Consistent assessment of the energy and economic performance of second generation biofuel production processes using energy market scenarios

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ABSTRACT

This paper proposes a consistent way of assessing the performance of second generation biofuel production using energy market scenarios. During biofuel production a number of products and services can be co-generated while import of energy services (e.g. electricity and heat) in addition to the fuel supply may also be needed. This needs to be reflected by a well-defined performance indicator enabling a comparison between different process alternatives. A marginal production perspective is proposed for the definition of a general energy performance indicator, recalculating all services to primary energy on a system level. The Energy Price and Carbon Balance Scenarios (ENPAC) tool developed at Chalmers is used for the definition of the energy system background. Thereby, a scenario-specific comparison of the processes' thermodynamic performance is possible. The usefulness of the approach is illustrated for production of synthetic natural gas (SNG) from biomass. The shortcomings of common performance indicators are also discussed.

INTRODUCTION

Significant increase of production of biofuels for transportation has sparked much debate among researchers and policy-makers. On the one hand, biofuels are seen as a powerful option for greenhouse gas (GHG) emission reduction, and their use is promoted by targets for a 20% renewable energy share within the transport sector by 2020 in the European Union [1]. On the other hand their impact on food production and prices as well as their climate change mitigation potential is uncertain, as evidenced by a number of studies that present contrasting results (see for example [2, 3]). A general consensus is that there is a need for identification of sustainability criteria for biofuel production in order to be able to compare different alternatives on a common basis and to assess their actual potential regarding different aspects [4, 5].

A prominent example of a major comparative study that adopts a life cycle analysis (LCA) perspective within the biomass-based transportation fuel sector is the JRC-EUCAR-CONCAWE well-to-wheel study [6], in which second generation biofuels are recognized to have a high GHG emission reduction potential. The latter study has been analysed by Wetterlund et al. [7] who note that it has a major shortcoming by not taking into account the fact that biomass is not an unlimited resource. Increased use of biomass within the transport sector most likely will cause a deficit of biomass within another energy sector in the future. Covering this deficit with a fossil alternative will cause an increase of CO_2 emissions on the overall system level, thereby drastically reducing the GHG emission reduction potential of several biofuel options within the transportation sector. The concept of system expansion is

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adopted in reference [7] which accounts for alternative use of biomass within an assumed energy system background.

The necessity to carefully define the background system and the interactions with corresponding energy services is also discussed in detail by Gustavsson and Karlsson [8]. They analyse CO_2 mitigation costs from a system perspective and discuss several ways of accounting for energy services. Two methods to account for by-products and services in connection to biofuel production – electricity and heat – are compared: the multifunctional and the subtraction method where either electricity or heat is chosen as main by-product of the biofuel production process. The multifunctional method is deemed preferable as both heat and electricity are explicitly accounted for, while for the subtraction method the service not being the main by-product is only indirectly accounted for by compensation with the corresponding reference system marginal technology. Both methods – rigorously applied – should though yield the same results from a system level perspective. Besides considering monetary costs, primary energy costs and biofuel costs for CO_2 mitigation are also exemplified in their study, giving a more multifaceted illustration of system changes with introduction of biofuel processes.

The interactions between energy system background and end-use energy efficiency are also well illustrated in a recent study [9] on district heated buildings. As an example, end-use efficiency measures reducing the heat demand but increasing electricity demand are prone to result in minor primary energy savings for the studied background case. This is due to the fact that base load heat demand is satisfied with a combined heat and power (CHP) generation plant and the reduced heat demand on the end-user side indirectly leads to a reduced power generation on the supply side while at the same time the electric power demand on the system level increases. The choice of background system is therefore a crucial and non-straightforward aspect when dealing with the system aspects of new processes that are to be implemented in the future.

In this study the ENPAC tool [10] developed at Chalmers within the EU Pathways project [11] is used for the necessary energy system background definition. The tool can be used to generate consistent scenarios depicting possible cornerstones of future energy markets. Based on these scenarios a consistent evaluation of biofuel production processes is possible as the background energy system is specified with corresponding marginal technologies for the different energy services, including appropriate conversion efficiency values for these technologies. Energy and economic efficiency, as well as CO_2 emission consequences, of the introduction of second generation biofuel processes can be analysed as illustrated in this paper for production of synthetic natural gas (SNG) from biomass feedstock. The capability of the energy market scenario tool is thereby extended to allow a multifaceted scenario-specific evaluation of different processes, enabling identification of robust alternatives from an economic, thermodynamic and environmental viewpoint.

METHODOLOGY

In order to be able to evaluate the performance of a new process that is to be introduced to an existing background energy system it is important to clearly define the system boundaries and the underlying assumptions for the evaluation. The life-cycle-perspective for this study is a well-to-tank perspective meaning that no specific application for the produced biofuel is considered. This is different to other studies investigating biofuel process alternatives [6, 7], but the idea with this study is to not limit the application to biofuels for the transport sector but rather to adopt a general view on system energy efficiency based on the underlying scenarios. The case of SNG production that is used for illustration of the methodology in this paper might be such an example as SNG is not limited to transport applications but might also replace fossil natural gas in any of its other applications within the power or chemical sector.

The approach applied in this study is illustrated in Figure 1. Possible by-products from a new process such as heat and electricity compete with marginal technologies within the existing energy system and thereby indirectly influence the overall performance of a new process considering energy efficiency and CO_2 emission consequences. Even the feedstock used for the new process is subject to competition with a marginal user since biomass is not an infinite resource. Replacing biomass with an alternative – most likely fossil – feedstock in the process defined as the marginal user in the background energy system has a non-negligible impact on the CO_2 balance of the new process. The different system aspects – energy performance, CO_2 emission consequences and economic performance – are discussed in more detail in the following paragraphs.

