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Modelling and life cycle assessment of biomass-based synthetic natural gas production

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ABSTRACT

Meeting Austria's 2040 carbon neutrality target requires a rapid transition to industrial-scale processes. Biomass-based technologies are pivotal in this shift, as they reduce reliance on fossil resources while producing high-value products. This study models and evaluates the potential environmental impacts of producing biomass-based synthetic natural gas (Bio-SNG) through gasification and methanation, incorporating scenario analysis. Seven impact categories were assessed: acidification potential, eutrophication, land use, fossil resource use, water use, particulate matter, and climate change. Among the Bio-SNG scenarios, the Bio-SNG-W scenario, which utilises wind-generated electricity, shows the lowest impacts across climate and most non-climate categories. Using the IPCC, 2021 methodology, the base case (bio-SNG) estimated net global warming emissions of 41 $kg_{CO2\ eq.}/MWh_{Bio\text{-}SNG}$, mostly due to wood chip preparation and electricity consumption. Thus, when wind power is used as the electricity source (Bio-SNG-W), the greenhouse gas emissions reduce to 25 $kg_{CO2\ eq.}/MWh_{Bio\text{-}SNG}$. In comparison, the emissions for natural gas production and processing, excluding the higher impact use phase, stand at 16 $kg_{CO2\ eq./MWhNG}$. Except for fossil resource use, Bio-SNG-related scenarios show higher emissions than their fossil-based counterpart, underscoring these processes' resource and energy intensity as well as showing a potential burden-shifting effect.

1. Introduction

Over recent years, numerous endeavours and initiatives have been undertaken to address the effects of climate change, primarily stemming from the excessive utilisation of fossil-based resources. To align with the carbon neutrality aim by 2050, the EU has revised its intermediate 2030 emission reduction target from 40 % to 55 % through the updated Fit for 55 legislative packages. Among many, it contains directives fostering renewable energy, energy savings, annual emissions capping and pricing, investments in clean transport, etc (Council of the EU; European Council, 2022). Furthermore, Austria has set two goals: achieving 100 % renewable electricity by 2030 and becoming climate-neutral by 2040 (Diendorfer et al., 2021).

According to the Intergovernmental Panel on Climate Change (IPCC), the chemical industry is responsible for significant greenhouse gas emissions, following the cement and steel sectors (Bashmakov et al., 2022). Renewable feedstock and energy sources used at an industrial scale are pivotal for emission mitigation and reducing fossil resource dependency (IPCC, 2022). Biomass is widely recognised in literature as a suitable feedstock for various thermochemical conversion processes, such as combustion, pyrolysis, liquefaction, and gasification (Ram et al., 2022). Gasification, a process that occurs at temperatures above 700 °C in the presence of a gasification agent (steam, air, oxygen, carbon dioxide or a combination) (Fuchs et al., 2020), converts organic materials, such as wood, agricultural residues, and other plant-based feedstocks into a versatile intermediate product known as synthesis gas (syngas). Syngas can be directly used as engine fuel or upgraded to liquid fuels or chemicals (Tanger et al., 2013).

Dual fluidised bed (DFB) gasification systems consist of two connected reactors: the combustion reactor produces the heat, which is transported by the bed material to the gasification reactor (Karl and Pröll, 2018; Hanchate et al., 2021). A major advantage of this setup is the production of nitrogen-free syngas, eliminating the need for a separation unit. The resulting syngas is often used to produce hydrogen, synthetic natural gas (SNG) and liquid fuels. There are demonstration projects in Europe, including GoBiGas in Sweden, Güssing in Austria, and others in Finland, Germany, and France (Larsson et al., 2018; Hofbauer et al., 2002). These projects focus on wood gasification due to

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wood availability, and its moisture content — key parameters that influence gasification efficiency and syngas quality (IEA Bioenergy, 2021; Biomass Energy resources - Forest Research; Molino et al., 2016). In 2020, Austria had approximately 800 million tons of forest biomass available, with about 750 million tons allocated for wood supply, limited by economic, environmental, and social factors (Avitabile et al., 2023).

Natural gas accounts for 23 % of the European electricity mix (Eurostat, 2023). Among fossil fuels, natural gas is regarded as the cleanest option, particularly regarding greenhouse gas emissions, including nitrogen oxides (NOx) and sulphur oxides (SOx) (Akbari and Kumar, 2024). However, due to insufficient domestic reserves, Europe relies heavily on natural gas imports, which have been affected by geopolitical tensions. This reliance, combined with growing climate concerns, positions biomass-based synthetic natural gas (bio-SNG) as a promising alternative to help meet the increasing demand.

Life cycle assessment (LCA) is a standardised method used to evaluate a product's environmental aspects and potential impacts throughout its lifetime, following the ISO 14040/44 standards (International Organization for Standardization, 2006a; International Organization for Standardization, 2006b). LCA is often used during the design phase of new technologies, providing several advantages, such as improving environmental performance, thus maximising the sustainability of technologies (Gear et al., 2018). An effective approach involves integrating process simulation and life cycle assessment in the early stages of process development. This integration offers guidance on environmental benefits and identifies critical areas requiring special attention during the design and experimental investigation of process steps. There are two main types of LCAs: Attributional LCA (ALCA) and Consequential LCA (CLCA). ACLA evaluates the global environmental impact of a product's life cycle, while CLCA evaluates the direct and indirect environmental consequences resulting from changes in the product's life cycle (Schaubroeck, 2023). These concepts, ALCA and CLCA, can be implemented both retrospectively and prospectively: the retrospective approach assesses the environmental performance of current technologies, while the prospective approach anticipates the potential impacts of future technologies or scenarios before they are implemented (Gay et al., 2024).

