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, providing a tool for evaluation of the trends in CO_2 emission levels and economics of such systems. 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 a wide range of economic conditions, mainly due to the high energy efficiency of the FC-based systems.
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Keywords: P-graph; CO_2 minimisation; Process synthesis; Combined energy cycles; Energy efficiency; High-temperature fuel cell

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 gas turbines (GT) and steam turbines (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 [1] and economic viability [2]. 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 such 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, as the solver needs to examine clearly infeasible combinations of integer variable values.

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Nomenclature

Abbreviations

CHP	combined heat and power
FC	fuel cell
FCCC	fuel cell combined cycle
GHG	greenhouse gas
GT	gas turbine
GTCC	gas turbine combined cycle
HTFC	high-temperature fuel cell
IGCC	integrated gasification combined cycle
MCFC	molten carbonate fuel cell
PNS	Process network synthesis
SOFC	solid oxide fuel cell
ST	steam turbine

Notations and variables

A_{CC} fixed term for calculating capital costs, €

B_{CC} linear cost coefficient for calculating capital costs, €/MW

CC capital cost, €

$\{F\}$ a set of fuels

$\{MCFC\text{-}GT\}$ a set of FCCC systems comprising a MCFC and a GT units each. This represents many units

$\{MCFC\text{-}ST\}$ a set of FCCC systems comprising a MCFC and a ST units each

$\{Q\}$ a set of steam streams

$\{SOFC\text{-}GT\}$ a set of FCCC systems comprising a SOFC and a GT units each

$\{SOFC\text{-}ST\}$ a set of FCCC systems comprising a SOFC and a ST units each

U_{Cap} operating unit capacity, MW

- 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 could be missed together with the opportunities for optimal solutions.

For handling process synthesis problems of practical complexity the process network synthesis (PNS) methodology based on the P-graph (process graph) could be efficiently applied. P-graph is a rigorous mathematical tool for unambiguous representation of processing networks. The combinatorial instruments associated with it – the axioms and theorems ensuring representation unambiguity [3], the algorithms generating the maximal network structure [4] and for generation of all possible solution structures [5], have several important properties making the approach superior to MP in solving network/process synthesis problems:

- The P-graph framework consists of axioms, theorems and algorithms. The latter are constructed in such a way that given the sets of candidate operating units and streams/matrerials they automatically generate the corresponding problem superstructure, following the rules and options specified by the operators. This is made possible by exploiting graph theory and advanced set manipulation, and helps in minimising subjectivity during synthesis.
- Optimisation of the generated superstructures avoids the examination of infeasible combinations of binary variables representing the process units, which is achieved by applying the branch-and-bound paradigm to the strict options defined by the superstructure. In contrast, the general integer programming solvers need to exam-

ine such combinations and evaluate them against constraints specified in the optimisation formulation. This feature considerably improves the efficiency of P-graph algorithms compared with the general interger programming solvers.

- As a side effect from the previous feature, the P-graph approach to PNS drastically reduces the combinatorial search space and is orders of magnitude more efficient than pure mathematical programming [5,6].

Another important issue is the realistic evaluation of the CO_2 minimisation potential. This issue has been studied in detail by Klemeš et al. [7] and detailed economic evaluation and real process implementation has been presented by Klemeš et al. [8]. Although biomass is nominally carbon-neutral, its harvesting, transportation and processing contribute to certain small carbon footprint [9] which study was further extended by Perry et al. [10]. These developments are taken into account in the presented investigation.

The presented procedure identifies FCCC systems and conditions favourable for CO_2 reduction employing sensitivity analysis. 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 both 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 and biomass resources

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,
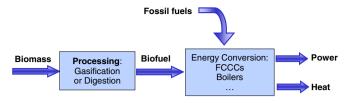
Fig. 1. FCCC system boundary and processing steps.

Fig. 2. Variation of FC efficiency with operating temperature.

the processing architecture shown in Fig. 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.