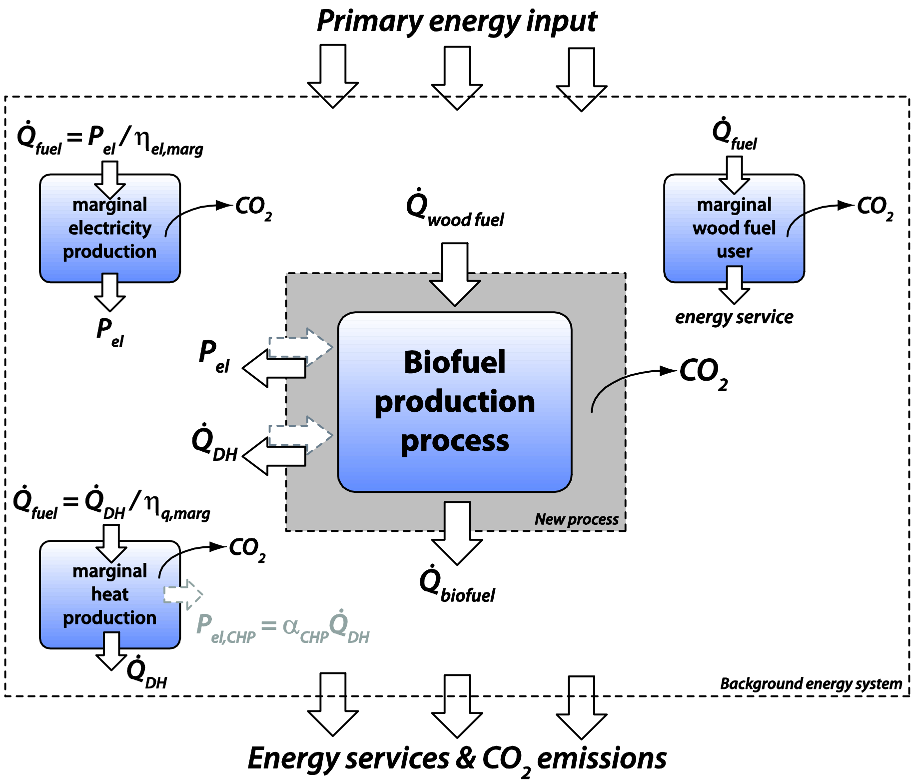

Figure 1: Schematic representation of the methodology accounting for marginal services of the background energy system the new process is to be integrated into.

Energy efficiency evaluation

The energy efficiency evaluation of a process can be done in various ways. The most commonly used performance indicators are the overall energy (η_{th}) and exergy efficiency (η_{ex}). Energy efficiency is based on the first law of thermodynamics comparing input and output of a system, while exergy efficiency combines the first and second law of thermodynamics. The definition of these two performance indicators may vary depending on system boundary definitions and conventions, but follows the general form of eqs. (1) and (2):

$$\eta_{th} = \frac{\sum_i \dot{Q}_{prod,i} + P_{el}^{-} + \dot{Q}^{-}}{\sum_j \dot{Q}_{fuel,j} + P_{el}^{+} + \dot{Q}^{+}} \qquad (1)$$

$$\eta_{ex} = \frac{\sum_i \dot{E}_{prod,i} + \dot{E}_{el}^{-} + \dot{E}_{q}^{-}}{\sum_j \dot{E}_{fuel,j} + \dot{E}_{el}^{+} + \dot{E}_{q}^{+}} \qquad (2)$$

For eq. (1), $\dot{Q}_{prod}$ and $\dot{Q}_{fuel}$ are the energy values of the resulting product(s) and fuel input(s), respectively. P_{el} represents the electricity and $\dot{Q}$ the useful heat (often in form of e.g. district heating) that either is exported (superscript "–") or imported (superscript "+"). The terms therefore only can appear either in the numerator (export) or the denominator (import). The same applies for the exergy value of electricity ($\dot{E}_{el}$) and heat ($\dot{E}_q$) in eq. (2), where $\dot{E}_{prod}$ and $\dot{E}_{fuel}$ represent the exergy value of product(s) and fuel(s).

Energy efficiency rates all energy services at the same level not taking into account their quality. A process having a large amount of process excess heat at low temperature might therefore seem to perform better than a process exporting a smaller amount of electricity. The aspect of energy quality is accounted for in the exergy efficiency, comparing all energy service based on their theoretical maximum potential for conversion to mechanical work output. The definition of chemical exergy of a fuel (most often done according to [12]) however is not straightforward and may in addition overestimate the potential for mechanical work potential, as for example stated by Gassner [13].

For cases where new processes are designed for integration with existing ones in order to achieve synergy effects, a marginal efficiency analysing the performance of the new process only can be useful in order to compare the integrated process to stand-alone or other integration options. This has been done for example in several studies comparing different alternatives for biomass- and waste-based electricity generation by integrated solutions in natural gas combined cycle plants [14-16]. A marginal efficiency for biomass/waste to electricity conversion $\eta_{el,marg}$ can be defined for this kind of process according to:

$$\eta_{el,marg} = \frac{P_{el,tot} - \eta_{el,NG} \cdot \dot{Q}_{fuel,NG}}{\dot{Q}_{fuel,bio}} \tag{3}$$

where $P_{el,tot}$ is the total electricity generation of the integrated process, $\dot{Q}_{fuel,NG}$ the fuel input in form of natural gas, and $\dot{Q}_{fuel,bio}$ the fuel input in form biomass/waste. The electrical efficiency $\eta_{el,NG}$ represents the stand-alone efficiency of a reference natural gas plant, implying the assumption that the electricity generation efficiency of the natural gas cycle remains unaffected by the integration of the new process. The marginal electrical efficiency $\eta_{el,marg}$ therefore represents the conversion from biomass/waste to electricity and can for example be compared to the efficiency of a stand-alone biomass-fired power plant to illustrate the more efficient use of biomass for electricity generation in an integrated process setup.