Some studies have investigated the production of SNG from lignocellulosic biomass gasification, primarily focusing on optimising process design, improving efficiency, and evaluating the economic feasibility of the technology (Bartik, 2024; Arteaga-Pérez et al., 2016; Katla-Milewska et al., 2024). Some research has also estimated the carbon footprint of bio-SNG production. For Bio-SNG produced through gasification of woody biomass followed by catalytic methanation, a carbon footprint of 27 $kg_{CO2\ eq.}/MWh_{Bio\text{-}SNG}$ has been reported for Austria (Hammerschmid et al., 2023), while Bargiacchi et al. estimated 0.76 $kg_{CO2\ eq.}/kg_{Bio\text{-}SNG}$ for Italy (Bargiacchi et al., 2021), equivalent to 49.4 $kg_{CO2\ eq.}/MWh_{Bio\text{-}SNG}$ converted through the higher heating value (HHV) of methane (15.4 kWh/kgCH4). Litheko et al. (2023) evaluated the environmental impacts of producing SNG through the Sabatier process, reporting carbon footprints of 1496, 51.1, and 33.5 $kg_{CO2\ eq.}/MWh_{SNG}$ (assuming an HHV of 55.4 MJ/kg_{SNG}) with electricity sourced from the South African grid, photovoltaics, and wind, respectively, and using CO_2 from direct air capture. Alternatively, when using CO_2 from a coal power plant and hydrogen generated by electrolysis as feedstock, the carbon footprint is reported as 1464, 22.3, and 5.40 $kg_{CO2\ eq.}/MWh_{SNG}$, accordingly (Litheko et al., 2023). Furthermore, Adelt et al. (2011) estimated the global warming potential of biomethane produced from biogas purification, including biomass production and fermentation, at 44.6 $kg_{CO22\ eq.}/MWh$.

Although several studies have investigated bio-SNG production, few have specifically assessed its integration into the Austrian gas grid, considering the holistic impacts on air, soil, and water. This is particularly important because only demonstration projects on this topic have been realised in Austria, with funding to foster research in process optimisation and scale up to commercial level. The goal of the current study encompasses four main objectives: (1) modelling and validation of an integrated biomass gasification unit combined with methane synthesis, (2) show, in detail, the climate change impacts of the proposed process, (3) assessing the potential environmental impacts of this system beyond climate change, and (4) comparing them to those of a reference case in Austria: natural gas production and processing.

2. Methods and data

In this study, the process modelling and mass and energy balance calculations are conducted using the Aspen Plus v12.1 flowsheeting tool (Inc. Aspen Technology, 2021). These calculations are integrated with a life cycle assessment (LCA) performed in Simapro v9.5.0.1 (Pré, 2023) to evaluate the technological and environmental performance of the bio-SNG process route. The models are primarily based on data from the literature and key assumptions, with any data gaps filled using information from the Ecoinvent database version 3.9.1.

2.1. Process description

The first part of the process consists of biomass provision, handling, and storage, as illustrated in Fig. 2. In this study, softwood chips, as characterised in (Schmid et al., 2021), were utilised as the feedstock. The composition of the biomass is provided in Table 1. The supplied woody biomass has a moisture content of 40 %. Thus, it is pre-dried to minimise energy consumption during gasification. Gasification occurs in a dual fluidised bed (DFB) reactor at 850–900 °C, where up to 40 % of the carbon in the biomass is combusted to supply the necessary heat for gasification (Larsson et al., 2018). Heat transfer to the gasifier is facilitated by the bed material, which consists of 80 % olivine and 20 % limestone. Gasification consists of complex reactions involving solid and gas phases, some of which are not in equilibrium. Typical gasification reactions include oxidation (Eqs. (1)–(3)), drying (Eq. (12)), pyrolysis and reduction (Eqs. (4)–(7)) (Ram et al., 2022; Maitlo et al., 2022; Hejazi et al., 2017).

After gasification, the gas undergoes a cleaning process to remove dust, tars, impurities, and moisture. This is typically done using cyclones, rapeseed methyl ester (RME) scrubbers, and activated carbon filters, as described in (Larsson et al., 2018; Hammerschmid et al., 2023; Jungbluth et al., 2007). Afterwards, the product gas is compressed and treated with ZnO to prevent sulphur deposition and catalyst poisoning. The next step is catalytic methanation at 320 °C in a nickel-based fluidised bed reactor (Hammerschmid et al., 2023). Ideally, Equations (9) and (10) require H_2/CO and H_2/CO_2 molar ratios of 3 and 4, respectively. However, the stoichiometric number (SN, Equation (11)) of the syngas produced from the gasification ranges from 0.3 to 2 (Seemann and Thunman, 2019). If the SN is lower than one, the hydrogen content

Table 1
Biomass composition on a dry weight basis (db). (Schmid et al., 2021; Puig-Gamero et al., 2018).

Ultimate analysis	
Carbon	50.7
Hydrogen	5.9
Oxygen	43
Nitrogen	0.2
Sulphur	0.005
Chlorine	0.005
Ash	0.2
Proximate analysis	
Volatile matter	85.6
Fixed carbon	14.2
Ash	0.2
Moisture, %	40
LHV, MJ/kg_{db}	18.9

is insufficient for a complete conversion to methane, resulting in a raw gas diluted with approximately 50 % CO_2. Gas upgrading follows, consisting of condensing the water formed and removing CO_2 using a monoethanolamine (MEA) scrubber, achieving 96 % CO_2 removal, as described in (Huber, 2024). Lastly, the gas is dried with triethylene glycol (TEG) and sent to the natural gas grid, in compliance with its standards: $H_2 \leq 10$ mol%, $CO_2 \leq 2.5$ mol%, CO 0.1mol% (Österreichische Vereinigung für das Gas, 2021).

$$C + O_2 \rightarrow CO_2 \quad \Delta H = -394\ kJ/mol \qquad \text{Eq. 1}$$

$$C + \frac{1}{2}O_2 \rightarrow CO \quad \Delta H = -111\ kJ\Big/mol \qquad \text{Eq. 2}$$

$$H_2 + \frac{1}{2}O_2 \rightarrow H_2O \quad \Delta H = -242\ kJ\Big/mol \qquad \text{Eq. 3}$$

$$C + CO_2 \leftrightarrow 2CO \quad \Delta H = 172\ kJ/mol \qquad \text{Eq. 4}$$

$$C + H_2O \leftrightarrow CO + H_2 \quad \Delta H = 131\ kJ/mol \qquad \text{Eq. 5}$$

$$CO + H_2O \leftrightarrow CO_2 + H_2 \quad \Delta H = -41\ kJ/mol \qquad \text{Eq. 6}$$

$$C + 2H_2 \leftrightarrow CH_4 \quad \Delta H = -75\ kJ/mol \qquad \text{Eq. 7}$$

$$CO + 3H_2 \leftrightarrow CH_4 + H_2O \quad \Delta H = -206\ kJ/mol \qquad \text{Eq. 8}$$

$$CO_2 + 4H_2 \leftrightarrow CH_4 + 2H_2O \quad \Delta H = -164.9\ kJ/mol \qquad \text{Eq. 9}$$

$$SN = \frac{H_2}{3CO + 4CO_2} \qquad \text{Eq. 10}$$

2.2. Model description

The process steps modelled were biomass drying, gasification, gas cleaning, methane synthesis and gas upgrading. The models were developed and validated based on literature data. Fig. 1 presents the process flowsheet in Aspen Plus. A few general assumptions for the modelling are listed below:

- Biomass is defined as a non-conventional solid using proximate and ultimate analysis following the concept described by (Timsina et al., 2019; Doherty et al., 2013)
- Biomass LHV is defined according to the HCOALGEN property models (Doherty et al., 2013)
- Peng-Robinson equation of state with Boston-Mathias modifications was the method used to estimate the physical and thermochemical properties of the components, as suggested by (Timsina et al., 2019; Fernandez-Lopez et al., 2017) for light gases and hydrocarbon mixtures in refineries, gas processing and petrochemical applications
- Steady-state and isothermal calculations
- No heat loss and pressure drop considered
- Tar formation is not included in the simulation, but is considered for LCA; Rapeseed methyl ester (RME) is used for tar removal, and the resulting tar-laden RME is assumed to be combusted

The model provides a detailed description of the gasification process, while both methane synthesis and gas upgrading are represented as black boxes. Methane synthesis has been thoroughly covered in previous studies (Bartik et al., 2021; Liu et al., 2016). Gas upgrading can be achieved using technologies such as absorption, adsorption, or membrane separation, depending on the gas grid specifications (Fendt et al., 2015).

Biomass dryer: Two blocks are used to describe the drying of biomass. The first is a stoichiometric reactor (D-1) combined with the second block, a flash separator (D-2). The WBIOMASS stream enters the reactor D-1 at atmospheric conditions (25 °C and 1 bar), with a moisture content of 40 %. Since the amount of moisture negatively affects the gasification efficiency, this content is reduced to 20 %. In the model, the drying step (105 °C, 1 bar) consists of converting part of the nonconventional moisture content into water in D-1 (Eq. (11)) (Aghaalikhani et al., 2019). The separator D-2 splits the converted moisture content from the nonconventional solid biomass. The heat required for drying is covered by heat integration from the gasification and methanation reactors.

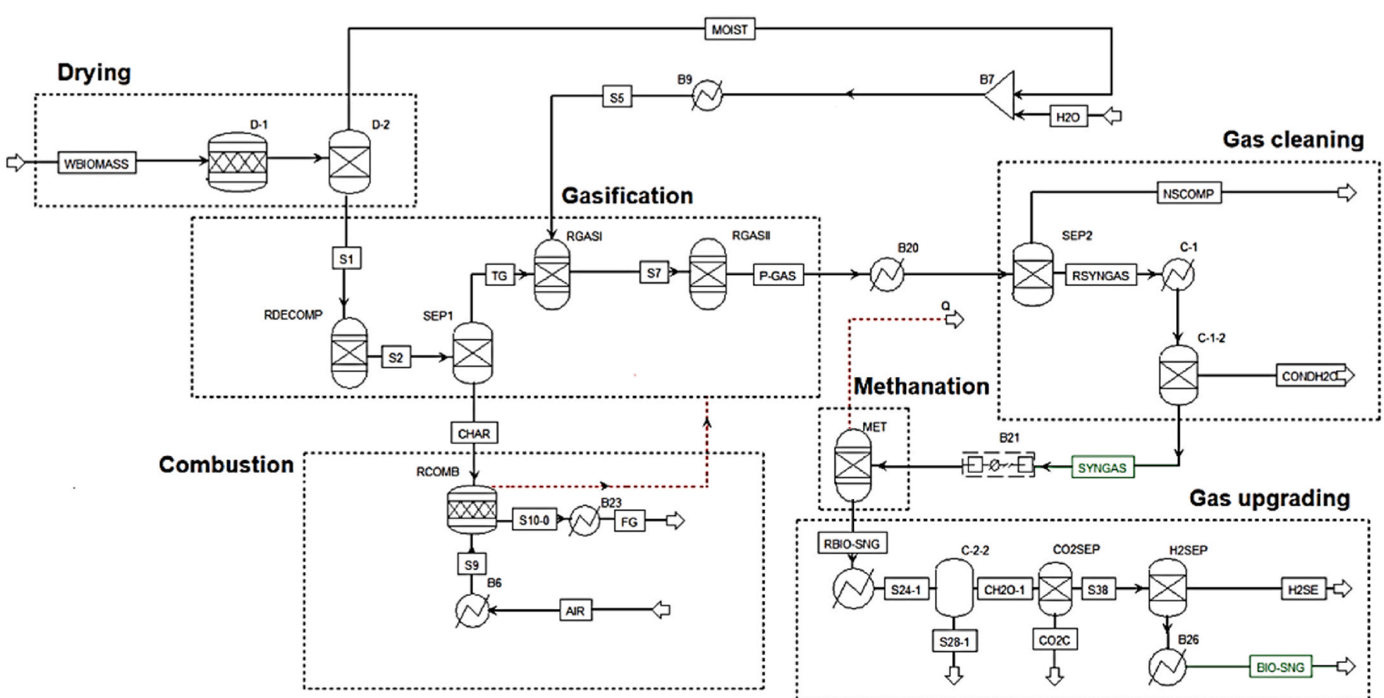

Fig. 1. Bio-SNG process flowsheet in Aspen Plus v12.1. D-1. RCOMB – RStoic; RDECOMP – RYield; RGASI, RGASII, MET – RGibbs; D-2, SEP1, SEP2, C-1-2, CO2SEP, H2SEP – Sep; B6, B9, B20, B23, B26, C-1, C-2 – Heater; C-2-2 – Flash2; B7 – Mixer; B21 – MCompr.

