BIOMASS AND BIOENERGY 35 (2011) 2950–2960

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Life cycle assessment of SNG from wood for heating, electricity, and transportation

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ARTICLE INFO

Article history:
Received 6 September 2010
Received in revised form
14 March 2011
Accepted 16 March 2011
Available online 9 April 2011

Keywords:
SNG
Polygeneration
Life cycle assessment (LCA)
Heating
Electricity
Transportation

ABSTRACT

The conversion of wood to synthetic natural gas (SNG) via gasification and catalytic methanation is a renewable close to commercialization technology that could substitute fossil fuels and alleviate global warming. In order to assure that it is beneficial from the environmental perspective, a cradle to grave life cycle assessment (LCA) of SNG from a first-of-its-kind polygeneration unit for heating, electricity generation, and transportation was conducted. These SNG systems were compared to fossil and conventional wood reference systems and environmental benefits from their substitution evaluated. Finally, we conduct sensitivity analysis for expected technological improvements and factors that could decrease environmental performance.

It is shown that substituting fossil technologies with SNG systems is environmentally beneficial with regard to global warming and for selected technologies also with regard to aggregated environmental impacts. On the condition that process heat is used efficiently, technological improvements such as increased efficiency and denitrification could further increase this advantage. On the other hand, lower GHG emissions and aggregated impacts are partly compensated by other environmental effects, e.g. eutrophication, ecotoxicity, and respiratory disease caused by inorganics. Since more efficient alternatives exist for the generation of heat and electricity from wood, it is argued that SNG is best used for transportation. In the light of a growing demand for renewable transportation fuels and commercial scale technological development being only in its initial stage, the production of SNG from wood seems to be a promising technology for the near future.

1. Introduction

Even though second-generation biofuels are not produced on a commercial scale yet, a number of pilot and demonstration units have been set up in recent years [1]. Among these is the production of SNG (synthetic natural gas) from lignocellulosic biomass via gasification and catalytic methanation, which is currently developed at the Paul Scherrer Institut (PSI) and other research institutes [2]. Serious technological progress has been achieved in Güssing (Austria) during tests of a 10 kW SNG pilot plant in 2004 and a 1 MW process development unit in 2009 [2,3]. Recent evaluations to build a 7.5 MW polygeneration SNG plant in Baden, Switzerland [4] and a 20 MW/80 MW SNG plant (in two stages) in Gothenburg, Sweden [5] are indications that the wood-to-SNG technology is coming closer to the commercialization stage.

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doi:10.1016/j.biombioe.2011.03.036

Arguments in favour of the production of SNG are potentially higher conversion efficiencies than other conversion routes such as BTL or lignocellulosic ethanol [1], economic robustness with regard to different levels of fuel and electricity prices [6], a broad usability of SNG, and the already existing natural gas supply infrastructure.

Several studies have recently raised attention to the fact that assessing the full environmental impacts over the whole life cycle of the production and use of biofuels is crucial to assure that these are truly more sustainable than fossil alternatives [7,8]. Even though a previous assessment of the environmental impacts of PSI's wood-to-SNG technology showed that the production and use of SNG in heating and transportation is beneficial from the environmental perspective [9], a renewed assessment seemed appropriate for two reasons: first, new engineering data for the potential first-of-its-kind 7.5 MW Baden plant was available [10] providing thus a better basis for the calculation of the environmental performance than the 10 kW Güssing pilot (which was used in the previous study). Second, the foreseen plant in Baden is a polygeneration plant producing heat, electricity, and SNG and therefore its design is fundamentally different from the pure SNG pilot in Güssing.

The aim of this study was to evaluate the environmental performance of the production and use of wood-derived SNG based on the Baden project plans. We used life cycle assessment (LCA) to analyze the environmental impacts generated during the life cycle stages of the production and use of SNG from cradle to grave. We compare the life cycle impacts of heating, generating electricity, and driving with SNG to fossil and wood-based reference systems. We then evaluate which of the potential uses of SNG is ecologically preferable. Finally, sensitivity analysis is presented for potential technological improvements and critical factors that could worsen the ecological performance.

2. Scope definition

2.1. *Compared systems*

The analyzed polygeneration plant produces SNG, heat, and electricity from wood. The SNG can be used in a natural gas boiler for domestic heating, in a large combined cycle natural gas plant (SNG CC), in a small combined heat and power unit (SNG CHP) or in a natural gas car for transportation (Fig. 1). The process heat that is recovered during the SNG production is used in a district heating system and a hospital, which require heat throughout the year. This heat would otherwise be produced with a natural gas boiler. The electricity is used to cover the plant's own demand.

The fossil reference systems include a light fuel oil boiler, a natural gas boiler, and a heat pump operated with electricity from natural gas for home heating. Since Switzerland's energy demand is still growing, we assume that electricity from SNG substitutes power from otherwise newly built combined cycle natural gas (NGCC) or nuclear power plants [11]. Petrol, diesel, and natural gas passenger cars are used as reference systems for the use of SNG in transportation. For a comparison with wood-based reference systems we also include a wood chip district heating.

2.2. *Function and functional unit*

The function of the analyzed polygeneration plant is a) to produce SNG, which is then used for heating, generating electricity or driving, and b) to generate (process) heat, which substitutes heat from the natural gas boiler of the district heating network. We account for the latter by using system expansion (see Section 2.3) and focus on the comparison of the use of SNG to different reference systems. There is no need to account for the generated electricity as it is produced and used exclusively within the SNG production process.

Since heating, electricity, and transportation are measured in different units (e.g. MJ, kWh and passenger kilometres (pkm)), we define the functional unit as the use of 1 m^3 of SNG in either one of these applications. The quantity of a service (heat, electricity or transportation) that is delivered by 1 m^3 of SNG is shown in Fig. 1. These values are the basis for the calculation of the net environmental benefit, which is used to compare the environmental advantages resulting from the substitution of different reference systems by SNG systems. It is calculated therefore as the difference between the impacts generated by SNG and reference systems.