All efficiency definitions noted above allow comparison of different process alternatives with each other, however they only consider the processes isolated from the surroundings and do not take into account possible interactions with the background energy system. This allows for an easily accomplished and quick comparison of different process alternatives but does not give any guidance on how the new process performs from an energy system perspective, the latter being crucial for evaluating the processes' potential for implementation in real systems.

System expansion

In order to compensate for the drawback of the isolated energy efficiency evaluation it is necessary to expand the system and take the background energy system into account, as illustrated in Fig. 1. This can be done by recalculating all energy services supplied and consumed to primary energy using the corresponding marginal conversion technology. The system efficiency η_{sys} defined in eq. (4) compares all primary energy input into the process to all output.

$$\eta_{sys} = \frac{\sum_i \dot{Q}_{prod,i} + \frac{P_{el}^{-}}{\eta_{el,marg}} + \frac{\dot{Q}^{-}}{\eta_{q,marg}}}{\sum_j \dot{Q}_{fuel,j} + \frac{P_{el}^{+}}{\eta_{el,marg}} + \frac{\dot{Q}^{+}}{\eta_{q,marg}}} \tag{4}$$

Again, only net flows are considered, meaning that only heat/electricity import or export is accounted for in eq. (4). The marginal efficiency terms for electricity and heat production $\eta_{el,marg}$ and $\eta_{q,marg}$ require specification of the marginal production technologies. For the case where one of the marginal energy service technologies is a co-generation application, the definition of eq. (4) has to be modified accordingly. Gassner [13] applied the concept of marginal reference technologies in combination with exergy-based conversion efficiencies for the marginal energy services to define a chemical conversion efficiency for biofuel production processes in a similar manner to that defined in eq. (4). The marginal technologies were set to heat pumps for heating services and natural gas combined cycle power plants for electricity production. These are obviously optimum technologies from a thermodynamic viewpoint, but it is questionable if they are the marginal technologies a biofuel process to be implemented in the current or near future energy system is actually competing with.

In addition to the problem of defining the marginal energy service providers, the alternative use of biomass is an important aspect when assessing the environmental efficiency in form of GHG emission reduction potential of a given process. Wetterlund et al. [7] compare two cases in their analysis of the European well-to-wheel study [6]: coal-power plants as marginal users of biomass applying co-combustion and no alternative user of biomass which corresponds to assuming that biomass is available in unlimited amounts. These two cases are evaluated against a number of possible background energy systems with corresponding marginal electricity production technologies in order to investigate the sensitivity of the results to the underlying assumptions. The probability of different combinations of marginal electricity production technologies and alternative biomass users is not analyzed though. In the present study, an energy market scenario tool is used for the construction of consistent future energy market scenarios, allowing for the energy performance evaluation of new processes according to eq. (4).

CO_2 consequences

The change in system level CO_2 emissions $\Delta CO_{2,sys}$ is evaluated as emissions per energy unit of biofuel supplied

$$\Delta CO_{2,sys} = \frac{\Delta n_{bio} \cdot c_{bio} - \Delta n_{el} \cdot c_{el} - \Delta n_q \cdot c_q - n_{biofuel}^{-} \cdot c_{fossil\,fuel}}{n_{biofuel}^{-}} \tag{5}$$

with Δn_i [MWh/year] being the change in use of biomass (*bio*) and production of electricity (*el*) and district heat (*q*), respectively. c_i [kg CO_2/MWh] are the specific emissions per unit of energy for each fuel/service *i*. $n_{biofuel}^{-}$ [MWh/year] is the production of biofuel replacing a fossil alternative with its corresponding specific emissions $c_{fossil\ fuel}$. Only the combustion emissions for the fossil alternative that is replaced are accounted for assuming comparable greenhouse gas emissions for the distribution of the biofuel alternative. As biomass is not considered CO_2 neutral but seen as a limited resource its increased use will lead to higher CO_2 emissions on a system level as indicated by the first term in the numerator on the right hand side in eq. (5). The specific emissions c_{bio} allocated to the biomass depend on the marginal user of biomass and the alternative fossil fuel used. In order to illustrate the difference for estimated CO_2 emission consequences, an additional evaluation is done assuming biomass use to be CO_2 neutral. This will result in the specific emissions of biomass use c_{bio} being zero, but also may affect the emissions for electricity and district heat production, if biomass-based technologies are used to provide these energy services.

Economic evaluation

As it is difficult to estimate the investment costs for a non-mature process such as second generation biofuel production, the economic evaluation in this study is based on the investment opportunity *IO*, representing the specific annual earnings for the production of biofuel according to eq. (6). The investment opportunity IO is then defined as the annualized investment cost for which the plant can achieve break-even operation, i.e. for which annualized investment costs are exactly equal to the net annual earnings. Investment costs can be annualized using the annuity factor, also referred to as the capital recovery factor.

$$IO = \frac{n_{biofuel}^{-} \cdot p_{biofuel} + (n_{el}^{-} - n_{el}^{+}) \cdot p_{el} + (n_{q}^{-} - n_{q}^{+}) \cdot p_{q} - n_{bio}^{+} \cdot p_{bio}}{n_{biofuel}^{-}} \tag{6}$$

In eq. (6) n_i represents the annual amount of fuel/service i that is produced (-) or consumed (+) and p_i its corresponding costs per energy unit. To get a correct absolute estimate of the investment of the investment opportunity it would be necessary to account for the operation and maintenance (O&M) costs as well. However, since the main goal of this study is the comparison of two stand-alone plants (SNG production and CHP plant) with integrated process configurations, the O&M costs can be expected to be similar for an integrated plant compared to stand-alone plants delivering the same energy services. For a comparative analysis they can therefore be omitted. The difference in investment opportunity between the stand-alone case and the integrated solution ΔIO therefore represents the increased income and thereby the economic opportunities for realizing the integration between the two processes.

$$\Delta IO = IO_{\text{SNG integrated to CHP}} - IO_{\text{SNG }\& \, CHP\ as\ stand\text{-}alone} \tag{7}$$

SNG PRODUCTION PROCESS

The biofuel production process chosen for illustrating the application of the described methodology is a production process for SNG from biomass. The process has been designed as an extension of an existing combined heat and power (CHP) plant [17] using an indirect gasification technology [18]. Two alternative drying technologies for the SNG biomass fuel and two levels of heat integration between the SNG and CHP process, resulting in four different configurations, are evaluated. The general concept for the process integration is illustrated in Figure 2.

