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Life Cycle Assessment of Substitute Natural Gas production from biomass and electrolytic hydrogen

Eleonora Bargiacchi [a], *Daniele Candelaresi* [b], *Antonio Valente* [c,*], *Giuseppe Spazzafumo* [b], *Stefano Frigo* [a]

[a] *University of Pisa, Department of Energy, Systems, Territory and Construction Engineering (DESTeC), Pisa, Italy*
[b] *University of Cassino and Southern Lazio, DICeM, Cassino, Italy*
[c] *ETH Zurich, Department of Chemistry and Applied Biosciences, Institute for Chemical and Bioengineering, Switzerland*

RESEARCH HIGHLIGHTS

- The LCA of six production routes of a substitute of natural gas is performed.
- The layout involving hydrogasification shows the most favourable performance.
- The electrolyser infrastructure arises concerns linked to acidification footprint.
- Methodological aspects affect the ranking of the considered technologies.

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ABSTRACT

The synthesis of a Substitute Natural Gas (SNG) that is compatible with the gas grid composition requirements by using surplus electricity from renewable energy sources looks a favourable solution to store large quantities of electricity and to decarbonise the gas grid network while maintaining the same infrastructure. The most promising layouts for SNG production and the conditions under which SNG synthesis reduces the environmental impacts if compared to its fossil alternative is still largely untapped. In this work, six different layouts for the production of SNG and electricity from biomass and fluctuating electricity are compared from the environmental point of view by means of Life Cycle Assessment (LCA) methodology. Global Warming Potential (GWP), Cumulative Energy Demand (CED) and Acidification Potential (AP) are selected as impact indicators for this analysis. The influence of key LCA methodological aspects on the conclusions is also explored. In particular, two different functional units are chosen: 1 kg of SNG produced and 1 MJ of output energy (SNG and electricity). Furthermore, different approaches dealing with co-production of electricity are also applied. The results show that the layout based on hydrogasification has the lowest impacts on all the considered cases apart from the GWP and the CED with SNG mass as the functional unit and the avoided burden approach. Finally, the selection of the multifunctionality approach is found to have a significant influence on technology ranking.

* *Corresponding author.*
E-mail address: antonio.valente@chem.ethz.ch (A. Valente).

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Introduction

In recent years, renewable energies are increasingly gaining relevance towards the achievement of environmental, economic and political objectives and for a diversification of the energy mix. Nevertheless, one of the main problems in the integration of renewable sources into the energy sector lies in the need for a reliable large-scale energy storage system that can decouple production from energy demand, especially for those non-programmable sources such as wind and solar. Generally, due to the use of a significant amount of power, electrolysis is an expensive process, but it could become cost-competitive and environmentally sustainable when powered by surplus electricity from renewable energy sources [1]. Such a surplus could occur either because the grid is not demanding for additional power or because it could create grid instability.

Under this context, biofuels production from solid feedstocks has been deeply investigated in recent years, because of its potential dual function of acting as long-term energy storage and processing the feedstock into a more versatile, storable and transportable chemical. A large variety of final fuels were proposed from the syngas obtainable from biomass gasification: methanol, ethanol, dimethyl ether (DME), substitute of natural gas (SNG) [2]. For the latter fuel, several different concepts for SNG production from biomass gasification were analysed [3], due to its promising overall energy efficiencies (up to 50%) especially in the presence of heat integration [4,5]. The exploitation of excess heat looked competitive also at small scales, although related to nearby heat demand [6]. Due to the high system complexity, some authors proposed an integrated methodology for the system design, in order to couple the often separated economic and energy integration aspects [7,8]. A multi-objective optimisation showed that a proper correction of the syngas composition with the addition of hydrogen from an electrolyser allows a higher plant efficiency, even if it penalises the plant economics [9]. The sorption enhanced gasification concept was proposed to further improve the system performances, eventually coupled to a Power-to-Gas plant to higher the SNG output mass flow [10]. Feeding the biomass syngas to a pressurised Solid Oxide Electrolyser (SOEC) would further improve the plant efficiency, mainly because the methanation reaction starts occurring directly in the SOEC [11].

Most of the published research on SNG production from biomass gasification focuses on plant design, energy efficiency or techno-economic aspects. Very few papers, though, address environmental perspectives.

Chandel et al. [12] explored the environmental implications of coal-to-SNG processes. Felder and Dones [13] assessed the ecological impacts of producing SNG from wood, finding out that SNG outperforms the oil derivatives and the fossil natural gas when the consumption of fossil resources is strongly weighted in the assessment. Regarding the end-users, the overall SNG impacts are lower when it is burnt in cars rather than in heating systems. Tasca et al. [14] performed an LCA of biomethane production from gasification of poplar short rotation forestry wood chips and anaerobic digestion of microalgae biomass. Gerber et al. [15] proposed a methodology to integrate LCA in techno-economic models, and they applied it to a thermo-economic model developed for the optimisation of SNG and electricity production from lignocellulosic biomass [7–9]. Skorek et al. [16] conducted a combined technical, economic and environmental assessment of the production of biomethane from three different pathways: manure fermentation and upgrading, manure fermentation and biogas methanation using renewable hydrogen from electrolysis and biomass gasification with syngas methanation. Lastly, Singlitico et al. [17] conducted a comprehensive review of LCA papers dealing with the production of biomethane, produced by anaerobic digestion, and SNG, produced by methanation and gasification.

This work aims at conducting an LCA on six different novel layouts for the co-production of SNG and electricity, which have not been covered yet by previous literature. Whereas in previous papers [18,19] an energy analysis was carried out, the layouts are hereby compared from the environmental point of view by means of LCA.