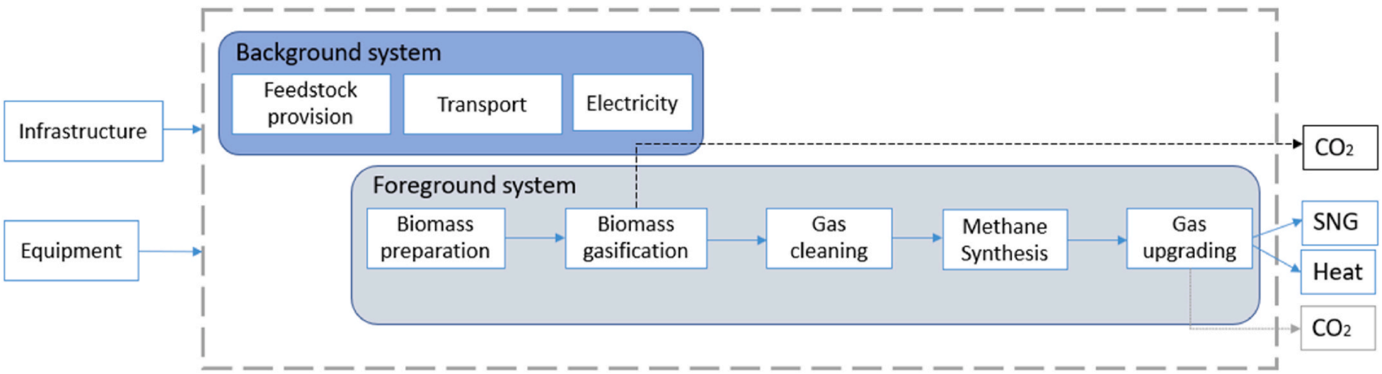

Fig. 2. System boundary. Foreground system – primary data, Background system – secondary data.

$$\text{Biomass (40\% moisture)} \rightarrow 0.0556\ H_2O + \text{Biomass (20\% moisture)} \quad \text{Eq. 11}$$

Gasification: The gasification step is modelled following the concept of (Doherty et al., 2013). Dry biomass enters the gasification section. The model divides gasification into four main unit blocks: RDECOMP, RGASI, RGASII and RCOMB. RDECOMP is a yield reactor that converts the nonconventional components defined in the ultimate analysis (Table 1) into conventional elements - C, H, O, N, S, Cl and ash (inert), with the use of a calculator block. SEP1 is a separator that directs char (assumed as carbon and ash) to the combustion reactor (RCOMB). The carbon split ratio in SEP1 is set to 0.30, accounting for the necessary char to provide the required process heat. The combustion section of the gasification unit RCOMB is represented by a stoichiometric reactor where char combustion with 1.12 excess air at 900 °C takes place (Doherty et al., 2013). The combustion reactions are generated in the reactor without user definition. Typical gasification reactions (Equations (1)–(7)) are assumed to reach equilibrium in RGASI, a Gibbs reactor operating at 850 °C and 1 bar. A second reactor, RGASII, operates under the same conditions but adjusts the product gas composition using temperature approach restricted equilibria. Steam is used as gasification agent and fluidising medium for the bed material, introduced into the reactor at a ratio of 0.75 relative to the biomass input (Doherty et al., 2013). The moisture separated in D-2 is combined with fresh water to meet the steam demand. Tar formation is not included in the model. Since the bed material is not considered in the model, heat streams represent the heat transfer between the bed material from the combustion chamber (RCOMB) to the gasification chamber (RDECOMP, RGASI and RGASII). Moreover, all N, Cl and S in the fuel (Table 1) are converted to NH_3, HCl and H_2S, respectively. In this model, the impurities from the raw syngas are removed by SEP2, while water is condensed in a combination of a cooler and a separator (C-1 and C-1-2), respectively. Excess heat is assumed to be produced during combustion.

Methane synthesis: The syngas is compressed to 10 bar in B21 and preheated to 250 °C (Hammerschmid et al., 2023) prior to entering the methanation reactor (MET). This reactor operates at 320 °C and is modelled using an RGibbs reactor, effectively representing the pressurised methanation in a fluidised bed reactor (Liu et al., 2016).

Bio-SNG upgrading: The produced gas contains moisture, CO_2, excess H_2 and other impurities, which are removed in separators C-2-2, CO2SEP and H-SEP, respectively. These are used to simulate the gas upgrading process to meet Austrian grid standards (Österreichische Vereinigung für das Gas, 2021).

2.3. Life cycle assessment

This LCA is based on the material and energy flows required by the bio-SNG system. This section details the scope definition, inventory analysis and impact assessment. The study follows an attributional approach, which does not account for market dynamics. The LCA was performed in Simapro v9.5.0.1, using Ecoinvent v3.9.1 database and the "APOS U" (allocation at point of substitution – unit) system model, which is commonly applied in multi-product processes.

2.3.1. Goal and scope definition

This study evaluates the environmental performance of producing synthetic natural gas from biomass (bio-SNG), focusing on Austria as the geographical context. The results are compared to those of conventional natural gas production. The use and end-of-life phases are excluded from the system boundary, based on the assumption that bio-SNG has the same chemical structure and composition as natural gas and is expected to substitute it in existing applications (Karka et al., 2017; Müller et al., 2020). Thus, the assessment follows a cradle-to-gate approach. The scope of the study includes all process steps from raw material acquisition to bio-SNG production, as outlined in Fig. 2.

To simplify the assessment and maintain conciseness, the system boundaries were adjusted based on the following assumption: (1) The infrastructure and equipment construction are assumed to be outside the scope of this assessment due to insufficient data availability. (2) Similarly, transportation within and beyond the factory gate is excluded for the same reason. (3) However, the feedstock preparation and supply chain are included in the datasets from Ecoinvent.

The functional unit of the LCA is 1 MWh of Bio-SNG output, and the life cycle inventory and impact analysis are related to this functional unit. As heat is produced alongside Bio-SNG, multi-functionality is accounted for through physical allocation based on energy, with the corresponding factors provided in Table SII.2 of the supplementary material. Different scenarios are considered in process simulation and LCA to see their effect on the process and, consequently, their environmental impacts. The following scenarios are evaluated:

- **Bio-SNG** (base case scenario): includes drying wood chips, DFB gasification, gas cleaning, methane synthesis and gas upgrading as outlined in section 2.1
- **Bio-SNG-T**: Including the **transport** of woody biomass over an average distance of 200 km
- **Bio-SNG-W**: Switching the electricity source from the Austrian electricity mix to **wind**
- **Bio-SNG-P-Em**: **P**artially **Em**itting total produced CO_2. Storing only the CO_2 captured during raw-**Bio-SNG** upgrading. This CO_2 can be forwarded for potential short-term storage and later used as feedstock in another process
- **Bio-SNG-N-Em**: **N**o direct CO_2 **Em**issions. Similar to Bio-SNG-P-Em, but also considering the capture of the CO_2 produced from biomass combustion in the dual fluidised bed (DFB) gasification process
- **NG-P**: Conventional natural gas production

2.3.2. Inventory analysis

Data quality and transparency are crucial for the reliability of the

LCA. The inventory for this study was compiled using results from the simulation model described above, literature, and the Ecoinvent v. 3.9.1 database. As stated in the goal and scope, Austria is assumed to be the plant's location. Therefore, datasets are primarily selected based on their relevance to Austria. When specific data for Austria are unavailable, datasets from neighbouring countries or the European average are used as substitutes. The main inventory items and their sources are presented below, followed by their respective datasets in Simapro (Table 2).