The thermal load of both the combustion boiler and the gasification unit is set to 100 MW_{th}. For the CHP steam power plant, no feedstock drying is assumed with the fuel being fed at 50 wt-% moisture according to the reference data the model is based on [19]. The biomass fuel fed to the SNG process is dried from its initial moisture content of 50 to 20 wt-% prior to gasification. The thermal input on a wet fuel basis to the SNG process is therefore less than 100 MW_{th} on a lower heating value (LHV) basis due to the higher moisture content. The biomass fuel input to the CHP plant decreases for the integrated solutions as additional fuel is supplied to the boiler in the form of non-gasified char. At the same time the steam generation decreases in the CHP plant since part of the boiler duty is used for running the endothermic gasification process. This decrease in steam generation can be partially compensated for by thermally integrating the two processes making use of excess heat from the SNG process for increasing the steam generation within the CHP plant.

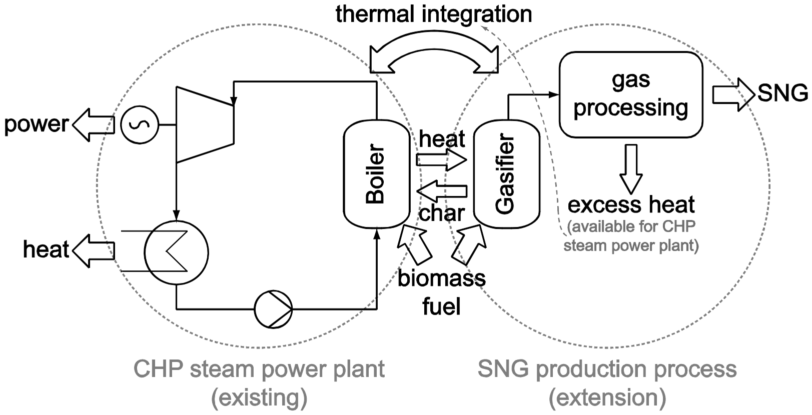

Figure 2: Concept of integrating SNG production to existing energy infrastructure in form of CHP steam power plants [17].

The two alternative feedstock drying technologies prior to the gasification step that are evaluated within the process design are steam drying (case 1) and low-temperature air drying (case 2). The two levels of thermal integration represented are a balancing (case A) and a maximum integration (case B) case. In the case of balancing thermal integration (A) only the freely available excess heat from the SNG process is used for steam generation and consecutive power and district heat generation within the CHP steam power plant. Maximum thermal integration cases (B) refer to a tight thermal integration between the SNG and CHP plant, even making use of internal heat pockets within the SNG process in order to maximise the overall electricity generation. In this case, all high temperature heat available from the SNG process is used to generate steam that is supplied to the CHP plant. After expansion in the steam turbine, low pressure steam is returned to the SNG plant where it is used to provide low temperature process heating that is supplied by high temperature excess process heat in Case A process configurations. For further details on the integration study, the reader is referred to [17].

In order to evaluate the integrated solutions in comparison to a stand-alone SNG plant an additional case has been defined in this study for an SNG plant of similar design where only the non-gasified char is used in the combustion unit, supplying heat to the gasification process. The remaining energy in the flue gases is used for combustion air preheating and district heating purposes. No power generation is assumed for the stand-alone case, the process' energy performance thereby resembling the first industrial scale SNG plant that is currently under construction in Gothenburg/Sweden [20]. The existing CHP steam power plant is operating in the same way as before without any modifications for the stand-alone case. In Figure 3 the two alternatives for introduction of SNG production (stand-alone (1 case) and integrated solutions (4 cases)) are illustrated, also indicating the yearly operating hours as discussed in the energy market scenario section. Table 1 summarizes the key energy figures for the SNG stand-alone plant, for the four integration cases, as well as for the CHP plant with which the SNG process is integrated.

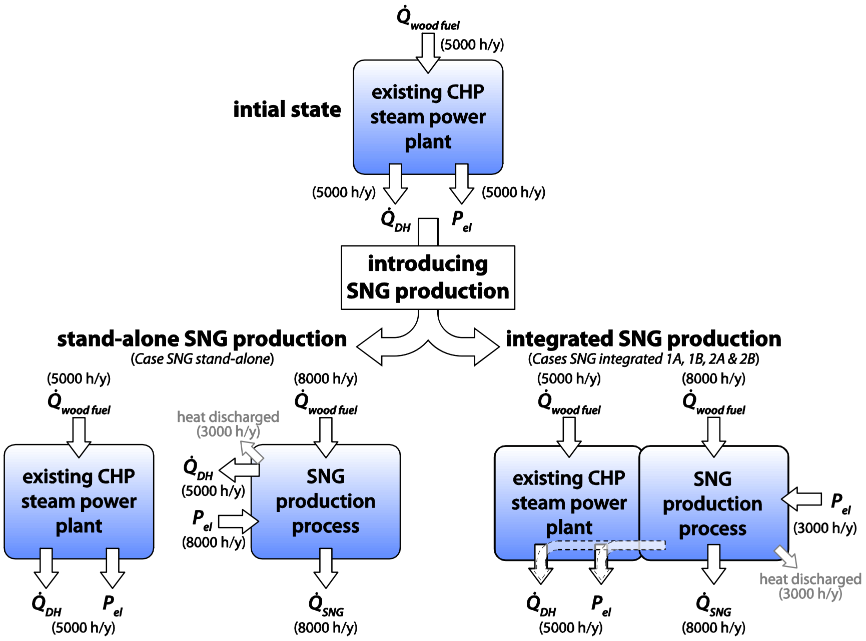

Figure 3. Illustration of the stand-alone and integrated operation for the SNG production process as extension of an existing CHP steam power plant.