Case-study

In a previous paper [18] different layouts were analysed to evaluate the energy balance of the production of SNG starting from biomass and electrolytic hydrogen. Two alternative scenarios were considered: (i) only the SNG is produced (Fig. 1) and (ii) SNG and power are cogenerated (Fig. 2). The efficiencies of the different analysed layouts range from 52.4% to 73.8% (Eq. (1)) with chemical power (fuel) accounting for 73–100% of the total output.

$$\eta_{plant} = \frac{\dot{m}_{SNG} \cdot HHV_{SNG} + Electricity_{out}}{\dot{m}_{biomass} \cdot HHV_{biomass} + Electricity_{in}} \quad (1)$$

Different power units define different sub-scenarios:

- gas turbine (GT);
- steam injected gas turbine (STIG);
- internal combustion engine (ICE);
- solid oxide fuel cell (SOFC) fed by syngas at 6 bar (SOFC6);
- SOFC fed by syngas at 30 bar (SOFC30);
- the case of hydrogasification (HG) that does not involve the co-production of power.

All the considered plants are fed with lignocellulosic biomass, with an average composition of 40.32% carbon, 34.48% oxygen, 20.00% humidity, 4.88% hydrogen, 0.24% ash, 0.08% nitrogen, 64.87% volatile matter and 14.89% fixed carbon (weight %) and a Higher Heating Value (HHV) of 19 MJ/kg on a dry basis [18,19]. An alkaline electrolyser supplies the hydrogen that is necessary for the biomass hydrogasification in the first layout (HG, Fig. 1) and the hydrogen employed for the methanation reaction in the cogenerative layouts (Fig. 2). In the layouts with cogeneration of SNG and electricity, electrolytic oxygen is used in the gasifier and the power unit to separate carbon dioxide from exhaust gases more easily. The amount of oxygen used into the gasifier is related to the considered power unit since each of them has particular requirements of feeding gas composition and temperature. In

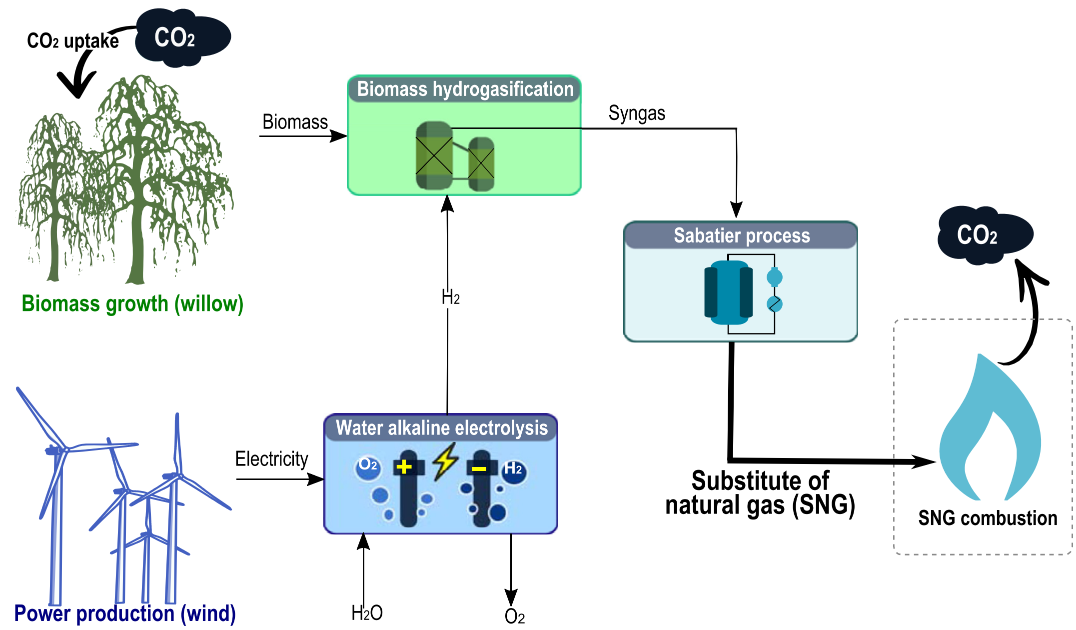

Fig. 1 – System diagram in case only SNG is produced (HG case).

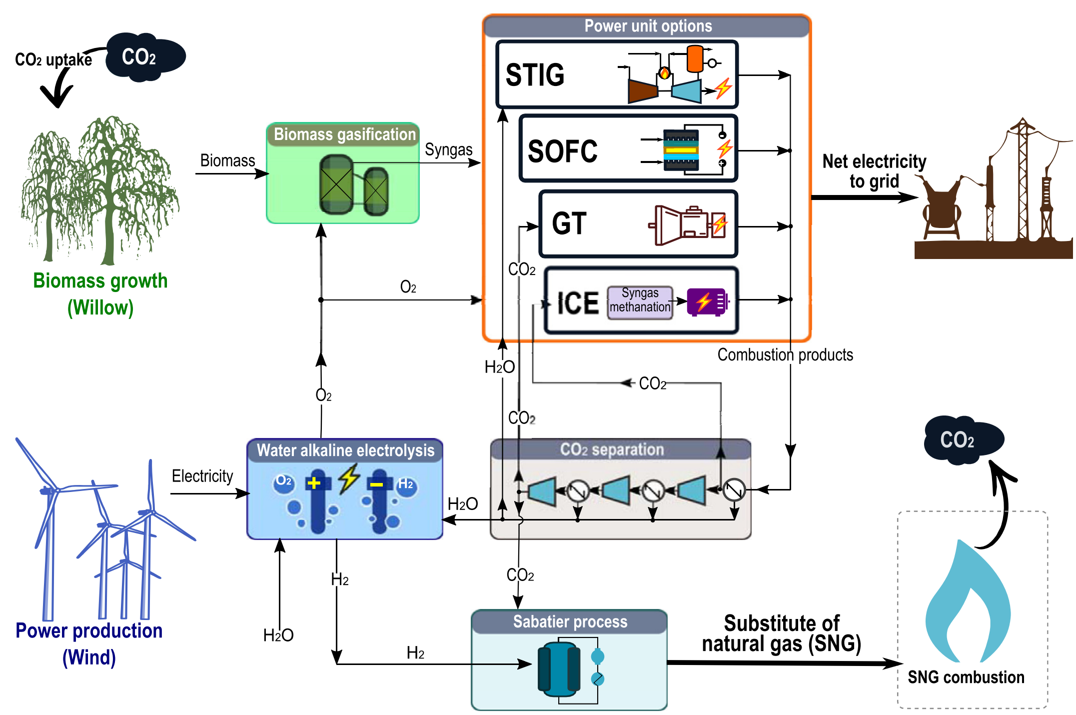

Fig. 2 – System diagram in case SNG and electricity are co-produced. The power unit varies in dependency of the chosen case study. SOFC refers to both SOFC6 and SOFC30 layouts.