- Data on woody biomass and natural gas production were retrieved from the Ecoinvent database, with German datasets selected.
- Data on the catalysts needed for the synthesis processes were derived from literature (Hammerschmid et al., 2023; Bartik et al., 2021). Only the datasets for their components were considered, excluding the actual production of the catalysts.
- Data on bio-SNG production come from the mass and energy balances obtained from 2.2.
- Data on RME, TEG, MEA, and olivine were also sourced from the Ecoinvent database. Since Ecoinvent lacks datasets for olivine production, silica sand was used as an alternative for the bed material of the DFB gasification.
- The Austrian electricity mix, sourced from Ecoinvent, was assumed for the processes requiring electricity.
- Emission data were based on mass balances and literature sources (Larsson et al., 2018).
- The solid waste and effluents are assumed to be disposed of via sanitary landfills (40 %) and incineration (60 %) (Jungbluth et al., 2007), with processes sourced from the Ecoinvent database.

Table 2
List of the datasets used in Simapro.

Material/Energy Flows	Data sets used
Inputs: materials/fuels, electricity/heat	
Wood chips	Wood chips, wet, measured as dry mass {DE}| softwood forestry, spruce, sustainable forest management | APOS, U
Bed material	Silica sand {GLO}| market for | APOS, U Limestone, crushed, washed {RoW}| market for limestone, crushed, washed | APOS, U
RME - Fatty acid methyl ester	Fatty acid methyl ester {RoW}| market for fatty acid methyl ester | APOS, U
Monoethanolamine	Monoethanolamine {GLO}| market for | APOS, U
Triethylene glycol	Triethylene glycol {RER}| market for triethylene glycol | APOS, U
Activated carbon	Activated carbon, granular {GLO}| market for activated carbon, granular | APOS, U
Zinc oxide	Zinc oxide {GLO}| market for | APOS, U
Nickel-alumina catalyst	Nickel, class 1 {GLO}| market for nickel, class 1 | APOS, U Aluminium oxide, non-metallurgical {RoW}| market for aluminium oxide, non-metallurgical | APOS, U
Air	Air
Electricity	Electricity, high voltage {AT}| market for | APOS, U
Outputs: Emissions to air/water/soil, waste treatment	
Nitrogen	Nitrogen atmospheric
Carbon dioxide	Carbon dioxide, biogenic
Ammonia	Ammonia
Hydrogen sulphide	Hydrogen sulfide
Hydrogen chloride	Hydrogen chloride
Nitrogen oxides	Nitrogen oxides, AT
Wastewater	Wastewater, average {Europe without Switzerland}
Bed material	Inert waste {CH}| market for inert waste | APOS, U Limestone waste
Catalyst waste	Catalyst waste
Fly ash	Wood ash mixture, pure {CH}| treatment of, sanitary landfill | APOS, U Wood ash mixture, pure {CH}| treatment of, municipal incineration | APOS, U

2.3.3. Impact assessment

In several comparative LCA studies, the primary focus is on determining which product has lower greenhouse gas emissions and uses fewer fossil resources (Müller et al., 2020; Sternberg and Bardow, 2015). However, to avoid burden shifting, it is recommended to include impact categories that are both relevant and reliable. Therefore, the impact assessment in this study was conducted using seven impact categories from the Environmental Footprint 3.1 (EF 3.1d) method, selected based on their relevance and alignment with similar studies (Wang et al.):

- **Acidification potential** evaluates the emission of airborne acidifying substances.
- **Eutrophication potential** is defined as the accumulation of nutrients, mainly nitrogen and phosphorus compounds, in the soil and water bodies due to human activity, causing overgrowth of plants and algae, affecting the ecosystem (Devlin and Brodie, 2023).
- **Land use** assesses the extent of land area occupied by a particular activity, how the land is utilised, and its effect on the ecosystem. While this category is typically considered in processes involving agricultural activities, it was included in this study due to the high demand for woody biomass, which requires extensive forest areas and certain agricultural practices for its harvest.
- **Fossil resource use** considers energy carriers, such as fossil fuels and renewable energy sources (Fazio et al., 2018).
- **Water use** is a relative unit based on water scarcity factors. Thus, it measures the relative amount of water used (Impact Categories).
- **Particulate matter** measures the risk of diseases due to its emissions and those of its precursor compounds.
- **Climate change** impacts arise from GHG emissions in the atmosphere and are divided into three sub-categories: biogenic, fossil, and land use & land use change. In the EF 3.1 method, a 0/0 approach is assumed for biogenic CO_2 uptake and emissions, i.e., only net impacts are presented. In this study, however, both biogenic and non-biogenic emissions are explicitly accounted for. In this approach, CO_2 uptake by biomass is considered biogenic with a factor of −1, while CO_2 emitted after gasification and methanation is also considered biogenic with a factor +1 (−1/+1 approach). To factor this in, an additional single-issue method is applied: IPCC, 2021 GWP (incl. CO_2 uptake).

Table 3
Impact categories, characterisation factors, impact indicators and methods.

Impact category	Characterisation factor	Impact indicator	LCIA Method
Acidification potential	mol H^+ equivalents/kg pollutants	Mol H^+ $_{eq.}$	Accumulated Exceedance (Posch et al., 2008)
Eutrophication Terrestrial	mol N equivalents/ kg pollutants	Mol N $_{eq.}$	Accumulated Exceedance (Posch et al., 2008)
Land use	–	Pt	Soil quality index based on (Bos et al., 2016; De Laurentiis et al., 2019)
Fossil resource use[a]	–	MJ	Van Oers (Van Oers et al., 2002)
Water use[b]	m^3 of water equivalents	m^3 depriv.	Available WAter REmaining (AWARE) (Boulay et al., 2018; UNEP and Life Cycle Initiative, 2016)
Particulate matter	–	Disease incidences	PM model (Fantke et al., 2021)
Climate change	kg CO_2 equivalents/kg GHG	kg $CO_{2eq.}$	IPCC2021 (IPCC, 2021)

[a] Abiotic resource depletion or Resource depletion/use, fossils.
[b] Water deprivation potential (WDP).

