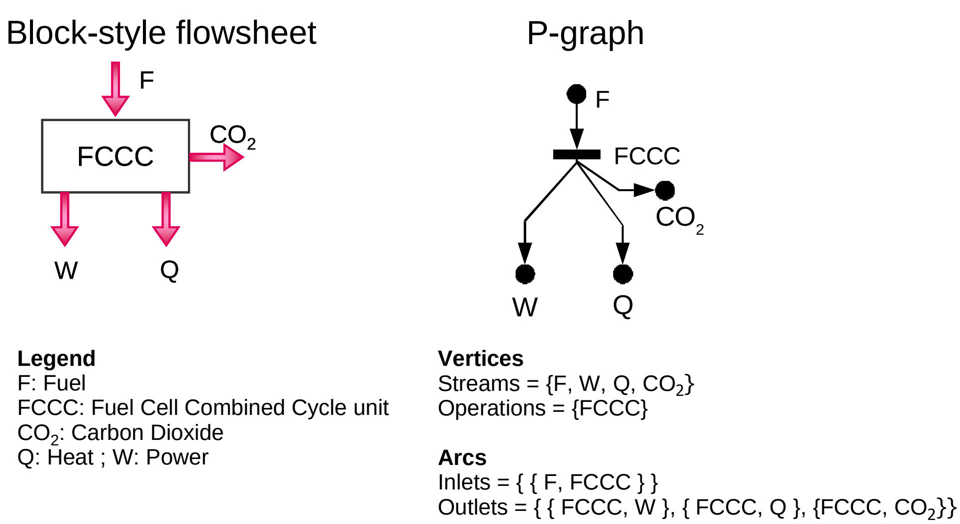


Figure 3. FCCC representations

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). Figure 3 illustrates the FCCC system representation using conventional block-style diagram and P-graph fragment.

4. Applying P-graph: small-scale heat and power using FCCC

4.1. Case study description

A case study is considered, with CHP generation from agricultural residues (AR) 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 projections are slightly higher than the current ones as the price increases are likely: 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 and the carbon tax at 40 €/(t CO_2). Five main cases have been explored (Table 1). The plant life time is 10 years. The carbon footprint of the biomass (agricultural residues) has been assumed at 0.025 t/MWh (tonnes CO_2 per MWh of material) and that for natural gas 0.2063 t/MWh. The fertilised yield in the biogas digester is taken 0.0768 t/(MWh AR).

Parameters	Case 1	Case 2	Case 3	Case 4	Case 5
$Price_{AR}$, *€/MWh*	1	10	20	23	30

Table 1.Main cases investigated

An additional case has been evaluated, derived from Case 3 in Table 1, where the availability of the agricultural residues has been limited to 30 MW (Case 6).

4.2. Modelling and synthesis procedure

In order to apply the P-graph approach, certain types of information need to be obtained, evaluated and supplied to the synthesis algorithms. This includes:

- Identification of the involved materials and streams – raw materials, products and intermediates;
- Identification of the candidate operating units – allowing more than one candidate for performing the same task;
- Specification of the units' performance – this takes the form of specifying the amounts of the outputs per unit amount of a chosen input stream;
- Identification of upper and lower bounds for units capacities, material amounts including raw materials availability;

All these steps are illustrated below with selected examples from the case study.

4.2.1. Identification of the materials and streams

This step produces the specifications for the inputs to and outputs from the system, along with those for the intermediate materials. The latter can be regarded as the "stepping stones" on the paths from the system inputs to the products. As an example, the materials/streams identified for the biomass processing stage from Figure 1 are listed in Table 2.

Material	**Type**	**P-graph classification**	**Description**
AR	Biomass	Raw material	Agricultural residues
BR	Waste / side product	Product / output	Biomass residues (solid remainder from the biomass after gasification)
RSG	Intermediate fuel	Intermediate	Raw synthesis gas
CO_2	Waste, greenhouse gas	Product / output	Carbon dioxide emissions
PR	Waste / side product	Product / output	Particulates left from cleaning the syngas
SG	Clean biofuel	Intermediate	Clean synthesis gas suitable for utilisation as a fuel
BG	Clean biofuel	Intermediate	Biogas suitable for utilisation as a fuel
FRT	Useful byproduct	Product / output	Fertiliser obtained as a by-product from the anaerobic digester

Table 2.Materials and streams for the fuel preparation (biomass processing) stage

In addition, the relevant material/stream prices and other economic information are collected and specified, providing the basis for appropriate economic evaluation of the designs.

4.2.2. Identification of the candidate operating units

This modelling step produces a set of candidate operating units, capable of transforming certain materials/streams into other ones so that the desired products can be produced from the specified raw materials through the defined intermediates. The candidate operating units can be regarded as potential bridges between the stepping stones.

In this regard, an important necessary condition for generating a feasible processing network is to find sufficient operating unit candidates so that there is at least one path connecting every product to at least one raw material. After thorough evaluations, the candidate operating units shown in Figure 4 and Figure 5 have been identified. The

{FCCC} entry in Figure 5 stands for a number of various FCCC options, reflecting combinations of fuels, FC types and steam pressure levels.