2.3. *System delimitation*

The life cycle phases of the SNG production system are considered from cradle to grave, i.e. the wood production chain (growth and harvest), the transport of wood to the SNG plant, the conversion of wood-to-SNG as well as the pipeline transport, and the use of SNG for heating or transportation. Similarly, the entire life cycle from resource extraction to fuel use is considered in the reference systems.

ISO 14044 provides several methods for dealing with systems that generate multiple products, which include physical allocation (e.g. by energy or exergy), economic allocation, and system expansion. For dealing with the co-product heat during SNG production, system expansion was applied as the preferable option compared to allocation in the foreground system [12,13]. System expansion can either be realized by system enlargement or by accounting for the avoided burdens [14]. The avoided burdens approach which is used in this study can be explained as follows: the environmental impacts, which would have been generated from the alternative production of heat (for the district heating system and the hospital) using a natural gas boiler, are subtracted from the life cycle impacts of the SNG system. Alternatively the comparison could have been done by adding these impacts to all reference systems (system enlargement).

2.4. *Used LCIA methods*

For impact assessment, relevant impact categories were assessed with midpoint indicators from the CML [15] and Ecoindicator '99 [16] methods, as well as the cumulated energy demand (CED) [17] and the global warming potential (GWP) [18] (Table 1). For aggregated impact assessment the Ecoindicator '99 (H/A) [16] and Ecological Scarcity 2006 [19] methods are used, the latter especially since it applies to the Swiss context. We assume that wood is a CO_2-neutral energy source (i.e. the uptake of CO_2 by trees is equal to its subsequent release during

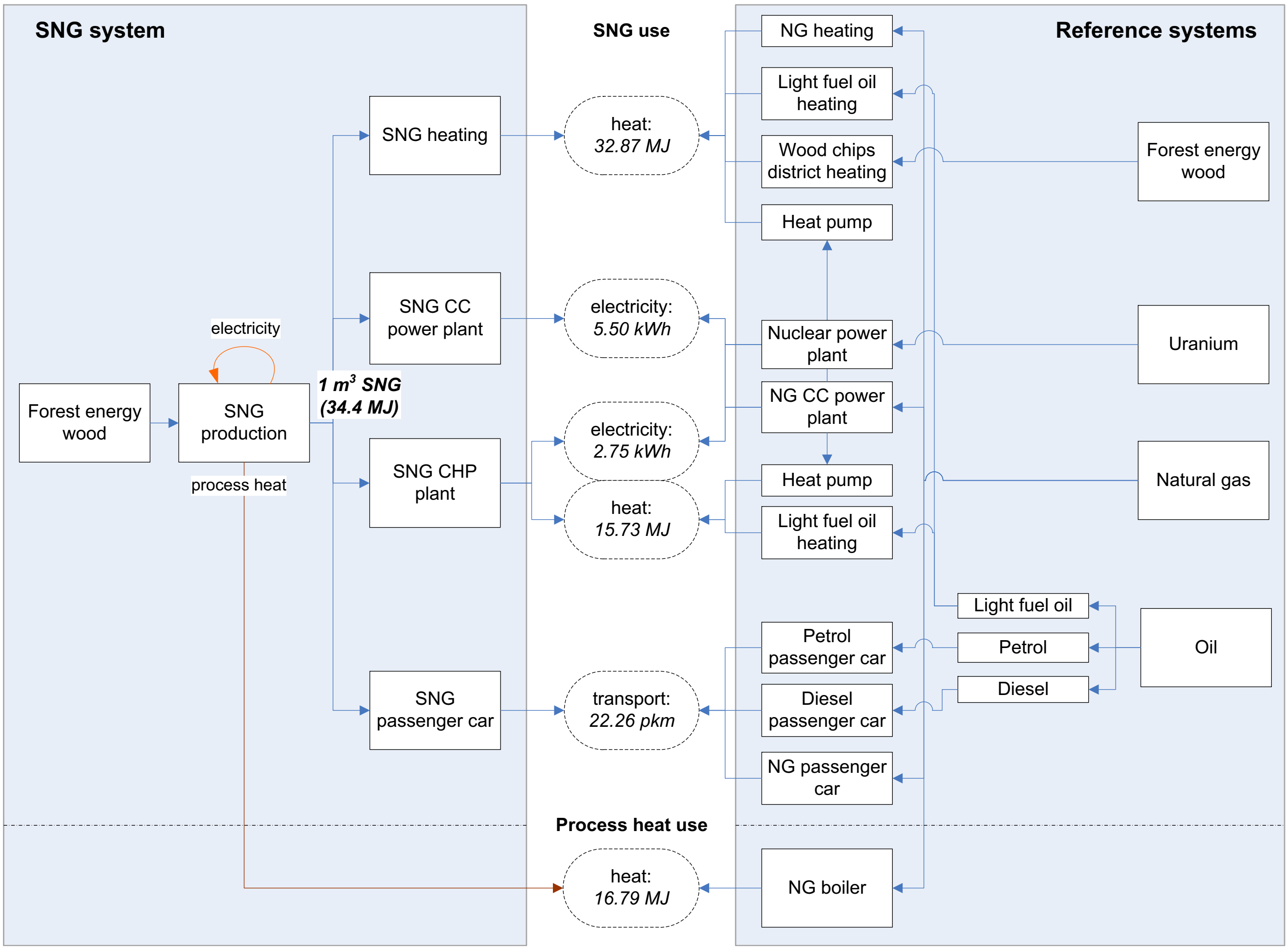

Fig. 1 – Compared SNG and reference systems. The numbers refer to the quantity of a service (heat, electricity or transport) that can be produced with 1 m^3 SNG. Process heat is always generated simultaneously and accounted for by system expansion. Electricity from co-generation at the SNG plant is consumed entirely during SNG production.

combustion) and therefore biogenic CO_2 was not considered in the impact assessment. This may not always be correct since the amount of CO_2 stored in the forest soil also depends on the type of forest management applied [20].

2.5. *Sensitivity analysis*

Seven scenarios were developed to account for potential future technology developments and factors that may worsen ecological performance at the SNG plant level.

I. The *increased efficiency* scenario assumes a wood-to-SNG conversion efficiency increase of 21 %, which seems achievable in the near future [21], especially for larger scale plants. Since less wood enters the process also fewer emissions are generated.