Table 3 presents the characterisation factors, impact indicators and methods for the evaluated impact categories (Environmental Performance Indicators | EPD, 2023).

3. Results and discussion

3.1. Modelling

The gasification section of the model was validated using experimental data from the literature, specifically from the 100 kW DFB gasification pilot plant at TU Wien (Schmid et al., 2021), and data from the GoBiGas 20 MWh demonstration plant, both operated on woody biomass (Larsson et al., 2018). Table 4 compares the syngas composition from biomass gasification with the corresponding literature data. The model's syngas composition aligns well with the experimental results from (Schmid et al., 2021), as the model was based on the same experimental results. However, slight differences in the H_2 and CH_4 composition compared to (Larsson et al., 2018), may be due to differences in bed materials, with the GoBiGas plant using potassium-activated olivine instead of a mixture of olivine and limestone as in (Schmid et al., 2021). As expected, the syngas composition also matches the one found in the model developed by Doherty et al. (2013), where woody biomass with a similar composition is assumed, and the same assumptions for modelling as described in 2.2 are considered. However, it differs slightly from the gas composition predicted by Puig-Gamero et al. (2018), which can be justified by the calculation method assumed in the RGibbs reactors (equilibrium vs restricted equilibrium).

The process simulation model is based on a commercial scale, considering a wood chip input corresponding to a 100 MW thermal power load (Hammerschmid et al., 2023). Table 5 summarises the main energy parameters for the base case scenario. The estimated bio-SNG cold gas efficiency (CGE) is 6 % higher than the literature value (Hammerschmid et al., 2023). The estimated electricity input was assumed to arise from the syngas compression (Table 5). The estimated cold gas efficiency in this model is 69 %, and around 34 % of the carbon can be found in the product, as estimated in the GoBiGas project (Larsson et al., 2018). By improving the process's heat demand, more carbon could be converted into the desired product, increasing the values of CGE and η_C. The desired bio-SNG composition is: $H_2 \leq$ 10 mol %, $CO_2 \leq$ 2.5 mol%, CO 0.1mol% based on Austrian gas grid standards (Österreichische Vereinigung für das Gas, 2021). While these standards specify upper limits for H_2, CO_2, CO and other trace components, they do not define a minimum methane concentration, provided that parameters such as Wobbe index, density, and heating value are met. For this study, a threshold of 96 vol% of CH_4 is assumed, consistent with common practice for biomethane quality requirements. A summary of the energy balance (Table SI2), as well as details of the stream results (Table SI3), can be found in the supplementary material.

3.2. Life cycle assessment results

The results of this LCA study are presented per functional unit, 1 MWh of Bio-SNG, considering all scenarios analysed: Bio-SNG, Bio-SNG-T, Bio-SNG-W, Bio-SNG-P-Em, Bio-SNG-N-Em, and NG-P. The results presented in the impact assessment follow a cradle-to-gate approach, excluding the transportation, infrastructure, use phase, and disposal. The summary of the inventory and the allocation factors considered are presented in Tables SII.1 and SII.2 in the supplementary material.

Table 4
Product gas compositions estimated by the model and literature.

Compound	This study (vol $\%_{db}$)	(Schmid et al., 2021) (vol$\%_{db}$)	(Larsson et al., 2018) (vol$\%_{db}$)
H_2	48.3	47.4	39–41
CO	22.2	21.3	20–23
CO_2	20.3	21.2	18–22
CH_4	9.2	8.9	7.9–8.6
LHV[a], MJ/m^3	11.3	11.0	9.6–10.4

[a] The LHV was calculated according to (Fernandez-Lopez et al., 2017) using the compositions above.

Table 5
Summary of main energy balance parameters for the base case.

Parameter	Unit	This study	Hammerschmid et al. (2023)
Biomass $_{input}$	MW	100	100
Electricity $_{input}$	MW	4.3	4.3
SNG_{out}	MW	69	65
$Heat_{out}$	MW	22.3[a]	14.2
CGE	%	69	65
η_C	%	34	–

[a] Potential heat output, additional heat integration is required for optimal energy recovery.

3.2.1. Non-climate change-related impacts

Fig. 3 presents the relative impact assessment results in relation to the maximum impact in each impact category. Table SII.3 and Figure SII.4 in the supplementary material summarise the impact assessment results as absolute values, as well as the process contribution analysis.

The **acidification potential** of the Bio-SNG scenarios ranges from 1.28 to 1.39 mol H^+ eq./$MWh_{Bio\text{-}SNG}$ compared to 0.43 mol H^+ eq. for the production of natural gas. In the base case (Bio-SNG), total emissions amount to 1.33 mol H^+ eq., with the dominant source of these emissions (approximately 86 %) attributed to the DFB gasification process. This process generates ammonia and hydrogen sulphide, significantly contributing to acidification. The remaining 14 % of emissions are attributed to background processes, including electricity production, wood chipping and skidding, as well as rapeseed production. In the scenarios evaluated, adding transport distances (Bio-SNG-T) or capturing all produced CO_2 (Bio-SNG-N-Em) increases total emissions by 4 % relative to the base case. Conversely, switching to wind electricity results in a 4 % reduction in total emissions – the lowest value of all bio-SNG scenarios at 1.28 mol H^+ eq. In the NG-P scenario, 0.43 mol H^+ eq. emissions are primarily associated with sour gas processing, especially the gas sweetening.

The **terrestrial eutrophication potential** impacts of the Bio-SNG scenarios are higher, at about 10 mol N $_{eq.}$ compared to 0.09 mol N $_{eq.}$ for natural gas production. In the base case (Bio-SNG), total emissions are 10.21 mol N $_{eq.}$/$MWh_{Bio\text{-}SNG}$, with the DFB gasification process being the primary contributor due to direct nitrogen emissions, through ammonia and NOx produced. These emissions strongly impact the overall eutrophication category. The scenario analysis shows trends similar to those observed in acidification potential: capturing all produced CO_2 (Bio-SNG-N-Em) increases emissions by 4 %, while adding transport distances (Bio-SNG-T) raises emissions by 2 %, compared to the base case. Switching to wind electricity (Bio-SNG-W) reduces emissions by 1 %. In the NG-P scenario, sour gas processing is the main source of emissions.