the cases of STIG and SOFCs there is no recycle of carbon dioxide, while in the ICE and GT there is a partial recycle of carbon dioxide that acts as a temperature moderator agent, which occurs, respectively, at 1 bar and 30 bar (i.e., upstream or downstream of the compression line). Gas expanders are used to adjust pressures in different parts of the plant. Further and extensive details can be found in Ref. [18].

Whereas in the previous work an energy analysis was carried out, in this paper the layouts are compared from the environmental point of view by means of LCA methodology.

First, an impact assessment of the six analysed layouts is carried out for three impact categories, in a base-case scenario elaborated with the avoided burden approach. Since five out of six layouts co-produce SNG and electricity, in order to explore the role of key LCA methodological aspects, a sensitivity analysis on the functional unit and on the methodology to handle multifunctionality is presented.

Methodology

In this work, an attributional LCA was performed, according to the ISO 14040 [20] and 14044 [21] guidelines. The standardised LCA methodology involves four main stages. In the first stage (goal and scope definition) the system boundaries, the functional unit (i.e., the flow that represents the main function of the system under analysis), the time, the geographical scope and the impact categories to characterise the environmental performance are defined.

The second stage (life cycle inventory analysis) describes the methods and the sources applied to quantify the main net flows of material and energy (e.g., heat, electricity, emissions, feedstocks, raw materials, wastes) crossing the system boundaries, in relation to the functional unit. For those systems performing more than one function or with more than one product (i.e., the so-called multifunctional systems), the approach to deal with this multifunctionality has to be also defined. In this regard, the ISO standard prioritises the use of “system subdivision” (i.e., the subdivision of a multifunctional system into multiple monofunctional systems). When the application of system subdivision is not possible, the allocation of impacts should be avoided by the “system expansion” approach. This approach consists in discounting the environmental burdens associated with the co-function (or co-products) considered to be produced through the conventional pathway. When system expansion is not applicable, allocation procedures can be applied to redistribute the inputs and the outputs among the co-functions according to physical (e.g., mass, mole, energy, exergy) or economic bases.

The third stage (life cycle impact assessment) consists in classifying the inventory substances in inputs and outputs according to the environmental selected impact categories. After the classification, the environmental impacts are characterised by means of a set of characterisation factors that are specific of the substance, the impact and the selected assessment method (e.g., ReCiPe, CLM, IPCC, VDI etc.).

Finally, in the last stage (interpretation), the main outcomes and recommendations are summarised in line with the goal and the scope of the study. In this phase, potential environmental hotspots can be identified and improvements can be proposed. The sensitivity of the results and the conclusions on key aspects or parameters can also be explored.

Goal and scope definition

The main scope of the present study is to compare different plant layouts for SNG production from biomass and electrolytic hydrogen from an environmental perspective.

The comparative assessment was performed by exploring the effect of different methodological assumptions. The system is polygenerative since it co-produces SNG and electricity; for this reason, different functional units (1 kg SNG, 1 MJ of total energy produced) were chosen for the assessment. It has to be remarked that in the first case (functional unit of 1 kg SNG) the main product SNG is considered to maintain the same composition in all the investigated layouts, as reported in Frigo and Spazzafumo [18], and producing SNG is the main function of the system.

The system boundaries include the main steps for SNG production from biomass growth and water extraction to SNG combustion (Cradle-to-Grave approach). The infrastructure was included in the study, with inventories detailed in Section Life Cycle Inventory and data collection.

The life cycle environmental performance is characterised by quantifying the environmental impacts of global warming potential 100 years horizon (GWP), non-renewable cumulative energy demand (CEDnr) and acidification potential (AP) by employing the impact assessment methods of IPCC 2013 [22], VDI [23] and CML-IA baseline [24], respectively. The selection of the life cycle impact indicators is based on their relevance in energy systems involving hydrogen production [25]. The LCA tool used to implement the Life Cycle Inventories (LCIs) was the SimaPro software [26].

Life cycle inventory and data collection

Materials and energy requirements and intermediate flows are calculated through simulation by means of Aspen Plus software [18]. Table 1 shows the net inputs and outputs considered to build the LCI for the six SNG systems under analysis.

It is important to note that the hydrogen (as an intermediate flow) needed in input to the methanation section to produce 1 kg of SNG corresponds to 0.262 kg for INV-HG system while it is equal to 0.515 kg for the remaining case studies. The production capacity is 559 kg SNG$\cdot$h^{-1} in all the systems under analysis. Inventory data for background processes are retrieved from ecoinvent database [29].

It should be noted that Strazza et al. [28] report in their inventory some material flows required in the SOFC that are not present in ecoinvent database. For this reason, nickel oxide inventory was based on [30,31], zirconium chloride and yttrium chloride inventories were modelled according to Refs. [32–35] respectively. In particular, nickel oxide, as a precursor of metallic nickel at 99.5% purity, was obtained by considering an intermediate process in the nickel extraction and purification process. Similarly, zirconium oxide was considered as a precursor for zirconium chloride, adding the material and energy requirements for the chlorination process of ZrO_2 at 1200 °C.

Regarding infrastructure and capital goods, the sections of methanation and gasification were included within a conventional chemical factory (organics) entry, while the power units and the electrolyser were separately considered as reported in Table 1.