Table 1. Key energy figures for SNG production alternatives and CHP stand-alone plant (based on [17]).

	Wood fuel input $\dot{Q}_{fuel}$	*SNG production* $\dot{Q}_{SNG}$	*Net electricity production* P_{el}	*District heat production* $\dot{Q}_{DH}$
	MW_{LHV} 1)	MW_{LHV}	MW	MW
SNG stand-alone 2)	90,3	62,7	-3,4	20,3
CHP stand-alone	100	-	31,7	76,8
SNG integrated 1A 2) 3)	161,9	62,7	24,7	68,4
SNG integrated 1B 2) 4)	161,9	62,7	27,6	64,1
SNG integrated 2A 5) 3)	161,9	62,7	23,2	60,1
SNG integrated 2B 5) 4)	161,9	62,7	28,3	54,9

1) based on wet fuel LHV (50 wt-% moisture)
2) feedstock dried by steam drying
3) balancing thermal integration
4) maximum thermal integration
5) feedstock dried by low temperature air drying

Energy market scenarios

Four different energy market scenarios for around year 2030 are used based on two fossil fuel price levels and two levels of CO_2 emission charge. The fossil fuel price levels represent base-line and soaring estimates according to the Energy Trends to 2030 of the European Union [21]. The CO_2 emission charge levels of 27 and 85 $€_{2005}$/t CO_2 represent low and high ambitions for CO_2 emission reduction, respectively. All prices are evaluated in $€_{2005}$ with the corresponding exchange rates applied when necessary. Additional assumptions made for the scenario modelling in this study are support for the production of renewable electricity amounting to 20 $€_{2005}$/MWh and biomass marginal usage corresponding to co-firing in coal power plants. The latter assumption implies that the use of biomass is not CO_2 neutral, reflecting the fact that biomass is not an unlimited resource. The CO_2 emissions for different fuels are evaluated on a life cycle basis including emissions associated with production and distribution [22]. The district heat market is difficult to represent with a general model as it is largely dependent on the plant location and no global or even national market with common marginal technologies exists. For this study it is assumed that the excess heat from the SNG plant is competing with combined heat and power (CHP) plants for intermediate heating load. This technology therefore determines the economic value of available excess heat accounting for the complete investment costs for a new CHP plant. This reasoning is a generalisation that overestimates the value of excess heat that needs to be considered in the analysis of the results. The annual full load operation of the CHP plant being the marginal producer of district heat is assumed to be 5000 hours. During these hours the SNG plant (assumed full load operation of 8000 h/y) can expect to sell its available excess heat to the corresponding market price. For the integrated solutions this implies that cogeneration of power and heat for the SNG process only is possible during part of the year as well (5000 h/y). The rest of the year the integrated plants are operating in the same way as the stand-alone alternative. This actually should be possible due to the flexibility of the integration of the indirect gasification unit [17, 18]. These assumptions are supposed to reflect a location for the SNG plant close to a larger city such as Gothenburg/Sweden with a well developed district heating network and a number of competing excess heat suppliers. Costs for extra piping necessary to connect the SNG plant to the district heating grid are not accounted for in this study. Table 2 summarises the assumptions and resulting figures for the four energy market scenarios for the year 2030 used in this study.

Table 2. Energy market scenarios for 2030.

Scenario		**1**	**2**	**3**	**4**
Fossil fuel price level (input)[1]		***low***	***low***	***high***	***high***
Crude oil	€$_{2005}$/MWh	31	31	49	49
Natural gas	€$_{2005}$/MWh	24	24	37	37
Coal	€$_{2005}$/MWh	7.5	7.5	10	10
CO_2 charge (input)		***low***	***high***	***low***	***high***
	€$_{2005}$/t CO_2	27	85	27	85
End user prices and policy instruments					
Wood fuel (forest residue)	€$_{2005}$/MWh	25	45	28	48
Electricity (incl. CO_2 charge)	€$_{2005}$/MWh	53	70	58	76
Natural gas (incl. CO_2 charge)	€$_{2005}$/MWh	34	47	47	60
Marginal electricity production technology[3]		Coal	Coal,CCS	Coal	Coal,CCS
District heating[4]	€$_{2005}$/MWh	52	71	53	73
Renewable electricity support (input)[2]	€$_{2005}$/MWh	20	20	20	20
CO_2 emissions					
Electricity	kg CO_2/MWh	679	129	679	129
Biomass[5]	kg CO_2/MWh	336	336	336	336
Natural gas	kg CO_2/MWh	202/217[6]	202/217[6]	202/217[6]	202/217[6]
District heating[4]	kg CO_2/MWh	156	387	156	387

[1] World market prices [21]

[2] average value for Europe [10]

[3] $\eta_{el,Coal} = 0.51$, $\eta_{el,Coal,CCS} = 0.40$

[4] biomass CHP plant $\eta_{tot} = 1.08$, $\alpha = 0.42$ [19]

[5] Coal power plant marginal user of biomass

[6] combustion only / life cycle perspective (incl. production and transport) [22]

RESULTS & DISCUSSION

All results are reported on a per year basis. Table 3 gives the energy figures for the four integrated cases of SNG production and the stand-alone solution. In addition the absolute change with respect to the initial conditions (only the existing CHP plant operating) is indicated.