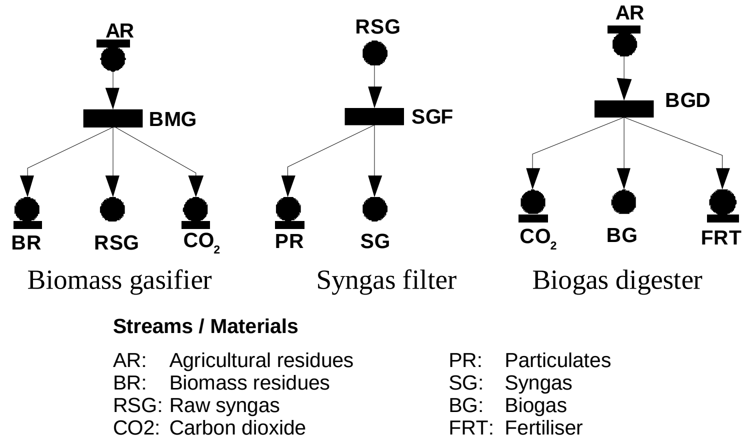


Figure 4. Fuel preparation (biomass processing) options

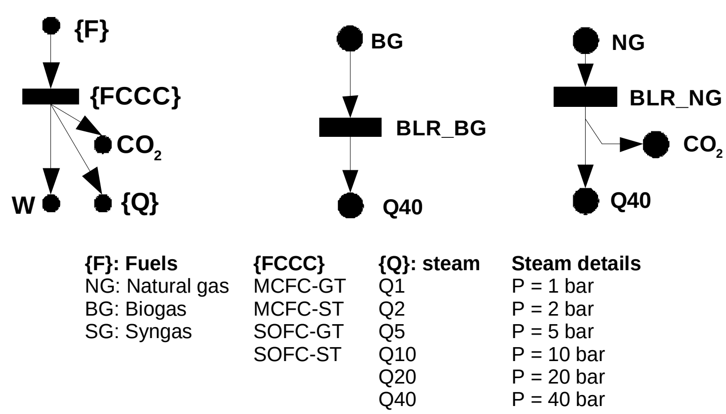


Figure 5. Energy conversion options

4.2.3. Specification of the units' performance and investment

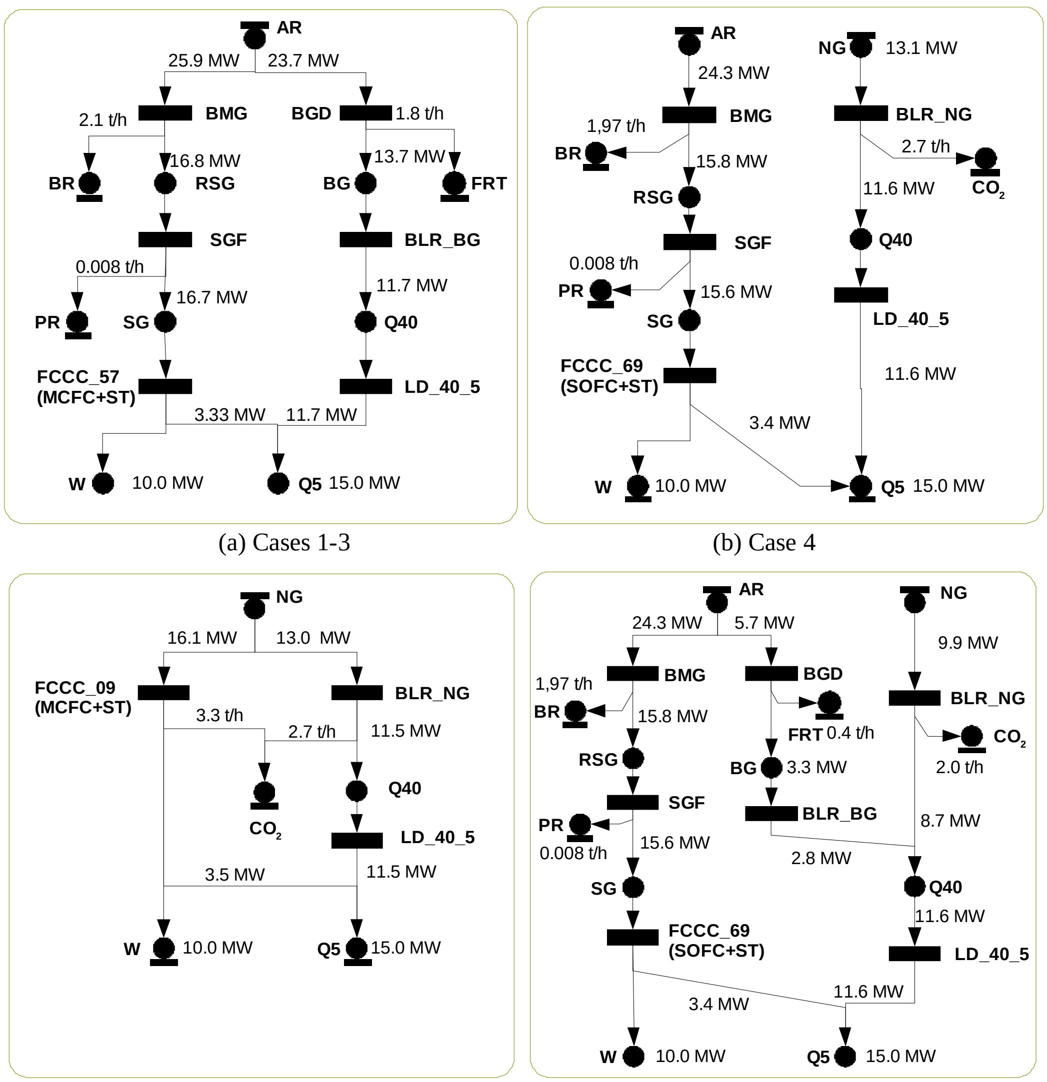
The various candidate operating units generally feature different performance and capital costs. Usually, more expensive devices and systems are more efficient in converting the inputs into outputs and generate less waste. The performance of the units takes the form of specifying the amounts of the outputs per unit amount of a chosen input stream. Other forms of specification are also possible to implement.