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 cycle integration [11]. 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 the bottoming cycles and this energy generation potential is usually almost fully utilised by either ST or GT alone. Therefore, any involvement of more than one bottoming cycle cannot substantially increase the overall efficiency but can rather 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 700 °C [2,11] where both MCFC and SOFC feature various process streams, which after pinch analysis reveal that the fuel cells define threshold heat integration problems. To utilise the heat efficiently, the cells should be the topping cycles. The choice of the bottoming cycles can be made between steam and gas turbines.

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 Fig. 2 [12] 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
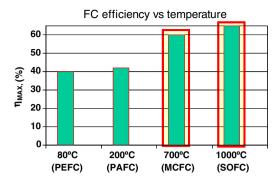
FC exhausts. Any drop in the temperature drastically decreases this potential.

2.3. Biomass resources

One important issue, when using biomass for generation of useful energy, is to identify an exploitable biomass resource and the distances of its transportation. In some rural communities there are significant volumes of agricultural residues – biomass of both animal and vegetation origin, which can be utilised for energy generation. Especially when the energy installations are of relatively small capacity – about 1–10 MWe, the biomass can be acquired from within the close vicinity of the energy plant. In such a case, the transportation costs for the waste biomass can be neglected, since the waste biomass needs to be transported to processing and/or landfill sites anyway and the distances are relatively small. In the current work it is assumed that this is the case and no biomass transportation costs are calculated. Moreover, the biomass price itself is used as a factor in the sensitivity study as this covers a variety of different local situations and contexts.

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 [3,13].

Operating units and process streams are modelled by separate sets (O and M, respectively) and the arcs are expressed as ordered pairs. For example, 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. 3 illustrates the FCCC system representation using a conventional block-style diagram and a P-graph fragment. According to the given P-graph fragment, the vertices will be represented with the following sets:

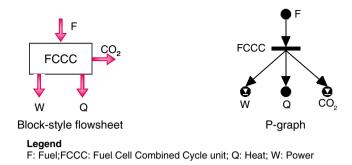$$M = \{F, W, Q, CO_2\}$$
$$O = \{FCCC\}$$

Legend
F: Fuel;FCCC: Fuel Cell Combined Cycle unit; Q: Heat; W: Power

Fig. 3. FCCC representations.

The arcs will be represented with the following pairs:

Inlets = {{F, FCCC}}
Outlets = {{FCCC,W}, {FCCC,Q}, {FCCC,CO₂}}

4. Modelling procedures

4.1. General 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 on the capacities of the operating units.

All these steps are illustrated on the selected examples from the case study in Section 5 (applying P-graph: heat and power generation using FCCC).

4.2. Representation of the operating and capital costs

The system operating costs and/or profits are estimated including several types of financial flows:

(i) Direct costs for using fuels and raw materials (e.g., biomass)
(ii) Specifically the biomass cost may vary widely and eventually cost nothing to the CHP plant under investigation and the farmers may even need to pay to the plant, which is reflected by a negative price of the biomass. This would depend on the economic situation of any particular implementation of a FCCC-based system. In the current study no particular market situation is assumed. Instead, the biomass cost is defined as a factor in a sensitivity analysis. The reason for this is simple – depending

on the efficiency of the agriculture and the local business culture the biomass may be viewed as a valuable resource worth paying for. This is the case in some highly developed European countries such as Denmark. On the other hand, in some cases the biomass waste may be viewed as a dangerous waste and the companies releasing it must pay for its processing and disposal. This may be the case with some poultry slaughter houses in Bulgaria, for instance.

(iii) The produced heat and power are sold at market prices, which generates revenues.
(iv) There are some side streams classified as waste to dispose of – e.g., particulates and other biomass residues, which are impossible or uneconomic to process. These waste streams are associated with corresponding disposal costs.