II. In the *denitrification* scenario NO_x emissions are reduced by 80% through a selective catalytic reduction (SCR) unit. Ecoinvent data was used for the material and energy demand of the SCR [22].

III. In the *process heat substitutes oil boiler* scenario we assume that the process heat from the SNG plant replaces heat from a light fuel oil boiler instead of a natural gas boiler.

IV. In the *process heat substitutes wood boiler* scenario we assume that heat from an already existing wood boiler is replaced by process heat. This allows for a non-biased comparison with conventional wood heating systems as it eliminates the avoided burdens from replacing the natural gas boiler. The scenario is not very realistic, however, since in the case of an existing wood boiler, an SNG plant would probably be built in a different location.

V. The *50% process heat unused* scenario is designed to assess the ecological performance if an important fraction of the process heat remains unused.

VI. The *100% process heat unused* scenario assesses the ecological performance if process heat remains completely unused.

VII. The *European (UCTE) electricity mix* scenario assesses the sensitivity of using the more carbon intensive European electricity mix instead of the Swiss mix for the plant's surplus electricity demand (the fraction that cannot be covered by its own production).

Table 1 – Overview of life cycle impact assessment (LCIA) methods used.

Impact category	Abbreviation	Unit	Source
Midpoint indicators			
Global warming potential	GWP	kg CO_2-eq.	[22]
Fossil fuels	FOSS	MJ surplus	[20]
Respiratory disease caused by inorganics	RESP	DALY	[20]
Photochemical oxidation	SMOG	kg ethylene eq.	[19]
Acidification	ACID	kg SO_2 eq.	[19]
Eutrophication	EUTRO	kg PO_4 eq.	[19]
Ecotoxicity	ETOX	PAF*m^{2}*yr	[20]
Land use	LAND	PDF*m^{2}*yr	[20]
Cumulated energy demand	CED	MJ in/MJ out	[21]
Aggregated impact assessment methods			
Ecoindicator ’99 (H/A)	EI’99	mPts.	[20]
Ecological Scarcity 2006	ES’06	Pts.	[23]

3. Life cycle inventories of compared systems

3.1. SNG system

3.1.1. *Wood growth, harvest and transportation*

Forest energy wood is produced either during thinning operations or as a co-product of timber harvesting. A recent analysis showed that from a sustainability perspective the current use of forest energy wood in Switzerland could be increased by roughly 50% [23]. To model the material and energy flows, ecoinvent v2.2 data was used. The principal physical inputs during wood growth include land, solar energy, and CO_2 from the atmosphere.

We assume that 72% of the harvested wood is softwood and 28% hardwood, which reflects Switzerland’s average wood consumption [24]. Ecoinvent data for harvest and thinning represent Swiss conditions. Impacts generated during this phase are allocated to the co-products timber, industrial wood, and energy wood-based on their economic value.

We assume an average transport distance from the forest road to the plant of 24 km (own calculation), and that transport takes place with a 28 t lorry.

3.1.2. *SNG production*

The SNG production process includes the following main steps: wood drying, gasification, gas cleaning, methanation, gas separation, and feed-in of the SNG into the natural gas network. Process data was obtained from the engineering company CTU [10]. Fig. 2 shows the process stages as well as the principal process inputs and outputs.

The plant is assumed to operate 7500 h y^{-1} during 30 years. Its infrastructure needs were estimated by linear down-scaling of data from a larger methanol plant [25]. To cover electricity needs that exceed the plant’s own generation, the Swiss electricity mix was used.

3.1.2.1. *Wood drying*. The forest wood chips arrive at the plant with a water content of 50% of its wet mass (dry matter content of 188.6 kg m^{-3}) and a corresponding lower heating value of 3.294 GJ m^{-3}, which is typical for forest wood [24]. To optimize gasification conditions and energy efficiency wood is pre-dried with hot air to a water content of 200 g kg^{-1} using excess process heat.

3.1.2.2. *Gasification*. The fast internally fluidized bed (FICFB) gasification technology is used [26]. Several alternative

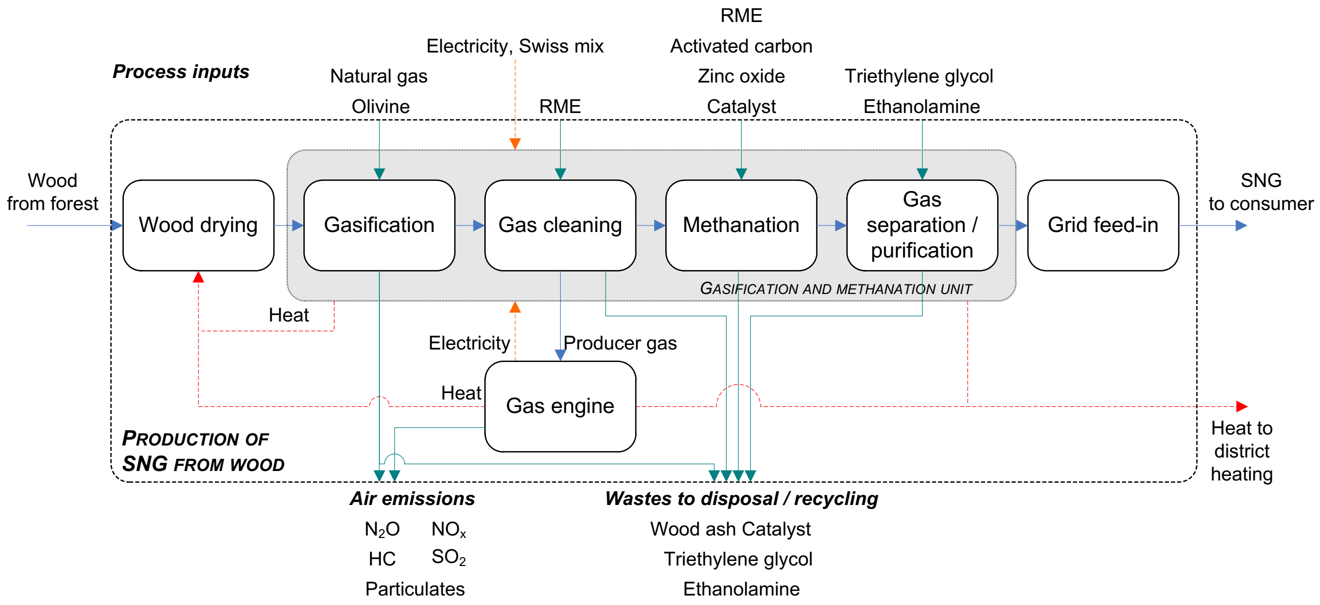

Fig. 2 – Principal SNG production stages as well as process inputs and outputs (RME = rape methyl ester; HC = hydrocarbons).