Apart from the built-in ones, all the inventory data were taken from ecoinvent 3.5 [36,37]. The biomass was willow wood chips and particles, from short rotation coppice, from ecoinvent database. The carbon balance was quantified by using the biomass composition reported in Section Case-study. In this regard, given the biomass input the same in

Table 1 – Inventory data for the SNG technologies considered in this study. (Amount per kg of SNG produced).

Flow	I/O	Unit	INV-HG	ICE-BS	STIG	GT	SOFC6	SOFC30
Electrolysis[a]								
Wind electricity (to H_2)	i	kWh	12.85	25.22	25.24	25.24	25.23	25.27
Wind electricity (H_2 compression)	i	kWh	$5.17\cdot10^{-2}$	$1.01\cdot10^{-2}$	$1.01\cdot10^{-2}$	$1.01\cdot10^{-2}$	$1.01\cdot10^{-2}$	$1.02\cdot10^{-2}$
Deionised water	i	kg	2.94	5.77	5.77	5.77	5.77	5.78
KOH	i	g	0.22	0.44	0.44	0.44	0.44	0.44
Oxygen	o	kg	2.10	4.20	4.20	4.20	4.20	4.20
Electrolyser (1 kW)	i	p	$1.60\cdot10^{-4}$	$3.20\cdot10^{-4}$	$3.20\cdot10^{-4}$	$3.20\cdot10^{-4}$	$3.20\cdot10^{-4}$	$3.20\cdot10^{-4}$
Methanation								
Wastewater	o	kg	1.05	2.17	2.17	2.17	2.17	2.18
Waste steel, recycling	o	kg	$9.12\cdot10^{-5}$	$9.12\cdot10^{-5}$	$9.12\cdot10^{-5}$	$9.12\cdot10^{-5}$	$9.12\cdot10^{-5}$	$9.12\cdot10^{-5}$
Waste zeolite, landfilling	o	kg	$2.49\cdot10^{-4}$	$2.49\cdot10^{-4}$	$2.49\cdot10^{-4}$	$2.49\cdot10^{-4}$	$2.49\cdot10^{-4}$	$2.49\cdot10^{-4}$
Rhodium, catalyst (GLO)	i	kg	$1.25\cdot10^{-6}$	$1.25\cdot10^{-6}$	$1.25\cdot10^{-6}$	$1.25\cdot10^{-6}$	$1.25\cdot10^{-6}$	$1.25\cdot10^{-6}$
Aluminium oxide, catalyst (GLO)	i	kg	$2.48\cdot10^{-4}$	$2.48\cdot10^{-4}$	$2.48\cdot10^{-4}$	$2.48\cdot10^{-4}$	$2.48\cdot10^{-4}$	$2.48\cdot10^{-4}$
Chromium steel 18/8 (GLO)	i	kg	$9.12\cdot10^{-5}$	$9.12\cdot10^{-5}$	$9.12\cdot10^{-5}$	$9.12\cdot10^{-5}$	$9.12\cdot10^{-5}$	$9.12\cdot10^{-5}$
Gasification								
Biomass production, SRC	i	kg	1.79	1.79	1.79	1.79	1.79	1.79
Water, deionised	i	kg	–	1.28	–	–	–	–
Electricity	o	kWh	–	1.79	4.73	2.20	4.09	3.72
Electricity (bottom cycle)	o	kWh	–	0.94	–	1.37	1.13	1.32
Capital Goods								
Chemical factory, organic	i	p	$4.00\cdot10^{-10}$	$4.00\cdot10^{-10}$	$4.00\cdot10^{-10}$	$4.00\cdot10^{-10}$	$4.00\cdot10^{-10}$	$4.00\cdot10^{-10}$
Power unit								
SOFC (230 kW)[b]	i	p	–	–	–	–	$6.81\cdot10^{-7}$	$4.04\cdot10^{-7}$
Turbine (micro, 100 kW)	i	p	–		$1.83\cdot10^{-6}$	$1.98\cdot10^{-6}$	$2.31\cdot10^{-6}$	$2.01\cdot10^{-6}$
Turbine (10 MW)	i	p	–	–	$2.78\cdot10^{-8}$	$1.66\cdot10^{-8}$	–	–
Inverter (500 kW)	i	p	–	–	–	–	$1.57\cdot10^{-7}$	$1.86\cdot10^{-7}$
Generator (200 kW)	i	p	–	$2.29\cdot10^{-7}$	$3.47\cdot10^{-7}$	$3.56\cdot10^{-7}$	$2.89\cdot10^{-7}$	$2.51\cdot10^{-7}$
Compressor (300 kW)	i	p	–	$2.02\cdot10^{-7}$	$3.47\cdot10^{-7}$	$3.04\cdot10^{-7}$	$2.10\cdot10^{-7}$	$4.47\cdot10^{-7}$
ICE + generator (160 kW)	i	p	–	$1.20\cdot10^{-7}$	–	–	–	–

[a] The life-cycle inventory for alkaline water electrolysis is taken from Valente et al. [27].
[b] The life-cycle inventory for solid oxide fuel cell (SOFC) is taken from Strazza et al. [28].

each layout, a CO_2 uptake equal to −1.77 kg CO_2/kg biomass was applied. Regarding fuel combustion emissions, all the layouts adopt the same composition as conventional natural gas to which fossil characterisation factors were applied. Since the layouts refer to upcoming technologies, the electricity displaced by the plant was assumed from a 2030 scenario (Table 2) with a higher renewable share than current mixes, which is conservative for the purpose of this study. The electricity used for the electrolysis process and compression duties was assumed to be produced from wind power.

In this study, the assessment was performed to explore the effect of different methodological assumptions. Using 1 kg of SNG as the functional unit, avoided burdens approach was applied in the base scenario. As mentioned above, this multifunctionality approach consists in discounting the burdens associated with the co-product (i.e., electricity) that is considered to displace the production of the conventional Italian mix electricity (2030 base). In the second scenario, the burdens of the whole system were distributed between the two products (SNG and electricity) according to an energy allocation. Since each layout produces SNG and electricity in different proportions, allocation factors are different among layouts (see Table 3). The allocation factors (AF) for the i-th layout were calculated according to equations (2) and (3), where the SNG energy content was calculated based on its Lower Heating Value (LHV).