The capital costs of all operating units have been assumed to change linearly adhering to the form given in Eq. 1:

$$CC = A_{CC} + B_{CC} \cdot U_{Cap} \tag{1}$$

where the operating unit capacity is measured by its throughput of a key inlet stream. In the view of the uncertainty of the costs for fuel cells and biomass-based technology, this assumption is the most reasonable. Table 2 lists the capital cost coefficients used in the case study. Background for more detailed evaluation of the capital and appropriate assessment have been published by Taal et al. [14].

4.3. Optimisation objective

The synthesis of a processing network, such as the energy conversion systems considered here, requires a choice of the best possible solution among a number of options. This optimisation task has several possible objectives. The most obvious are the system profit to be maximised (cost to be minimised) and the amount of CO_2 emissions to be minimised. Although it is mathematically possible to define a multiobjective criterion to optimise, using profitability alone seems most coherent with the logic of the market economy, since it drives the behaviour of the companies and communities. Therefore the system profit is used in the current work as the sole objective to minimise. The CO_2 emissions are used as an additional criterion only at the analysis stage.

4.4. Sensitivity analysis procedure

The current work aims at estimating and analysing the economic viability and the potential for environmental impact reduction of energy conversion systems. The considered components, especially the FCCC systems, are at their best experimental technology currently having little or no market penetration. Because of this, many of their parameters inherently feature some degree of uncertainty.

As a result, the real issue regarding the economic viability and environmental impact of this technology should be

what is the range of conditions for which FCCC-based systems can minimise the corresponding CO_2 emissions while featuring maximum economic efficiency. For the purpose of the current study, the following parameters have been varied in order to evaluate the sensitivity of the economic and environmental performance of the FCCC systems:

- Price of the biomass (varied between −10 and 40 €/MW h).
- Introduction of taxation of the CO_2 emissions. The level of the eventual carbon tax has been set to 40 €/t.
- The duration of the payback period for the process capital costs (two levels considered: 10 and 20 years).

5. Applying P-graph: heat and power generation using FCCC

In this section an application of the formulated modelling procedure is presented, including the identification of case study data, description of the results, as well as a sensitivity analysis. The case study has been formulated based on the authors' comprehensive industrial experience.

5.1. Case study description

The problem at hand requires CHP generation from waste biomass (agricultural residues) and/or natural gas, using a number of potential operating units for the fuel pre-processing as well as FCCC options. It is assumed that the biomass is suitable for both gasification and anaerobic digestion. Power and heat demands have been set to 10 MW and 15 MW, respectively. The energy prices are chosen relatively high since future price increases are likely: 100 €/MW h for power, 36.8 €/MW h for heat and 30 €/MW h ($\sim$300 €/(1000 m^3)) for natural gas. The price of the fertiliser by-product from biogas digestion is assumed 50 €/t. The carbon tax and the biomass price have been chosen as factors for the sensitivity analysis. The tax is considered at 2 levels: 0 and 40 €/t CO_2. The biomass price is varied in the general range from −10 €/MW h to 30 €/MW h. The interval lower bound means that the farmers

need to pay for the disposal of the biomass disposal, while the upper bound reflects payments to be received by the farmers.

The plant payback time is initially set to 10 years. The following parameters have been specified:

- The carbon footprint of the biomass (agricultural residues) has been set to 0.025 t/MW h (t CO_2 per MW h of biomass) according to the information provided in [9].
- The carbon footprint of natural gas is set to 0.2063 t/MW h, which corresponds to the entire carbon content of the natural gas.
- The fertiliser yield in the biogas digester is taken 0.0768 t/MW h, which is an approximate estimate derived from a simplified digester mass balance.

5.1.1. 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 considered system, are listed in Table 1. The material prices given in Table 1 follow a strict convention about the sign. Inputs are assigned positive prices if the plant has to pay for them and negative ones if it receives payment. Similarly, all outputs generating revenues are assigned positive prices and those generating costs – negative prices.