4.2.4. Identification of upper and lower bounds

This bit of information is also important and is used by the optimisation solver to decide which units and raw materials to be used, starting with the most efficient or profitable options. These are usually limited in terms of operating unit capacities or the availability of the respective resources.

4.3. Results and discussion

CHP networks have been synthesised for the defined options using the P-graph algorithms developed gradually by Friedler et al. (1992, 1993, 1995, 1996). The resulting topologies are presented in Figure 6 and the corresponding annual profit and CO_2 emissions are given in Figure 7.



(a) Cases 1-3 (b) Case 4

(c) Case 5 (d) Case 6

Figure 6. Resulting energy system flowsheets

Starting from a low price of agricultural residues and gradually increasing it, the resulting energy network topology remains the same (Cases 1-3, Figure 6(a)). The main factor is the competition between natural gas and agricultural residues prices. When the estimate of the latter reaches 23 €/MWh, the optimal design switches to Figure 6(b). This is a hybrid between biomass utilisation and natural gas top-up. Figure

6(c) shows the complete switch to natural gas with the agricultural residues reaching 30 €/MWh. The sixth case featuring the availability limit of 30 MW on the agricultural residues produces the flowsheet in Figure 6(d). It illustrates that for the particular economic conditions the biomass utilisation is so profitable that it justifies investing in two parallel gas boilers (Profit 2.218 MM€/y).

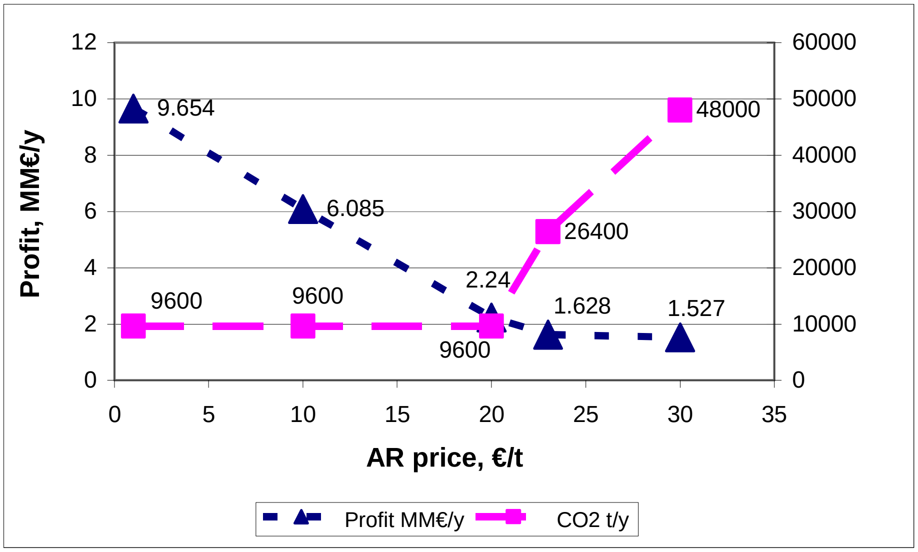


Figure 7. Profits and CO_2 emission levels

5. Conclusions and future work

This contribution provides a tool based on a procedure for efficient evaluation of early-stage energy technologies, following the approach set by the EMINENT2 project (Klemeš et al., 2007) 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 and appear to be some of the best tools for solving this task. 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. From the presented material it can be concluded that biomass can be a viable energy supply option, where the possible high efficiencies also mean smaller resource demands.

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. With regard to the scope of the studies, considering complete supply chains for energy and value-added products as well as CO_2 transport, storage and sequestration is necessary.

6. Acknowledgements

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