gasification technologies exist (energy efficiencies, suitability for SNG, and other process details are discussed in [2,27,28]). The FICFB gasification process consists of separate gasification and combustion chambers. In the gasification chamber, hot steam and the bed material olivine are used as energy carriers to gasify wood under the absence of oxygen. The resulting producer gas consists of hydrogen, carbon monoxide, carbon dioxide, and methane as well as other hydrocarbons, tars, and ash. In the combustion chamber the energy required to maintain this endothermic process is transferred to steam and olivine through the combustion of wood and incompletely gasified wood fractions (coke and tars). Natural gas can be co-fired for starting up the plant or to temporarily support combustion. Emissions from combustion are among others, nitrogen oxides, particulates, sulphur dioxide, hydrocarbons, and nitrous oxide. Wood ash is disposed of in a sanitary landfill.

3.1.2.3. *Gas cleaning*. During gasification, tars as well as other substances are formed from traces of nitrogen, sulphur, chlorine, and metals contained in the wood and transferred into the product gas, from which it needs to be cleaned. This is done in several steps including a baghouse filter to remove particles as well as a washing step with rape methyl ester (RME) as organic solvent to remove water and tars.

3.1.2.4. *Heat and power generation*. One third of the cleaned producer gas is used in a gas-powered combined heat and power unit to generate electricity. The plant's external electricity demand is thereby substantially lowered. Infrastructure was estimated from ecoinvent data for a small gas-powered heat and power plant. Emission values for NO_x and particulates are based on CTU data. Excess process heat is collected from various points during gasification, methanation, and from the combined heat and power unit by means of a central heat collection system and distributed to the district heating network.

3.1.2.5. *Methanation*. Two thirds of the cleaned producer gas is used for SNG production requiring further gas cleaning. It involves the following steps: non-volatile organic carbon compounds (e.g. organic sulphur and aromatics) are eliminated in a second gas washing step with RME, which is subsequently regenerated using N_2 and recycled CO_2 from the gas separation as stripping gas. Since not all of the H_2S is removed from the producer gas and H_2S leads to a deactivation of the methanation catalyst [2], two further adsorption steps using active carbon and a zinc oxide bed are necessary. The used activated carbon is burned in the gasification combustion chamber and thereby disposed of. ZnO reacts with H_2S to form ZnS, which can be regenerated to ZnO with atmospheric oxygen. The product SO_2 can be converted with calcium carbonate to calcium sulphate [9] and disposed of in a sanitary landfill.

Next, the producer gas is methanised. As an overall reaction, H_2 reacts with CO or CO_2 catalyzed by the nickel–aluminium catalyst to CH_4 and CO_2 or H_2O (see Ref. [2] for reaction details). The reaction is exothermic and process heat is transferred to the central heat collection system. The catalyst needs to be replaced periodically. As in Ref. [9] we assume that 98% of the catalyst can be recycled and therefore only 2% are disposed of in a hazardous waste incineration plant.

3.1.2.6. *Gas separation and purification*. After methanation, the raw-SNG consists mainly of CH_4, CO_2, unconverted H_2, traces of NH_3 as well as some water. CO_2 and water are removed in two subsequent steps, a washing step to remove CO_2 with monoethanolamine and a drying step using triethylene glycol to remove water. The spent solvents monoethanolamine and triethylene glycol are disposed of in a hazardous waste incineration plant. H_2 is removed by membrane separation and recycled to the methanation stage. The traces of NH_3 react with diluted sulphuric acid and are disposed of with the process water in a regular waste water treatment plant.

3.1.2.7. *Grid feed-in*. Except for mandatory gas odoration (which has been neglected due to the small amounts of odoration substance consumed) the SNG is now composed of >96% methane and meets the standards regarding the composition of grid-quality natural gas [29]. SNG is fed into a 100–500 kPa pressure gas pipeline, for which the gas pressure at the plant is sufficient and therefore no further compression is required.

An energy balance including all relevant energy inputs shows an overall energy efficiency of 58%, of which 39% is in form of SNG and 19% in form of process heat (Table 2). The overall efficiency is lower than results of recent process models that show efficiencies >70% [21], but it should be kept in mind that the present analysis is made from actual plans for a first-of-its-kind plant and for a plant size that is presumably suboptimal from the efficiency perspective.

3.1.3. *Process heat use*

The district heating network and the hospital require heat throughout the year, which is generated by a modulating natural gas boiler. Excess process heat from the SNG production is used to substitute a part of this heat demand.

3.1.4. *Transport of SNG*

SNG is transported through the existing pipeline network of Switzerland. For SNG heating, we assume that it is first transported in a 100–500 kPa network and then in a local 110 kPa network. Ecoinvent processes for the gas network infrastructure, the energy demand for the gas transportation, and the

Table 2 – Energy balance for the production of 1 m^3 SNG from wood.

Energy input MJ	% of energy input	
86.52	97.4%	Wood chips
0.55	0.6%	Electricity
0.94	1.1%	RME
0.80	0.9%	Natural gas
88.81	100%	Sum
Energy output MJ	% of energy input	
34.40	38.7%	SNG
16.79	18.9%	Heat
51.19	58%	Sum

emissions from pipeline leakage were used for Swiss conditions [30]. An important uncertainty is associated with data for methane leakages, especially from the local gas grid [30].