Table 2 – Italian 2030 energy mix for electricity production (TWh). Data from Ref. [38].

Installed Technology	Installed Capacity (TWh)	Share (%)
Gas	118.00	38.5
Gas, CC	36.09	11.8
Gas, conventional	9.69	3.2
Gas, CC, 400 MW	44.68	14.6
Gas, conventional, 100 MW	27.54	9.0
Coal	0.00	0.0
Oil and others	2.00	0.7
Oil, conventional	0.43	0.1
Oil, cogeneration	1.57	0.5
Geothermic	7.10	2.3
Bioenergy	15.70	5.1
Biogas, gas engine	11.96	3.9
Wood chips	3.74	1.2
Solar	74.50	24.3
PV, rooftop	30.15	9.8
PV, ground mounted	43.06	14.0
CSP	1.27	0.4
Wind	40.10	13.1
Onshore, <1 MW	10.70	3.5
Onshore, 1–3 MW	24.17	7.9
Onshore, >3 MW	3.27	1.1
Offshore	1.96	0.6
Hydro	49.30	16.1
Hydro, Pumped storage	1.43	0.5
Hydro, Reservoir	30.64	10.0
Hydro, Run-on	17.23	5.6
Tot	306.70	100.0
Tot RES	186.70	60.9

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Table 3 – Allocation factors for the two co-products (SNG and electricity) in the energy allocation scenario.

Plant layout	SNG allocation factor	Electricity allocation factor
GT	80%	20%
ICE	84%	16%
HG	100%	–
SOFC30	74%	26%
SOFC6	73%	27%
STIG	75%	25%

$$AF_{SNG,i} = \frac{FU_{SNG} \cdot LHV_{SNG}}{Electricity_{out} + FU_{SNG} \cdot LHV_{SNG}} \quad (2)$$

$$AF_{electricity,i} = \frac{Electricity_{out}}{Electricity_{out} + FU_{SNG} \cdot LHV_{SNG}} = 1 - AF_{SNG,i} \quad (3)$$

In order to further explore the effects of the sensitivity of the results to allocation factors, an extreme case in which the produced electricity is not dispatched is also discussed. In this case, the burdens are attributed only to the SNG production.

In addition, when the main functional unit was 1 MJ of total energy in output, the system does not present co-functions; therefore, no multifunctionality approaches are followed.

Results and discussion

SNG mass as the functional unit

Based on the inputs and assumptions specified in section Methodology, carbon footprint, acidification footprint and non-renewable energy footprint were calculated for the six analysed layouts (see Figs. 3–5 respectively).

The layout having the lowest GWP impact (−0.45 kg CO_2 eq/kg SNG) is the SOFC6 due to its higher production of electricity which results in higher credits (see Fig. 3). The layouts with still negative or null GWP impact are the SOFC30, the STIG and the GT, with −0.42, −0.39 and 0.00 kg CO_2 eq/kg SNG, respectively. The highest GWP impacts are registered for the ICE (0.26 kg CO_2 eq/kg SNG) and the HG solutions (0.76 kg CO_2 eq/kg SNG). In the latter case, the lower impacts attributed to wind generation (51% lower than in the other configurations) do not compensate the lack of environmental credits for electricity fed to the grid.

The layout reporting the lowest AP footprint (0.0143 kg SO_2 eq/kg SNG) is the HG (see Fig. 4), because of the low wind electricity consumption. The layouts STIG, SOFC6 and SOFC30 have similar AP footprint, accounting for 0.0171 ÷ 0.0173 kg SO_2 eq/kg SNG. The GT layout implies 0.0188 kg SO_2 eq/kg SNG. The ICE layout causes the highest AP footprint (0.0197 kg SO_2 eq/kg SNG) due to reduced electricity production and therefore lower environmental credits in the avoided burdens approach.

As far as the CEDnr is concerned, the SOFC30, SOFC6 and STIG layouts outperform the other solutions, reporting impacts of −14.75, −14.17 and −13.48 MJ/kg SNG, respectively. This is ascribable to the environmental credits given to the electricity fed to the grid. The GT and ICE layouts cause intermediate, but still negative CED impact (−7.21 and −3.07 MJ/kg SNG). The HG is the plant that has the most relevant CED impacts, accounting for 6.39 MJ/kg SNG. As for the carbon footprint, this layout is penalised by the lack of environmental credits for electricity production.

Impact breakdown

In all investigated layouts, the major GWP impact (38–49% on the total) is given by the SNG combustion (see Fig. 3). Electricity production from wind power plants represents 4–6% over the total carbon footprint, and other processes (i.e., deionised water production and wastewater treatment) account for only 3–4% of the share for all layouts. With respect to the environmental credits, the higher benefit is given by the CO_2 uptake from the atmosphere by the biomass (between −45% and −35% of the total carbon footprint). With the energy mix employed in the present study, the environmental benefits related to the electricity production avoided emissions range between −18% (SOFC layouts) and 0% (HG layout).

The highest impact on AP is ascribable to the electrolyser infrastructure (60–79% of the overall impacts) for all considered layouts, as shown in Fig. 4. In particular, the major contribution to AP is ascribable to the mining of catalyst metals (nickel and rhodium) for electrodes manufacturing. Wind electricity production, other processes and biomass supply account for 9%, 5–7% and 2–5% of the total impacts, namely. The environmental benefits for electricity production can contribute significantly (up to −21% in the SOFC and STIG layouts) to decrease the AP overall footprint. The HG layout shows a minor acidification footprint due to the lower amount of hydrogen required and proportionally lower burdens embodied in the electrolyser infrastructure per functional unit (Table 1).