As expected, the **land use** impacts in the Bio-SNG are significantly higher, ranging from 36272 to 37661 Pt/$MWh_{Bio\text{-}SNG}$, compared to just 94 Pt in the fossil-based case. This difference is primarily due to the high demand for wood chips in the DFB gasification process. In contrast, the land use impacts in the NG-P scenario are largely attributed to the area occupied by the infrastructure required for natural gas production, which is relatively low compared to the land required for wood cultivation.

The impact of **fossil resource use** in the Bio-SNG scenarios is relatively low, ranging from 303 to 752 MJ/$MWh_{Bio\text{-}SNG}$, as opposed to 3678 MJ/MWh_{NG} of NG-P. In the Bio-SNG base case, approximately 46 % of these impacts are attributed to background processes associated with

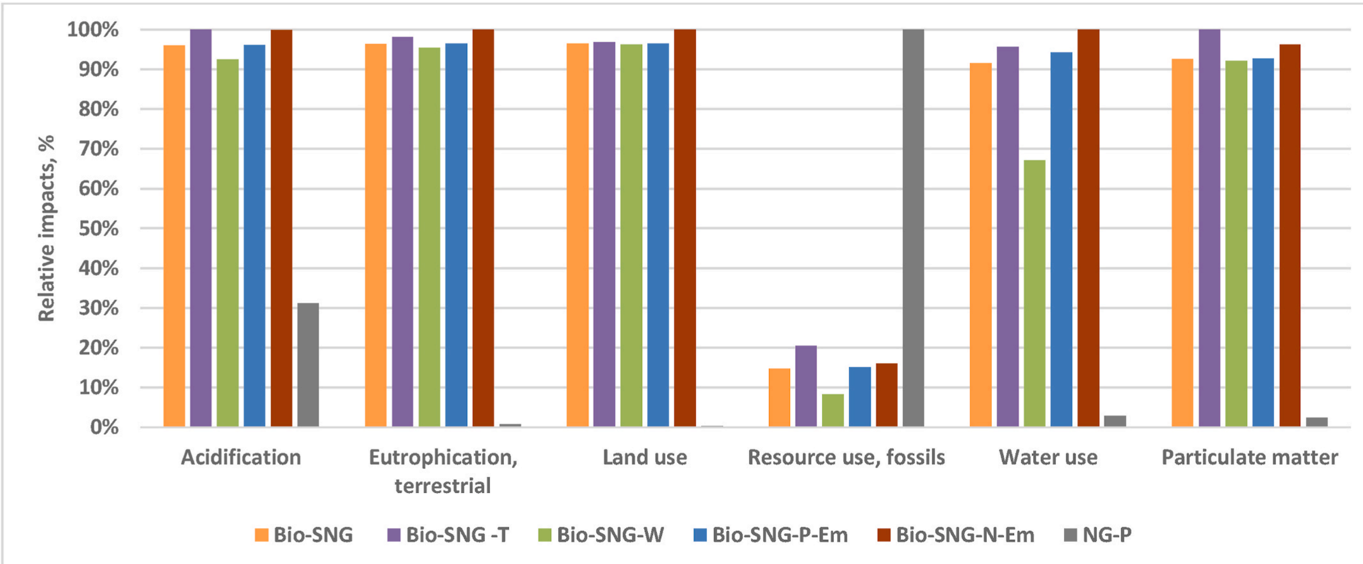

Fig. 3. Impact assessment results for non-climate change impacts relative to the highest impact in each category.
T-transport, W- wind, P-Em – Partial direct CO_2 emissions, N-Em – No direct CO_2 emissions, NG-P – Natural gas production.

wood chips, such as harvesting and chipping, as defined in the Ecoinvent database. The remaining impacts are mainly associated with electricity production. The Bio-SNG-W scenario shows the lowest impacts, while Bio-SNG-T presents higher impacts due to the additional effects of wood transport. In contrast, the fossil reference scenario shows significantly higher impacts, primarily due to natural gas production.

Water use in the Bio-SNG scenarios ranges from 11 to 16 m^3 depriv., which includes both the process water and the water required for background processes, such as irrigation for wood chips and the production of activated carbon. In contrast, the water demand in the natural gas production scenario is primarily associated with the materials used in infrastructure, totalling approximately 0.48 m^3 depriv.

The impacts of **particulate matter** in the Bio-SNG-related scenarios range from 1.51E-05 to 1.64E-05 disease incidences/$MWh_{Bio\text{-}SNG}$. As this category is linked to air pollution, the primary contributors are direct emissions from combustion processes, which release fine particles in the flue gases. These substances include nitrogen oxides, sulphur oxides, ammonia, and black carbon. In the Bio-SNG base case, the emissions come mostly from gasification (combustion of biomass-based char to provide heat), with additional contributions from background processes such as RME production and electricity generation. The transport scenario (Bio-SNG-T) has the highest emissions, as road traffic also contributes to particulate matter through its own emissions. In the natural gas scenario, the total impact is 3.96E-07 disease incidences/MWh_{NG}, with sour gas processing responsible for around 70 % of total emissions.

3.2.2. *Climate change impacts*

Climate change impacts are presented in Fig. 4 while a Sankey diagram referring to the net impacts is presented in the supplementary material (Figure SII.5). In the base case (Bio-SNG), around 91 % of the fossil emissions, 38 $kg_{CO2\ eq.}/MWh_{Bio\text{-}SNG}$, are attributed to background processes, primarily electricity generation and biomass provision, representing scope 2 and 3 emissions. In the scenario where the feedstock transport distance is extended to 200 km (Bio-SNG-T), fossil impacts increase by 37 % due to the additional fuel consumption for transport. When wind energy is used as the electricity source (Bio-SNG-W), fossil impacts decrease by 34 %, as the electricity is sourced entirely from renewable energy. The implementation of partial or total CO2 capture (Bio-SNG-P-Em and Bio-SNG-N-Em) has a negligible effect on this subcategory, as the only notable impact is a reduction in surplus heat