For SNG used for transportation, gas is transported in the 100–500 kPa network and compressed to 25–30 MPa at the service station to fuel passenger cars. Approximately 0.22 kWh electricity are required for the compression of 1 kg SNG [25].

3.1.5. *SNG use*

For SNG heating, SNG is burned in a modulating gas boiler typical for home heating (<100 kW) with an efficiency of 0.96.

Two systems were considered for generating electricity with SNG: (a) the use of SNG in a large combined cycle power plant (SNG CC, >200 MW) with an electric efficiency of 0.57 and (b) the use of SNG in a micro combined heat and power plant (SNG CHP, 100 kWe) producing electricity and heat with efficiencies of 0.29 and 0.46, respectively.

For transportation, SNG is used to fuel a natural gas car complying with the Euro 5 standard. Airborne emissions for the car operation, emissions to water and soil (e.g. heavy metals), as well as infrastructural requirements (e.g. car and road construction and maintenance) are based on data for a natural gas Euro 3 car [25] and were adapted to the Euro 5 standard.

3.2. *Reference systems*

3.2.1. *Fossil reference systems*

The production and refining of crude oil and its import in form of light fuel oil, diesel or benzene as well as the production and import of natural gas are based on ecoinvent data for Switzerland [30,31].

For fossil heating systems we used a light fuel oil boiler (10 kW), a modulating natural gas boiler (<100 kW), and a heat pump operated with electricity from natural gas as equivalents to the SNG home heating system [30–32].

The reference electricity systems include a 400 MWe combined cycle natural gas (NGCC) power plant [30] and a mix of nuclear power from pressure water (55%) and boiling water reactors (45%), corresponding to the current Swiss nuclear mix as it is unclear which type would be built in the future [33]. The heat produced by the SNG CHP plant is assumed to replace either heat from the natural gas or light fuel oil boilers described above.

For transportation, we use passenger cars complying to the emission standards Euro 5, which came into effect in Europe in 2009 [25]. This does not reflect today's average car fleet which consists to about 50% of Euro 1–3 cars [34]. It is assumed instead that consumers will decide between new cars of the Euro 5 standard and the SNG car.

3.2.2. *Conventional wood heating*

Conventional wood-based heating is represented by a 1 MW district heating system [35]. The boiler efficiency is 90%, however, a 11% heat loss is assumed for the district heating network [36]. For wood chips the same upstream chain (wood growth, harvest, and transport) as for the SNG system is used. A transport distance of 18 km was assumed.

4. Life cycle impact assessment results

4.1. *Impacts along the life cycle*

Table 3 shows the global warming potential (GWP) as well as Ecodindicator '99 (EI'99), and Ecological Scarcity 2006 (ES'06) scores that are related to the production and use of 1 m^3 SNG.

No greenhouse gas (GHG) emissions are generated during *wood growth*. In the EI'99 method land use is strongly weighted and solely responsible for the impacts. The appropriateness of such a strong weighting for managed forests may be questioned, especially since EI'99 points are allocated to wood products only, and not to other forest services e.g. protection from avalanches or recreational value. In the ES'06 method next to land use also the use of energetic biomass resources contributes to the impact score.

GHG emissions from *wood harvesting* are related to the use of fossil fuel. The EI'99 and ES'06 scores are dominated by the emissions from harvesting machinery, especially NO_x, and particulates.

Table 3 – Impacts generated along the life cycle of the production and use of 1 m^3 SNG for heating, electricity generation (CC), combined heat and power generation (CHP), and transportation.

SNG use	GWP (kg CO_2-eq.)				EI'99 (H/A) (mPts.)				ES'06 (pts.)			
	Heating	CC	CHP	Transport	Heating	CC	CHP	Transport	Heating	CC	CHP	Transport
Wood growth	–	–	–	–	43.85	43.85	43.85	43.85	208	208	208	208
Wood harvest	0.17	0.17	0.17	0.17	21.35	21.35	21.35	21.35	247	247	247	247
Wood transport	0.03	0.03	0.03	0.03	3.05	3.05	3.05	3.05	36	36	36	36
SNG production	0.15	0.15	0.15	0.15	88.50	88.50	88.50	88.50	1'023	1'023	1'023	1'023
SNG transport	0.15	0.02	0.15	0.05	2.02	0.71	2.02	2.36	58	10	58	78
SNG use	0.02	0.02	0.03	0.02	3.83	3.54	5.21	16.40	125	59	80	485
Car and road infrastructure	–	–	–	0.73	–	–	–	77.86	–	–	–	1'275
Gross impact	0.51	0.38	0.52	1.15	162.60	161.01	163.99	253.38	1'699	1'585	1'653	3'353
Avoided burdens from process heat use	−1.18	−1.18	−1.18	−1.18	−76.38	−76.38	−76.38	−76.38	−561	−561	−561	−561
Net impact	−0.67	−0.80	−0.66	−0.04	86.22	84.62	87.61	177.00	1'138	1'024	1'092	2'792