With respect to the CEDnr, the major (negative) contribution is given by the electricity credits for the cogenerative layouts (−70% to −56%), while the most significant positive contribution is ascribable to electricity production from wind power (17–26%) (see Fig. 5). Other processes and biomass supply are responsible for 9–14% and 3–4% of the share, namely. Since the HG layout has no environmental credits from electricity production, the wind electricity production, other processes and the biomass supply account for 51%, 32% and 16% of the total CEDnr footprint.

Energy output as the functional unit

Since five out of six investigated layouts are cogenerative, it is worth investigating the sensitivity of the results to functional unit changes. Fig. 6 shows the impact assessment for a functional unit of 1 MJ of energy output. The layout that implies the lowest GWP, AP and CED is the one with hydrogasification (HG). The second lowest GWP is with the ICE layout, which, on the other hand, gives the highest impacts in terms of AP and CEDnr. The SOFC30, SOFC6 and STIG layouts report similar impacts on all the considered indicators, slightly lower than the GT layout. Conventional natural gas has higher impacts than the proposed layouts in terms of GWP and CEDnr but

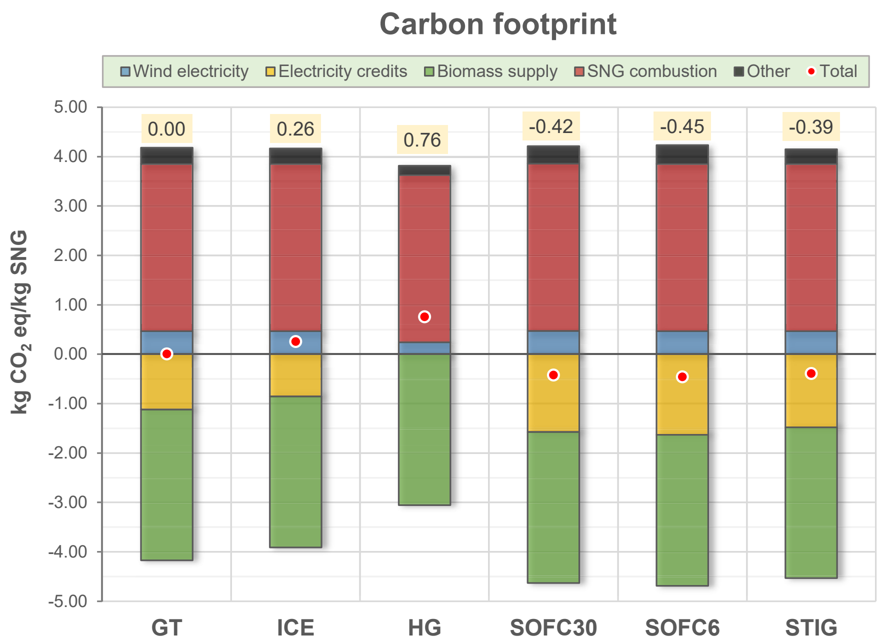

Fig. 3 – Impact breakdown for the GWP indicator for the six analysed layouts.

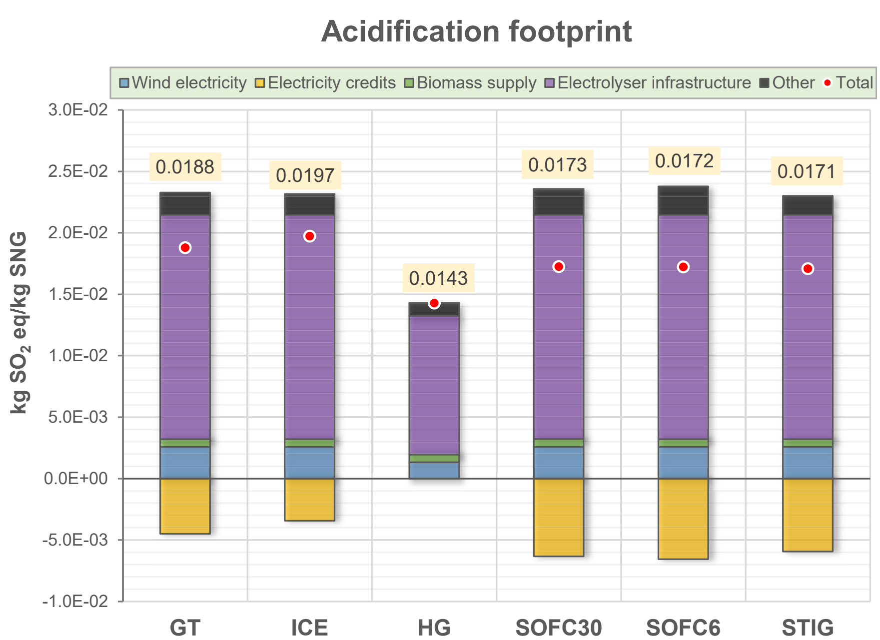

Fig. 4 – Impact breakdown for the AP indicator for the six analysed layouts.

outperforms SNG in terms of AP. This found to be closely linked to the use of fertilisers and pesticides in the biomass growth stage in the six layouts producing SNG.

Multifunctionality handling

The impact assessment results and the ranking among the layouts change according to the chosen multifunctionality methodology. In the base-case scenario (avoided burdens approach), the SOFC6, SOFC30 and STIG layouts (in this order) outperform all the other layouts in the GWP and the CEDnr impacts, while the layout with the lowest impact on the AP is the HG (see Fig. 7). The base-case results have been already deeply discussed in sections SNG mass as the functional unit and Impact breakdown.

On the contrary, when using an allocation approach (scenario 2) the layout with the lowest impacts on all considered indicators is the HG (see Fig. 8). The layouts having the highest GWP impact are the SOFC6 and SOFC30 layouts. The rest of the ranking is completely overturned. Still in the energy allocation approach, the layouts with the most significant AP and CEDnr impacts are the ICE, and secondly, the GT.