In addition to the relevant material/stream prices (Table 1), other performance and economic data are specified (Table 2), providing the basis for appropriate economic evaluation of the designs.
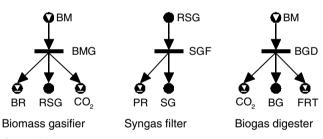
5.1.2. Identification of the candidate operating units

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

Table 1
Materials and streams

Stream	Type	P-graph classification	Description	Price
BM	Biomass	Raw material	Agricultural residues	Varied
BG	Clean biofuel	Intermediate	Biogas suitable for utilisation as a fuel	–
BR	Waste/side product	Product/output	Biomass residues (solid remainder from the biomass after gasification)	−10 €/t
CO_2	Waste, greenhouse gas	Product/output	CO_2 emissions	Varied
FRT	Useful byproduct	Product/output	Fertiliser obtained as a by-product from the anaerobic digester	50 €/t
NG	Fossil fuel	Raw material	Natural gas	36.8 €/MW h
PR	Waste/side product	Product/output	Particulates left from cleaning the syngas	−10 €/t
Q40	Steam	Intermediate	Steam at $P = 40$ bar(a)	–
Q5	Steam	Product/output	Steam at $P = 5$ bar(a) to satisfy user demands	30 €/MW h
RSG	Intermediate fuel	Intermediate	Raw synthesis gas	–
SG	Clean biofuel	Intermediate	Clean synthesis gas suitable for utilisation as a fuel	–
W	Power product	Product/output	Electrical power to satisfy user demands	100 €/MW h

Table 2
Capital cost coefficients and performance data used in the case study

Unit type	Key stream (MW)	A_{CC} (€)	B_{CC} (€/MW)	Min cap. (MW)	Max cap. (MW)	Performance
BGD	BM	4939	0.327	0	100	BG: 0.58 MW/MW FRT: 0.0768 t/MW CO_2: 0.025 t/MW
BLR_BG	BG	1646	0.109	0	100	Q40: 0.85 MW/MW
BLR_NG	NG	1646	0.109	0	100	Q40: 0.88 MW/MW CO_2: 0.2063 t/MW
BMG	BM	42000	0.080	0	100	RSG: 0.65 MW/MW BR: 0.0811 t/MW CO_2: 0.025 t/MW
{MCFC-GT}	{F}	$7.231 \cdot 10^6$	0.251	0	100	W: 0.580–0.672 MW/MW CO_2: 0.000–0.2063 t/MW {Q}: 0–0.250 MW/MW
{MCFC-ST}	{F}	$4.6 \cdot 10^6$	0.051	0	100	W: 0.590– 0.670 MW/MW CO_2: 0.000–0.2063 t/MW {Q}: 0.000–0.250 MW/MW
{SOFC-GT}	{F}	$9.131 \cdot 10^6$	0.270	0	100	W: 0.630–0.695 MW/MW CO_2: 0.000–0.2063 t/MW {Q}: 0.000–0.241 MW/MW
{SOFC-ST}	{F}	6.5×10^6	0.070	0	100	W: 0.600–0.695 MW/MW CO_2: 0.000–0.2063 t/MW {Q}: 0.000–0.240 MW/MW
SGF	RSG	6500	0.015	0	100	PR: 5×10^{-4} t/MW h SG: 0.99 MW/MW

Legend
BM: Biomass; BR: Biomass residues; RSG: Raw synthesis gas;
PR: Particulates; SG: Synthesis gas; BG: Biogas; FRT: Fertiliser

Fig. 4. Fuel preparation (biomass processing) options.