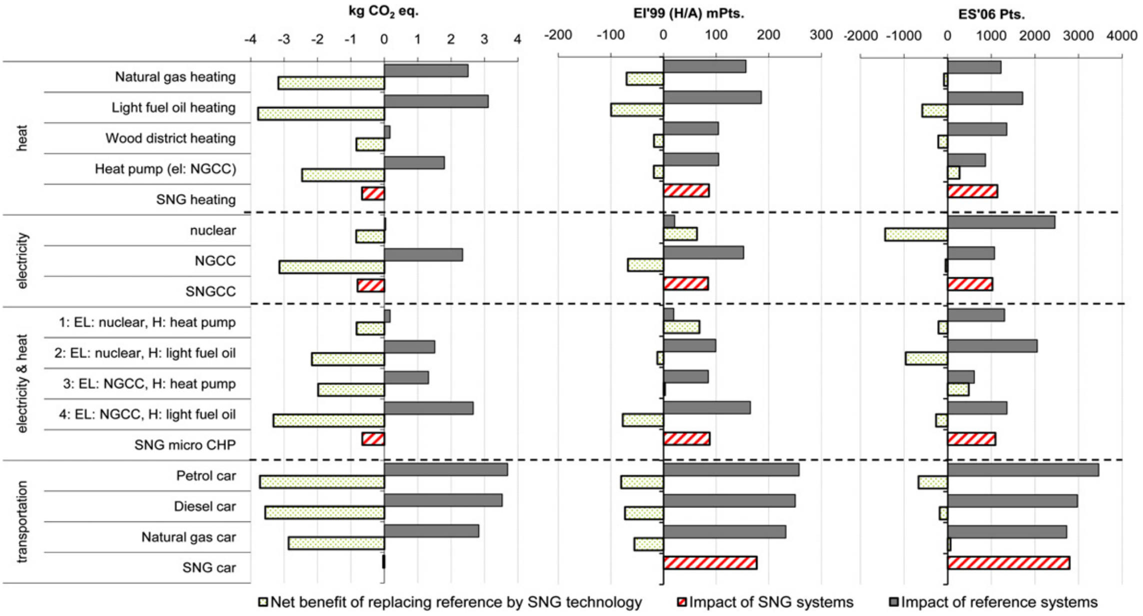

Fig. 3 – GHG emissions, EI'99 and ES'06 scores for reference systems (solid bars), SNG systems (striped bars), and net benefits of replacing reference through SNG systems (dotted bars). The net benefit is calculated as the difference of SNG and reference system impacts. The comparison with reference systems is based on the equivalent quantity of heat, electricity or transportation that is produced by 1 m^3 SNG (see also Fig. 1).

Wood transport by truck over short distances is rather efficient and thus the use of diesel and generated air emissions only cause small impacts.

SNG production is the most relevant life cycle stage contributing 35–54% to the overall EI'99 and 31–65% to the ES'06 score. With regard to GHG emissions it is the second most contributing stage with 13–39%. SNG production related EI'99 and ES'06 impacts are caused to 32–45% by NO_x and to 5–7% by particulate emissions from gasification and cogeneration in the gas engine. While the production of RME (biodiesel) is an important source of GHG emissions (15%), the involved land use generates additional EI'99 impacts (13%). The disposal of wood ash in the sanitary landfill also plays a role for all methods (5–10%). Furthermore, the consumption of Swiss grid electricity (40% nuclear power) is responsible for a small part of the ES'06 score (6%) and GHG emissions (25%). Natural gas that is used for the start-up of the plant also contributes to GHG emissions (6%).

Only minor impacts originate during the *transport of SNG* with all methods, except for GHG emissions if local networks are used (in case of SNG for heating and CHP), which exhibit significantly higher methane leakages. However, data with respect to these leakages is not well assured and the results should be seen critically [30]. SNG transport impacts are higher if SNG is used to fuel passenger cars due to the additional gas compression that is required. This is strongest for ES'06 due to the electricity consumption.

GHG emissions are also generated during the *use of SNG*, e.g. due to the electricity needed for boiler operation and the consumption of materials for building and maintaining the combustion infrastructure. EI'99 and ES'06 methods also strongly weigh air emissions such as NO_x, particulates, and benzene from SNG combustion. In the SNG transportation system, the environmental burdens are considerably higher due to tyre and brake pad abrasion that lead to soil and groundwater contamination with heavy metals (e.g. zinc and copper).

Road and passenger car production and maintenance are prerequisites for transportation with passenger cars. For all methods, considerable contributions (63% GWP, 30% EI'99, 38% ES'06) come from this step due to the large amounts of energy and resources required.

When accounting for the *use of process heat* to replace heat from the natural gas burner at the district heating hospital, net CO_2-eq. savings are achieved for all utilizations of SNG. Considerable impact reductions are also reached for EI'99 (30–47%) and ES'06 (17–35%).

4.2. Comparison with reference systems

Fig. 3 shows a comparison of reference systems to SNG used for heating, electricity, heat and electricity, and transportation. With respect to GWP, SNG systems perform considerably better than the reference systems since wood is basically a CO_2-neutral energy source. The GHG balance is negative due to the use of process heat to substitute the natural gas boiler.

From the Ecoindicator perspective, which strongly weighs the depletion of fossil fuels, the SNG systems mostly generate the lowest environmental burdens and therefore show considerable net benefits when substituting oil or gas based reference systems (e.g. transportation). The benefits of replacing nuclear power, heat pumps, and wood district heat are small or even negative.

From the Ecological Scarcity perspective, SNG systems show net benefits when nuclear power or oil based systems are substituted, but no or only small benefits when replacing heat pumps, wood heating and natural gas systems. The ES'06