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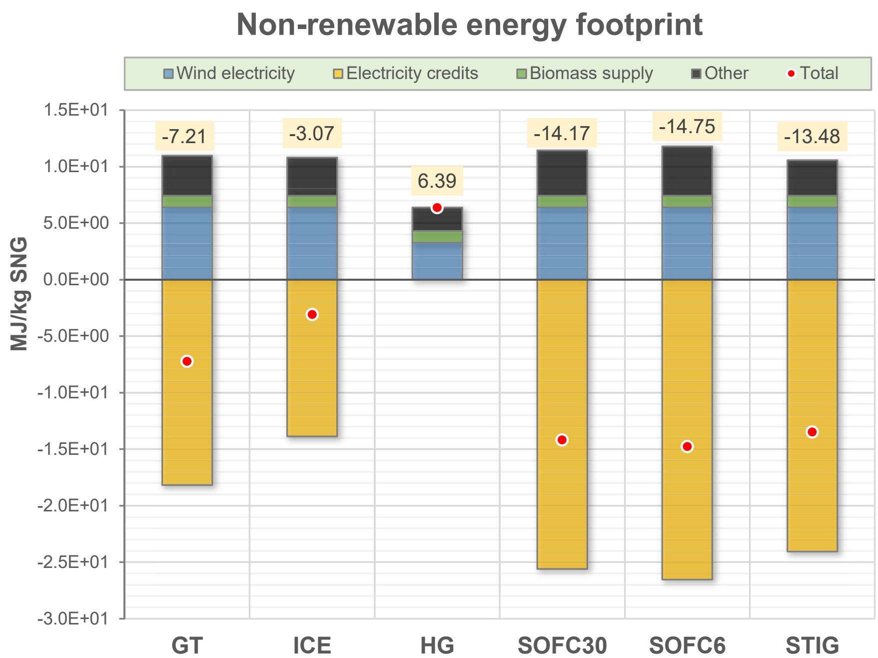

Fig. 5 — Impact breakdown for the CEDnr indicator for the six analysed layouts.

Regardless the multifunctionality approach applied, the overall GWP impacts of all layouts are significantly lower than in the case of NG, while the AP impacts of NG are much inferior than all the proposed layouts. With allocation approaches, the cogenerative solutions resulted penalised by the lack of credits from the co-produced electricity. Thus, although the ISO standards recommend avoiding allocation when possible, in this analysis allocation denotes a more conservative approach in contrast to the avoided burdens.

When exploring the effects of the uncertainty of allocation factors on the results, in the extreme case in which the produced electricity is not dispatchable, 100% of burdens and credits are attributed only to SNG. Counter-intuitively, in this case GWP impacts of the multifunctional systems are lower than their GWP impacts calculated using an allocation factors/ Table 3). This is due to the fact that the GWP impacts that are allocated are negative and, in absolute terms, the allocation factors reduce more benefits than impacts. In contrast to

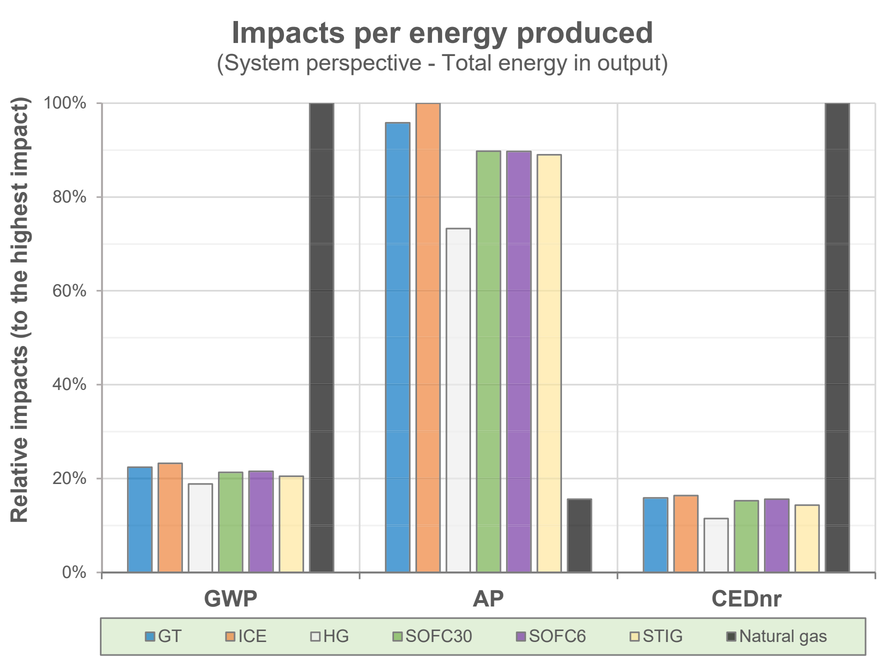

Fig. 6 — GWP, AP and CEDnr impacts for all investigated layouts.

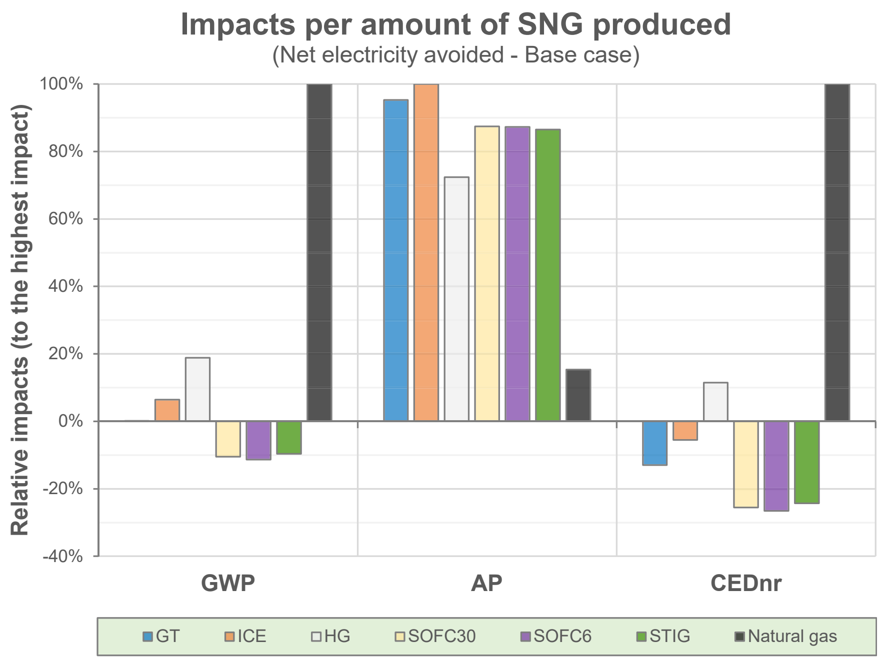

Fig. 7 — GWP, AP and CEDnr relative impacts for all investigated layouts, in the base-case scenario (avoided burdens approach).