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

{F}: Fuels — NG: Natural gas, BG: Biogas, SG: Syngas
{FCCC} — MCFC-GT, MCFC-ST, SOFC-GT, SOFC-ST
{Q}: steam — Q1, Q2, Q5, Q10, Q20, Q40
Steam details — P = 1 bar, P = 2 bar, P = 5 bar, P = 10 bar, P = 20 bar, P = 40 bar
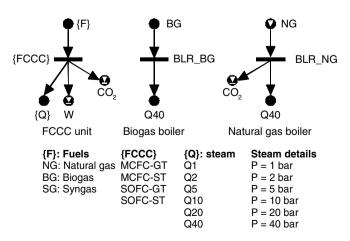
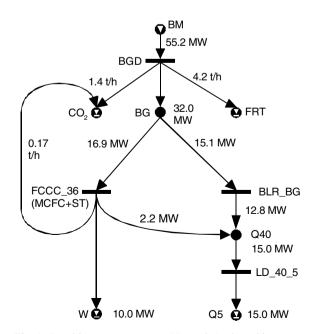Fig. 5. Energy conversion options.

Fig. 6. Resulting energy systems: Network 1 (cheap biomass).

shown in Figs. 4 and 5 have been identified. The {FCCC} entry in Fig. 5 stands for a number of various FCCC options, reflecting combinations of fuels, FC types and steam pressure levels.

5.1.3. 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. The capital cost data for the case study are given in Table 2.

5.1.4. 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
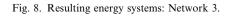

Fig. 7. Resulting energy systems: Network 2.

Fig. 9. Resulting energy systems: Network 4.

Fig. 8. Resulting energy systems: Network 3.

Fig. 10. Resulting energy systems: Network 5.
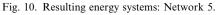
operating unit capacities or the availability of the respective resources.

5.2. Results and discussion

CHP networks have been synthesised for the defined options using the P-graph algorithms developed gradually by Friedler et al. [1–4]. This has been performed for the entire range of conditions described in Section 5.1 above.
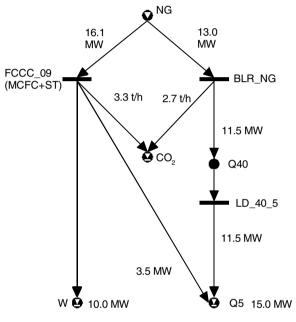
The initial conditions include:

- 0 €/t CO_2 tax.
- Biomass price variation −10–30 €/MW h.
- 10 years payback time.

The networks resulting for these conditions are presented in Fig. 6–11. The corresponding annual profit and CO_2 emissions are given in the first two curves of Figs. 15 and 16, respectively. If the network structures are fol-

Fig. 11. Resulting energy systems: Network 6.

Fig. 13. Resulting energy systems: Network 8.

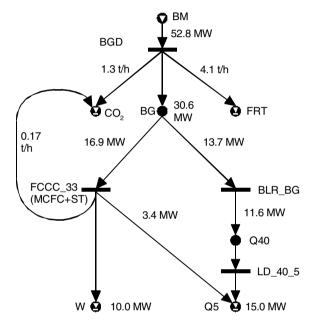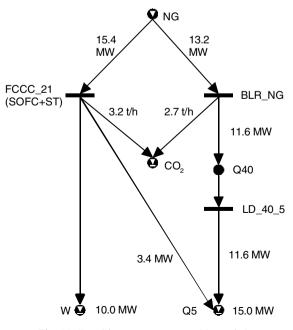Fig. 12. Resulting energy systems: Network 7.

Fig. 14. Resulting energy systems: Network 9.

lowed by the the involved materials, it can be noticed that for the cheapest biomass price, besides using exclusively the biomass as a primary energy source, the main energy conversion route for power generation is via biogas and using lower-efficiency FCCC blocks. Moving towards higher biomass price levels gradually changes the involved operating units, employing gasification and increasingly more efficient FCCC blocks. At biomass price of 20.35 €/MW h, (Fig. 10, Network 5) the auxiliary heat production switches from biogas to natural gas, while due to the high efficiency of the FCCC subsystems, the main CHP generation is still based on biomass gasification. At biomass price 23.57 €/MW h, using natural gas becomes more economc completely, which is reflected by switching the FCCC CHP blocks to using this fuel.