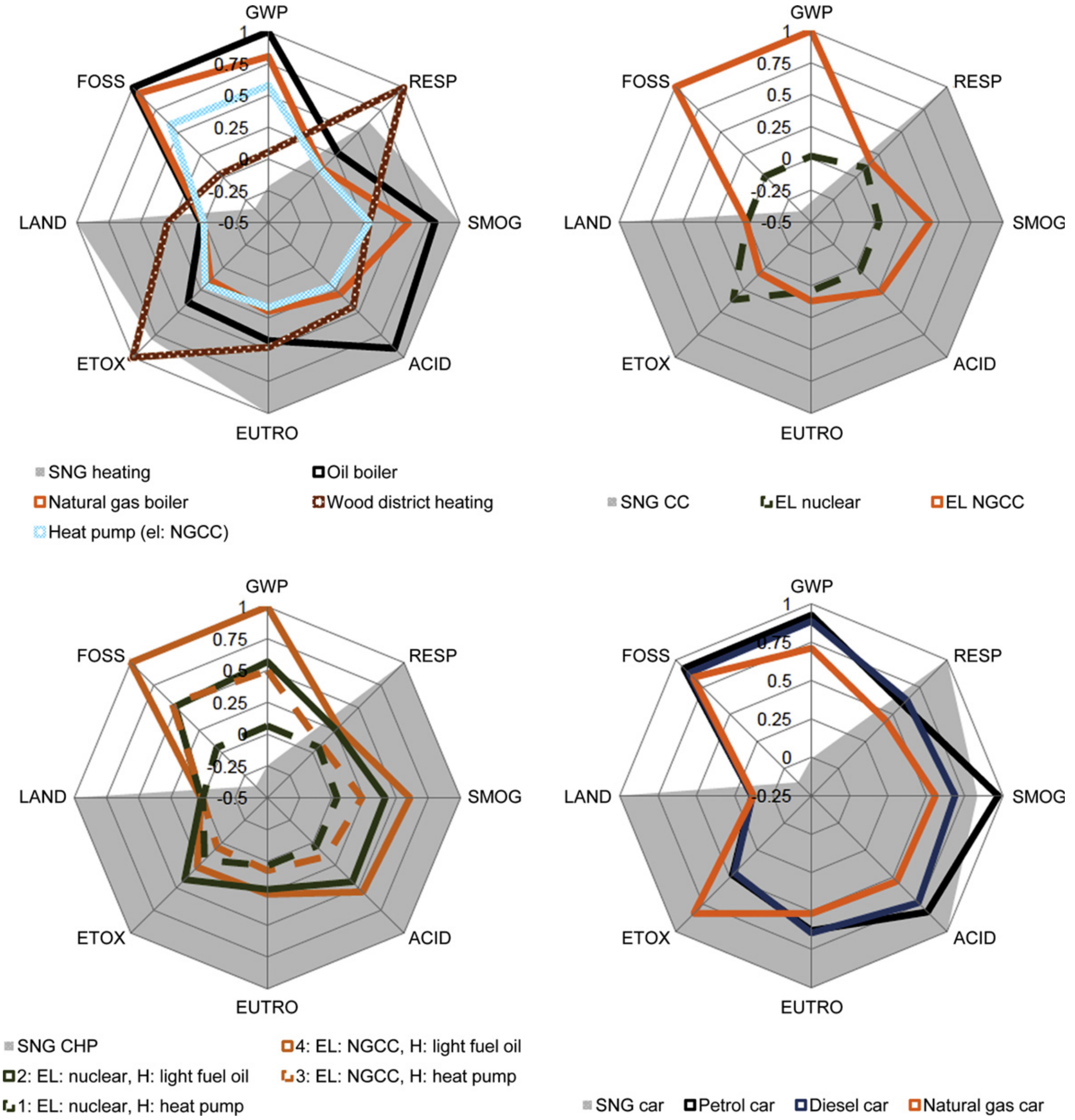

Fig. 4 – Comparison of selected midpoint indicator results for SNG systems. In each category 100% refers to the highest impact generated by one of the compared systems. Category abbreviations are explained in Table 1.

results differ therefore from the EI'99 perspective since more weight is given to emissions instead of fossil fuel depletion. Consequently, the advantage of SNG to natural gas systems is minimal. The two methods also disagree with respect to nuclear electricity: in contrast to EI'99, ES'06 weighs nuclear waste strongly and therefore the substitution of nuclear electricity seems beneficial.

4.3. *Midpoint indicator performance*

Fig. 4 shows environmental impacts from the compared systems for selected categories before weighting and aggregation to a single impact score (as e.g. for EI'99 and ES'06). The SNG systems (and the wood district heating) obviously outperform the reference systems with regard to the depletion of fossil fuels (FOSS) and global warming (GWP). At the same time, the SNG systems perform worse than the reference systems in almost all other categories. A principal driver for respiratory disease caused by inorganics (RESP), photochemical oxidation (SMOG), acidification (ACID), and eutrophication (EUTRO) are NO_x emissions, for which the SNG production (gasification and gas engine) is a major source. Further important impact sources for respiratory disease are particulate emissions, and for eutrophication nitrate, phosphate, and ammonia from the RME production chain. Next to air emissions, long-term ecotoxicity (ETOX) is also caused by the disposal of wood ash in the sanitary landfill and associated groundwater contamination with heavy metals. Wood-based systems also require more land, especially the SNG systems due to a lower overall energy efficiency. Conventional wood heating systems show a higher impact for respiratory disease caused by inorganics and ecotoxicity due to higher particulate

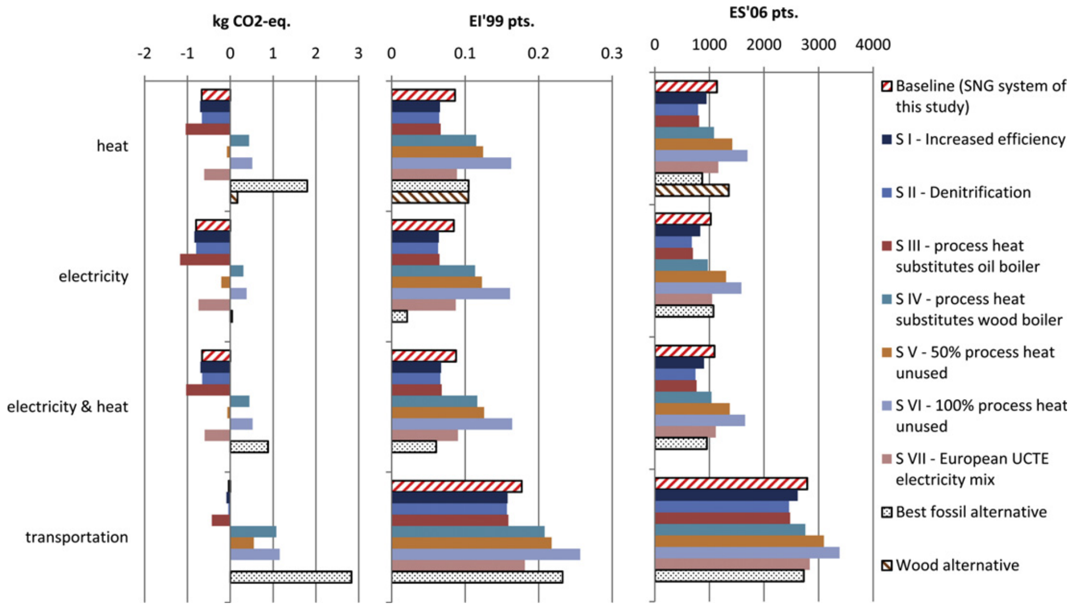

Fig. 5 – Sensitivity analysis results for SNG systems. Comparison with reference systems is based on the equivalent quantity of heat, electricity or transportation produced by 1 m^3 SNG.

emissions. Among the fossil reference systems, heat pumps and nuclear electricity perform best, followed by natural gas and finally oil based systems.