GWP, for AP and CEDnr indicators (impacts with positive value), a higher allocation factor to the SNG production corresponds to higher impacts. When looking at the comparison with NG impacts, in case the electricity is not fruitfully used and fed to the grid, the produced SNG gives higher AP and CEDnr impacts than the fossil alternative.

Clearly, this last extreme scenario would be disadvantageous as for economic profitability but, being it the most conservative, it gives an immediate upper value to the calculated impacts for intermediate cases (i.e., electricity dispatched to the grid in a small number of hours per year).

Overall, regardless layout configuration for the co-production of electricity (i.e., type of the power unit) and regardless LCA methodological aspects linked to multi-functionality approach and functional unit choice, the production of SNG using biomass and renewable electricity shows favourable performances under carbon- and energy-related life cycle impact categories when comparing with the

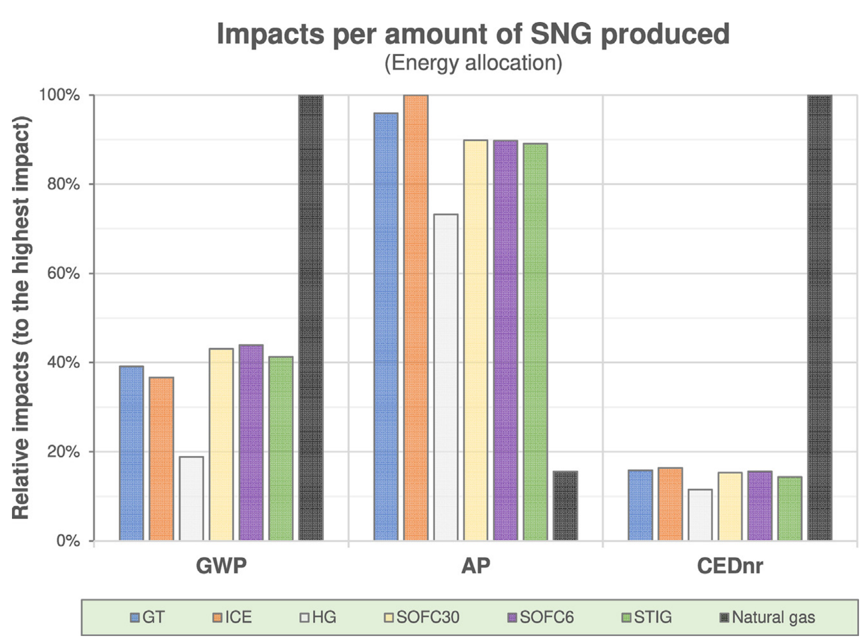

Fig. 8 — GWP, AP and CEDnr relative impacts for all investigated layouts, in the second scenario (energy allocation approach).

conventional NG. Impact trade-off is found for acidification potential, due to the water alkaline electrolysis. However, a shift from water alkaline to Proton Exchange Membrane (PEM) technology could potentially bring environmental benefits also on acidification concerns. On the other hand, the most conservative scenario proves that the fruitful exploitation of the co-produced electricity is crucial in order to make SNG production from biomass more environmentally favourable than the fossil alternative, at least under CEDnr. Finally, the choice of the multifunctionality approach led to prioritise the monofunctional solution (HG layout) under environmental aspects over multifunctional layouts co-producing electricity.

Conclusions and outlook

In the present paper, the LCA of six different layouts for the production of SNG from biomass and electrolytic hydrogen was performed according to three impact indicators (GWP, AP, CEDnr), and compared with the natural gas impacts. The analysis was carried out with different functional units and with two different approaches to deal with multifunctionality.

The results showed that, with all the proposed layouts, SNG production from biomass and renewable electricity led to lower environmental burdens in terms of GWP and CEDnr with respect to conventional NG, although it presents a higher AP. The critical contribution identified for acidification is the alkaline electrolyser manufacturing, in particular associated with mining of the metals employed as electro-catalysts such as nickel and rhodium. The multifunctionality approach was found to determine the technology ranking among the investigated alternatives; nevertheless, it did not overturn the overall results in terms of suitability with respect to conventional NG. In this regard, under GWP and CEDnr indicators, systems involving electricity co-production showed lower impacts when addressing multifunctionality through avoided burdens approach. In contrast, the allocation approach led to prioritising monofunctional layouts under the three analysed environmental criteria. This result confirms the relevance of performing sensitivity analyses on multifunctionality approaches as an insightful practice in decision-making processes.

Once the energy and environmental performance of all proposed layouts have been mapped, future works should investigate the economic performances or Life Cycle Costs (LCC), especially if in contrast with energy efficiency and environmental impacts.

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

Nomenclature

AF	Allocation Factor
AP	Acidification Potential
CED	Cumulative Energy Demand
DME	Dimethyl Ether
FU	Functional Unit
GWP	Global Warming Potential
GT	Gas Turbine
HG	Hydrogasification
HHV	Higher Heating Value
ICE	Internal Combustion Engine
LCA	Life Cycle Assessment
LCC	Life Cycle Cost
LCI	Life Cycle Inventory
LHV	Lower Heating Value
PEM	Proton Exchange Membrane
SOEC	Solid Oxide Electrolysis Cell
SOFC	Solid Oxide Fuel Cell
SNG	Synthetic Natural Gas
STIG	Steam Injected Gas Turbine

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