When subsequently the payback period is increased from 10 to 20 years, Networks 7–9 are generated (Figs. 12–14) in addition to the previous ones. A summary of the various topologies and the ranges of the sensitivity factors for which they result is given in Table 3.

Starting from a low price for the biomass and gradually increasing it, the resulting energy network topology changes in steps (Table 3). This shows that the topologies are relatively resilient to the variations in the biomass price. At the same time the profit changes essentially linearly for the ranges of biomass utilisation (Networks 1–4) and that of natural gas (Networks 5 and 6), respectively. The slope of the profit line changes between the different resources (biomass and natural gas).

The sensitivity analysis using the plots in Figs. 15 and 16 reveals that the main factor determining the resulting net-

Table 3
Summary of the resulting CHP network configurations

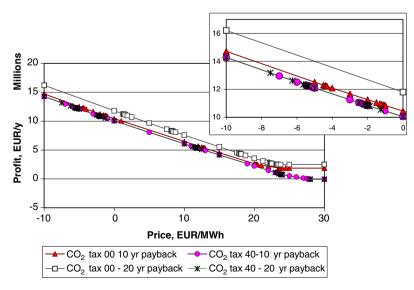| Network no.	Selected units	Fuels used	Biomass price range, €/MW h			
			Payback 10 years		Payback 20 years	
			No CO₂ tax	Tax 40 €/t	No CO₂ tax	Tax 40 €/t
1	BGD, FCCC_36 (BG), LD_40_5, BLR_BG	Biomass via gasification and digestion	−10 to 1.40	−10 to −5.40	−10 to −4.40	−10 to −5.40
2	BMG, SGF, FCCC_60 (SG), BGD, LD_40_5, BLR_BG	Biomass via gasification and digestion		−5.39 to −2.04	−4.39 to −1.04	−5.39 to −2.04
3	BMG, SGF, FCCC_57 (SG), BGD, LD_40_5, BLR_BG	Biomass via gasification and digestion		−2.03 to 11.81	−1.03 to 12.81	−2.03 to 11.81
4	BMG, SGF, FCCC_69 (SG), BGD, LD_40_5, BLR_BG	Biomass via gasification and digestion	18.00–22.39	11.82–23.96	12.82–20.34	11.82–23.96
5	BMG, SGF, FCCC_69 (SG), LD_40_5, BLR_NG	Biomass via gasification only and natural gas	22.40–23.21	23.97–27.99	20.35–23.55	23.97–27.99
6	FCCC_09 (NG), LD_40_5, BLR_NG	Natural gas only		28.00–30.00	23.56–30.00	28.00–30.00
7	FCCC_45 (BG,SOFC + ST), BGD, LD_40_5, BLR_BG	Biomass via digestion only	8.27–17.99			
8	FCCC_33 (BG,MCFC + ST), BGD, LD_40_5, BLR_BG	Biomass via digestion only	1.41–8.26			
9	FCCC_21 (NG,SOFC + ST), BLR_NG, LD_40_5	Natural gas only	23.22–30.00			

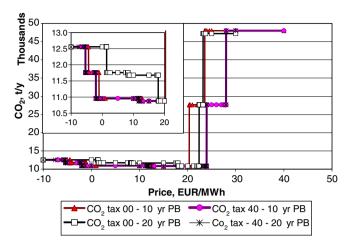

Fig. 15. Profits vs. biomass price.

Fig. 16. CO_2 emission levels vs. biomass price.

work structures is the competition between natural gas and biomass prices. The sensitivity towards the other two factors – CO_2 tax level and payback period is not as significant. Moreover, these plots also illustrate that for efficient energy systems imposing a CO_2 tax does not significantly reduce the corresponding emissions, but rather slightly widens the range in which biomass utilisation is economic. On the other hand, since even using biomass produces a certain CO_2 footprint, the tax notably reduces the profitability of all the schemes, including the biomass-based ones.

6. 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 [15,16] 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.

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