For the thermodynamic performance evaluation with the system efficiency η_{sys} according to eq. (4) it has to be accounted for the fact that the marginal heat production technology is a cogeneration technology. In addition, since excess heat from the SNG plant can only be delivered to the district heating network during part of the year, it is necessary to evaluate the efficiency based on the energy performance per year basis instead of the nominal duties. The system efficiency for this specific case is thus defined as:

$$\eta_{sys} = \frac{n_{\mathrm{SNG}} \cdot \mathrm{LHV}_{\mathrm{SNG}} + \frac{\left(P_{el}^{-} - \alpha_{marg} \cdot \mathrm{Q}^{-}\right)}{\eta_{el,marg}} + \frac{\mathrm{Q}^{-}}{\eta_{q,marg}}}{n_{\mathrm{wood\ fuel}} \cdot \mathrm{LHV}_{\mathrm{wood\ fuel}} + \frac{\left(\alpha_{marg} \cdot \mathrm{Q}^{-} - P_{el}^{-}\right)}{\eta_{el,marg}} + \frac{Q^{+}}{\eta_{q,marg}}} \tag{8}$$

In eq. (8) $n_{\mathrm{i}} \cdot \mathrm{LHV}_{\mathrm{i}}$ represents the energy input and output of fuel *i*. α_{marg} is the power-to-heat ratio of the marginal cogeneration heat production technology. Exported heat from the process causes a decrease in electricity production on the system level of $\alpha_{marg} \cdot \mathrm{Q}^{-}$ as the marginal cogeneration plant operation will be decreased. The difference between the net electricity export P_{el}^{-} and the term $\alpha_{marg} \cdot \mathrm{Q}^{-}$ determines whether a net increase or reduction of primary energy use for electricity is induced by the process on a system level. Again, only positive terms are counted in eq. (8).

Table 3. Annual energy figures for the different process alternatives.

	Wood fuel		*SNG*		*Electricity*		*District heat*	
	GWh/y	Δ1)	GWh/y	Δ1)	GWh/y	Δ1)	GWh/y	Δ1)
SNG stand-alone2)	1222	722	502	502	132	-27	485	101
SNG integr. 1A2)3)	1080	580	502	502	113	-45	342	-42
SNG integr. 1B2)3)	1080	580	502	502	128	-31	321	-64
SNG integr. 2A2)4)	1080	580	502	502	104	-55	301	-84
SNG integr. 2B2)4)	1080	580	502	502	131	-27	275	-110

1) change in annual production/consumption compared to inital state with existing CHP plant only ($Q_{wood\,fuel}$ = 500 GWh/y, P_{el} = 159 GWh/y, Q_{DH} = 384 GWh/y)

2) the absolute energy figure numbers are for both the CHP and SNG plant

3) electricity consumption of 3.4 MW during SNG-only mode (3000 h/y)

4) electricity consumption of 4 MW during SNG-only mode (3000 h/y)

In Figure 4 the system energy efficiency η_{sys} is illustrated for the different process alternatives and the four energy market scenarios. The difference in efficiency for this specific case study can be mainly attributed to the varying electrical efficiency of the marginal production technology in the corresponding scenario. A lower marginal electrical efficiency in scenarios 2 and 4 (coal condensing power plant with CCS) implies a better performance of the integrated solutions compared to the stand-alone alternative. An increased thermal integration (comparing cases B to A) leads to better system efficiency for all scenarios. For scenarios 1 and 3 integrated solutions perform worse than the stand-alone alternative except for the integrated SNG production with steam drying at maximum thermal integration (case 1B). The latter case is the one performing best within all scenarios. It has to be stated though that the difference in η_{sys} between the cases within one scenario is less than 3 %-points for all scenarios.

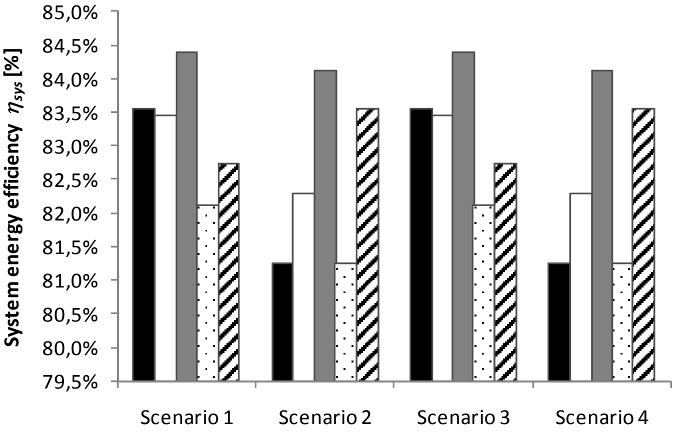

Figure 4. System energy efficiency η_{sys} for the different SNG production cases in the four energy market scenarios. Black: stand-alone, white: integrated 1A, grey: integrated 1B, dotted: integrated 2A, dashed: integrated 2B.

When analysing the CO_2 emission consequences of the introduction of an SNG production process it can be stated that all alternatives lead to an increase in CO_2 emissions per year for the given scenarios. For scenarios 1 and 3 where the marginal electricity production technology is coal-based condensing power without CCS the integrated solutions result in a better performance, while for scenarios 2 and 4, a stand-alone plant is the better option. This is due to the substantially higher amount of external electricity production for the stand-alone solution that leads to lower CO_2 emissions when this electricity is produced with CCS technology. The associated CO_2 emissions for biomass use do not differ between the scenarios and therefore are not the reason for the different results between the scenarios. With the biomass marginal user being a coal condensing power plant, the associated emissions of biomass use are approximated with emissions from coal combustion, CCS being used or not. This is an approximation that is valid as in case of CCS the negative CO_2 emission effect of biomass (CO_2 released during biomass combustion is stored underground resulting in a negative CO_2 emission from a life cycle perspective) is lost when it is replaced by fossil coal.