4.4. *Sensitivity analysis results*

Sensitivity analysis results are presented in Fig. 5. Significant improvements can be achieved with regard to EI'99 and ES'06 by increasing the overall plant efficiency or including a denitrification unit, and also with regard to GWP, by using the process heat to substitute an oil boiler instead of a natural gas boiler (S I–III). These measures could be combined to achieve even better results. On the other hand, performance seriously deteriorates if process heat is not used efficiently (S V–VI) and also somewhat if the European UCTE electricity mix is used for the plant's own supply (S VII).

Compared to the best fossil references, all SNG scenarios contribute less to global warming, even if process heat is not used efficiently. For EI'99 SNG used for heating or transportation has smaller impacts if process heat is used efficiently. For electricity generation and CHP the reference systems (nuclear power and heat pumps) clearly outperform the SNG system. From the ES'06 perspective, increased efficiency, denitrification and efficient use of process heat improve the environmental performance so that all SNG uses appear slightly better than the reference systems. The reverse is true for an inefficient use of process heat and to a small extent the use of the UCTE electricity mix.

Compared to the best wood reference, S I–III and S VII lead mostly to advantages, whereas the other scenarios causes worse performance. If process heat was used to substitute a wood boiler instead of the natural gas boiler (S IV), the SNG systems' environmental performances deteriorate. In this case, the generation of heat with a conventional district heating system appears to be the better alternative according to GWP and EI'99.

5. Discussion

GWP, EI'99, and ES'06 unanimously show that SNG is an environmentally friendly substitution for oil based heating and transportation systems. The substitution of electricity from natural gas systems is beneficial with regard to GWP and EI'99. The substitution of nuclear power yields benefits from the GWP and ES'06 perspectives. For GWP, the net benefit of the SNG system can be explained by the use of process heat, which is not assumed for the nuclear power plant.

The analysis of the environmental burdens along the life cycle also shows that a large fraction of the impacts is generated during the SNG production stage. These could be considerably reduced, and consequently the environmental

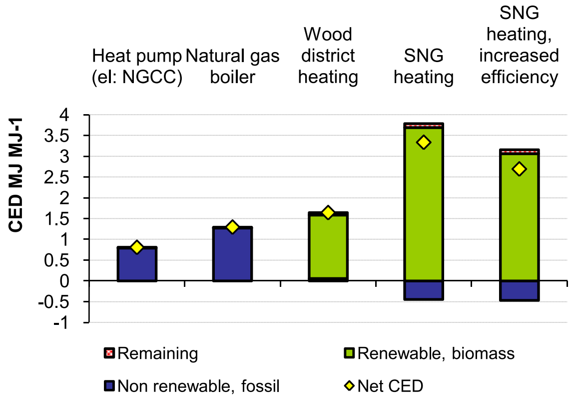

Fig. 6 – Cumulated energy demand (CED) for heating systems. The negative value of the SNG systems is due to the benefits from the use of process heat.

performance of the SNG systems enhanced, e.g. by increasing the conversion efficiency or installing a denitrification unit. The latter would lead to improvements in the categories eutrophication, acidification, and respiratory inorganics.

While SNG seems beneficial with respect to GHG emissions and the aggregated impact assessment methods (due to strong weight given to fossil fuel depletion and global warming), other environmental effects, e.g. impacts on human health by respiratory inorganics, do in fact increase.

The comparison to conventional wood heating systems does not yield a clear advantage for the SNG system. Moreover, from a resource efficiency perspective SNG heating is rather disadvantageous: compared to conventional wood heating, roughly twice the quantity of wood is required to produce the same quantity of heat (Fig. 6) and even for the increased efficiency scenario there is no break even. The reason is the lower overall conversion efficiency, which is a drawback of the SNG technology. This should also apply for the comparison of electricity derived from SNG and direct wood co-generation or gasification (own calculations showed higher heat and electricity yields for the direct wood use). However, this logic does not apply for transportation systems since biomass-derived transportation fuels generally require a conversion step.

An important future driver for SNG could be the increasing demand of biofuels for transportation (e.g. European 2020 biofuel targets [37]). Whether or not this will be the optimal environmental use of energy wood will also depend on the composition of the future energy demand and the availability of other renewable energy technologies to meet this demand. An answer to the question of the best use of energy wood can therefore not be provided in this work. However, in the light of medium term decreasing heat demands and increasing wind and solar power, wood-derived SNG could become an increasingly important biofuel for transportation, especially for longer distances where e-mobility currently faces limitations.

6. Conclusions

The production of SNG from wood in a polygeneration plant and its use in heating, electricity generation, and transportation systems outperforms fossil alternatives with regard to global warming. With respect to full life cycle impacts measured with Ecoindicator'99 and Ecological Scarcity 2006, the SNG systems perform better when replacing oil based heating and transportation systems, somewhat better when replacing natural gas systems and only slightly better or even worse when replacing heat pumps. There is disagreement between the methods whether it is worth substituting nuclear power. At the same time environmental benefits are compromised to some extent by impacts in other categories such as respiratory inorganics, ecotoxicity, and eutrophication. Considerable life cycle impacts are related to the SNG production and could be reduced by increasing process efficiency or limiting NO_x emissions. Such developments can be expected as commercial scale development is currently only in its initial stage. Regardless of the use of SNG, process heat must be used efficiently, or otherwise the environmental performance deteriorates significantly.

Compared to conventional wood heating systems a clear environmental advantage of SNG heating cannot be observed. From the resource perspective direct wood heating is more efficient. On the other hand, SNG for transportation seems to be a promising option, both with regard to environmental performance and future demand.

Acknowledgements

We would like to thank Conzepte Technik Umwelt AG (CTU) for providing SNG technology data, Serge Biollaz and Samuel Stucki from Paul Scherrer Institute for their internal reviews and the Swiss Competence Centre for Energy and Mobility (CCEM) for funding this study within the project "2nd Generation Biogas".

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