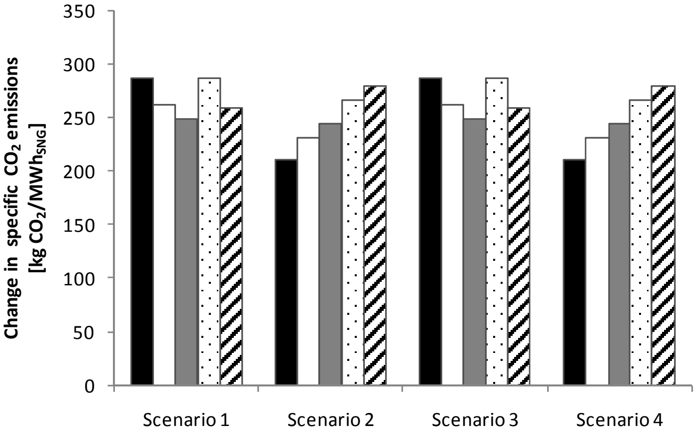

Figure 5. CO_2 consequences for the different SNG production processes in the four energy market scenarios. Black: stand-alone, white: integrated 1A, grey: integrated 1B, dotted: integrated 2A, dashed: integrated 2B.

The fact that all cases lead to an increase in CO_2 emissions can be explained by the fact that biomass is not considered CO_2 neutral in this study and that for all cases the marginal user of biomass is a coal power plant. This puts a large emission penalty on biomass to start with. In addition the SNG produced from biomass replaces fossil natural gas having lower specific emissions than coal. The CO_2 balance for the SNG process can therefore hardly be positive with the given assumptions.

Economically, all SNG production alternatives are not feasible as such within any of the scenarios. The annual investment opportunity for the different cases given in Figure 6 shows very low values of several thousand € per year, making it impossible to finance such a project. The difference in investment opportunity *ΔIO* between integrated and stand-alone cases is negative for all cases and scenarios, rendering an integration of the two processes economically unattractive. These figures clearly demonstrate that the economic viability of SNG production is largely dependent on the existence of specific support policies. No biofuel support policy has been assumed in the current study. The necessity of such a policy for rendering biofuel process alternatives economically interesting has been also been stated by Wetterlund and Söderström [23], among others. An additional factor influencing the investment opportunity of the integrated solutions negatively is the fact that the district heat delivery is decreasing. The decreasing heat demand having to be compensated by external combined heat and power production (e.g. a new CHP plant has to be built to cover the decreased heat delivery) puts high economical burdens on the integrated solutions. Such solutions therefore only would be viable in case of a decreasing heat demand on the end-user side or cheaper alternatives than building a new CHP plant for covering the deficit in DH production.

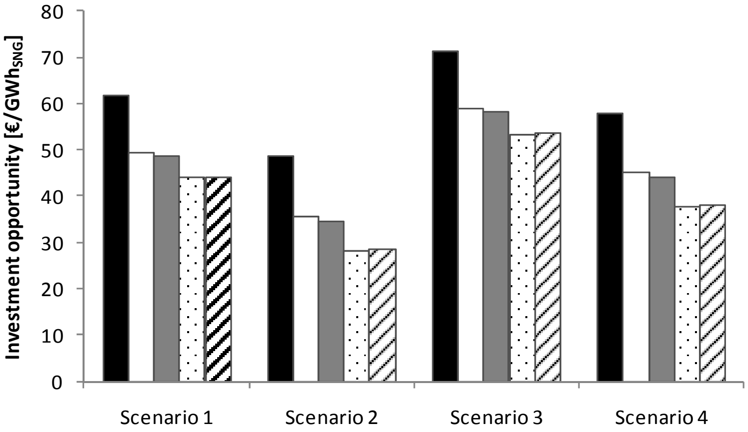

Figure 6. Specific investment opportunity *IO* for the different SNG production processes in the four energy market scenarios. Black: stand-alone, white: integrated 1A, grey: integrated 1B, dotted: integrated 2A, dashed: integrated 2B.

To illustrate possible performance improvements for the SNG production process from a system level perspective, an additional investigation on the opportunities for carbon storage from the SNG process has been performed. During SNG production storage-ready CO_2 is separated that is vented to the atmosphere in the study the current results are based on [17]. The CO_2 is at high level of purity in two streams within the SNG process, one of them also containing traces of H_2S, making further treatment before compression and storage necessary. Both streams are assumed to be sent to storage in a simplified estimation of the CO_2 consequences and investment opportunity *IO*. Only the amount of CO_2 stored is accounted for in this simplified analysis, neglecting marginal effects of increased electricity consumption within the SNG process for the compression of CO_2.The amount of CO_2 stored per year for all SNG production cases amounts to about 101 300 tons. Figure 7 shows the resulting CO_2 emission consequences and investment opportunity results .

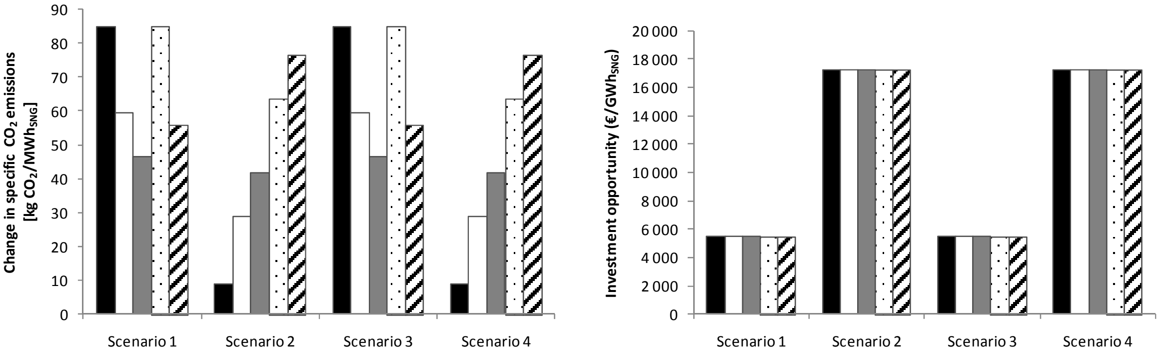

Figure 7. CO_2 consequences and investment opportunity for the different SNG production processes considering capture and storage of the CO_2 separated in the SNG process. Black: stand-alone, white: integrated 1A, grey: integrated 1B, dotted: integrated 2A, dashed: integrated 2B.

Considering the influence of CO_2 storage on the investment opportunity it can be stated that a substantial increase can be observed. This increase has to be weighed against the increased investment costs for the plant when implementing CO_2 storage. Another interesting observation is the fact that the difference between the stand-alone and integrated alternatives becomes negligible. The influence of CO_2 storage becomes very dominant for the economic viability, in particular for the scenarios with high CO_2 emission charges (scenario 2 and 4). The change in CO_2 emissions is still positive but the numbers are substantially reduced compared to no CO_2 storage (Figure 5). Allocating in addition lower specific emissions to biomass would improve the performance additionally. For the purpose of illustration the specific change in CO_2 emissions is shown for the case where the specific emissions of biomass c_{bio} are zero in Figure 8. This not only implies that the biomass use is CO_2 neutral, but also results in negative specific emissions for the district heat c_q as this technology is biomass-based as well and the cogenerated electricity replaces fossil-base electricity. No CO_2 storage is taken into account for the figures represented in Figure 8 but still the change in specific emissions is negative. Adding CO_2 storage would further improve the results.

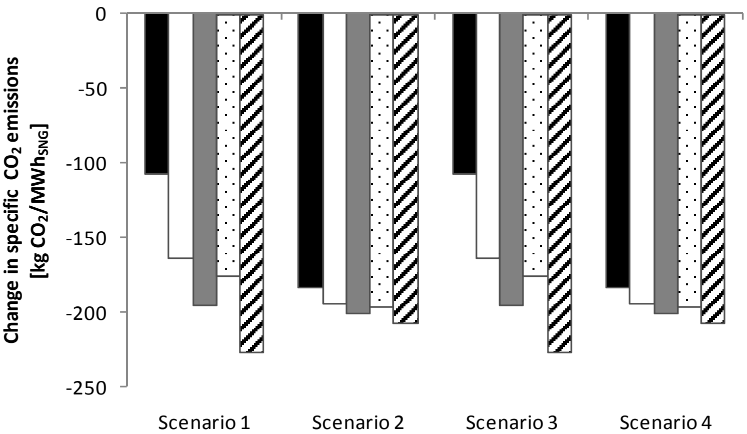

Figure 8. CO_2 consequences for the different SNG production processes considering biomass use CO_2 neutral. Black: stand-alone, white: integrated 1A, grey: integrated 1B, dotted: integrated 2A, dashed: integrated 2B.

CONCLUSIONS

In this paper, a consistent way of evaluating the performance of biofuel production processes using energy market scenarios has been demonstrated. Using this approach, a multi-faceted evaluation is possible accounting for the energy and economic performance, as well as for the CO_2 consequences within different possible future energy background. The method has been demonstrated for the example of SNG production process alternatives designed as stand-alone plant, or as integrated solutions to an existing CHP steam power plant. The energy performance on a system level of the integrated solutions is superior to the stand-alone alternative for all scenarios when aiming at a high level of thermal integration. The economic evaluation shows little to no profitable opportunities for SNG production from biomass in all scenarios. Additional policy support would be needed to render SNG production economically viable. The CO_2 emissions for SNG production increase for all scenarios due to the underlying assumption of biomass not being CO_2 neutral and coal power plants being the marginal user of biomass. Adopting the more conventional approach of considering biomass to be CO_2 neutral, the results are changed considerably showing a reduction of CO_2 emissions by introducing SNG production for replacing natural gas. However, this way of interpreting the results neglects the fact that biomass is not an unlimited resource and therefore overestimates the GHG emission reduction potential of the process. Based on the figures showing increased CO_2 emissions by introducing SNG production, the concept of replacing fossil natural gas by SNG produced from biomass seems questionable at first sight. The use of SNG though has not been specified in this study. When for example thinking specifically of the transport sector, assuming coal power plants as marginal users of biomass might not be the best reference background and the CO_2 consequence picture will change. Based on the assumptions adopted in this study, it can however be stated that using SNG from biomass for power generation purposes is not beneficial from a CO_2 emission perspective. A simplified evaluation of the influence of CO_2 storage within the SNG production process on the CO_2 emission consequences on the system level and the investment opportunity shows that CO_2 storage is largely dominant over process integration differences between the SNG production alternatives when looking at the investment opportunity. The CO_2 emissions are heavily reduced by CO_2 storage, but are still increasing for all scenarios when introducing SNG production from biomass. Again, it has to be pointed out that the underlying assumption of biomass being used in coal power plants on a marginal level puts severe emission penalties on the use of biomass as fuel input to the process.

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NOMENCLATURE

CCS	carbon capture and storage
CHP	combined heat and power
GHG	greenhouse gases
LCA	life cycle analysis
LHV	lower heating value
SNG	synthetic natural gas
NG	natural gas
O&M	operation and maintenance
IO	annual investment opportunity

Symbols

α	power-to-heat ratio
c	energy-specific CO_2 emissions
E	exergy
η	efficiency
n	annual energy use/production
p	energy-specific costs
P	power
$Q/\dot{Q}$	heat energy/thermal duty

Indices/Exponents

-	exported
+	imported
bio	biomass
el	electrical
ex	exergetic
fuel	fuel
marg	marginal
prod	product
q	heat
sys	system
th	thermal

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