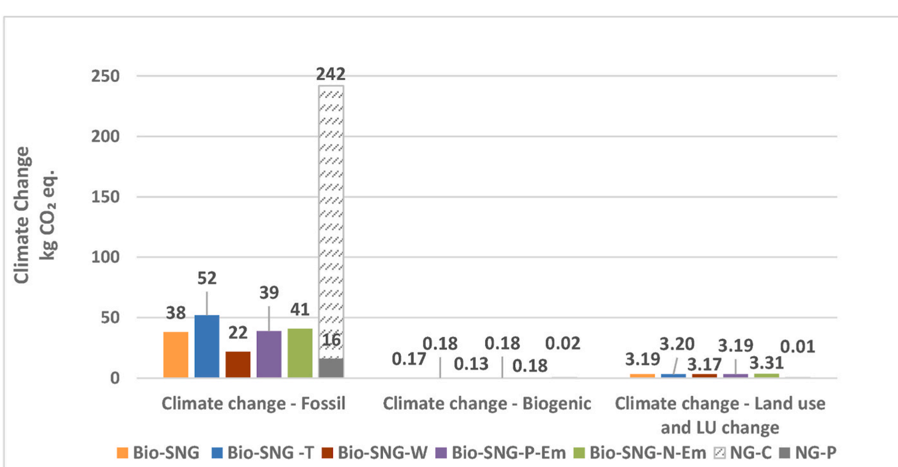

Fig. 4. Climate change LCIA results: fossil, biogenic and land transformation emissions. T-transport, W- wind, P-Em – Partial direct CO_2 emissions, N-Em – No direct CO_2 emissions, NG-P – Natural gas production, NG-C – Natural gas combustion.

production, which slightly affects energy demand. In the fossil-based scenario (NG-P), emissions are primarily driven by natural gas processing. These emissions are comparatively lower than the Bio-SNG scenarios, but if the use of natural gas is considered in combustion (NG-C), for example, then the fossil emissions reach a total of 242 $kg_{CO2\ eq.}$/MWh_{NG}. As previously noted, this method does not account for biogenic emissions, which is why the reported values are negligible. The land transformation impacts mainly result from land-use changes associated with wood extraction from forests. Since no sustainable forest management certificates for Austria are currently accessible, these impacts cannot be disregarded. However, because there is no crop rotation on the same soil, the resulting emissions remain relatively low.

The IPCC, 2021 **GWP100 (incl. CO_2 uptake)** approach explicitly accounts for fossil, biogenic, and land transformation GWP100 emissions, along with CO_2 uptake, over a 100-year timeframe (−1/+1 approach). Fig. 5 presents only the biogenic CO_2 uptake and emissions, since the fossil and land use-related emissions are identical in both methods.

Biogenic GWP100 emissions in the bio-SNG scenarios are primarily direct CO_2 emissions (scope 1 emissions). In the base case (Bio-SNG), these emissions amount to 298 $kg_{CO2\ eq.}$/$MWh_{Bio\text{-}SNG}$, while Bio-SNG-T and Bio-SNG-W show similar emissions of 297 and 294 $kg_{CO2\ eq.}$/$MWh_{Bio\text{-}SNG}$, respectively, as these scenarios do not significantly impact this subcategory. However, partial and total CO_2 capture lead to significant emission reductions of 50 % and 93 %, respectively. In contrast, biogenic emissions in the natural gas scenario (NG-P) are negligible, as expected. However, the biogenic emissions of the Bio-SNG scenarios are comparable to the fossil emissions of natural gas production and combustion (242 $kg_{CO2\ eq.}$/MWh_{NG}, Fig. 4). Although the natural gas combustion would already be outside the scope of the study, since it is part of the use phase, this value is provided for reference, since part of the Bio-SNG biogenic emissions stem from the combustion of biochar to meet the heat demand of the gasification process.

CO_2 uptake is largely driven by carbon absorption during biomass growth. It is calculated based on biomass carbon content (50.7 %) and the molecular weights of carbon and CO_2 (Nurdiawati et al., 2023). Thus, the total CO_2 uptake amounts to approximately 1.86 t CO_2 per ton of dry biomass.

Following IPCC recommendations (IPCC, 2021), most studies in literature report only the net climate change emissions, which include fossil and land transformation, when accounting for the footprint of biomass-based processes (Nurdiawati et al., 2023; Agostini et al., 2014). The biogenic emissions associated with such processes and the CO_2 uptake have net-zero impacts. The studies mentioned in the Introduction report GWP100 impacts in the same range as the values presented in Fig. 6. Hammerschmidt et al. (Hammerschmid et al., 2023) calculated a carbon footprint of 27 kg_{CO2} eq./$MWh_{Bio\text{-}SNG}$ based on ecological factors from Austrian and German databases. Both studies share similar assumptions and system boundaries thus, the difference in emissions is due to the ecological factors assumed.

Litheko et al. (2023) follows the same boundary approach, reported a wide GWP range (5–1500 $kg_{CO2\ eq.}$/$MWh_{Bio\text{-}SNG)}$ due to the location considered (South Africa), the electricity supply, and the CO_2 source. Bargiacchi et al. (2021), with a footprint equivalent to 49.4 $kg_{CO2\ eq.}$/$MWh_{Bio\text{-}SNG}$, considers a cradle-to-grave approach, including hydrogen production via wind-powered electrolysis and SNG combustion. Although in the same range, the impacts of this route would be much higher, due to the credit of approximately 200 $kg_{CO2\ eq.}$/$MWh_{Bio\text{-}SNG}$ given to biomass supply.

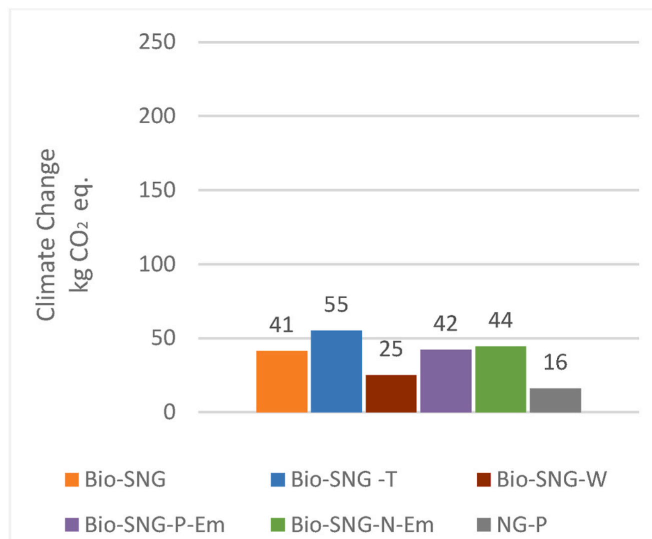

Fig. 6. Net Climate Change impacts.
T-transport, W- wind, P-Em – Partial direct CO_2 emissions, N-Em – No direct CO_2 emissions, NG-P – Natural gas production.

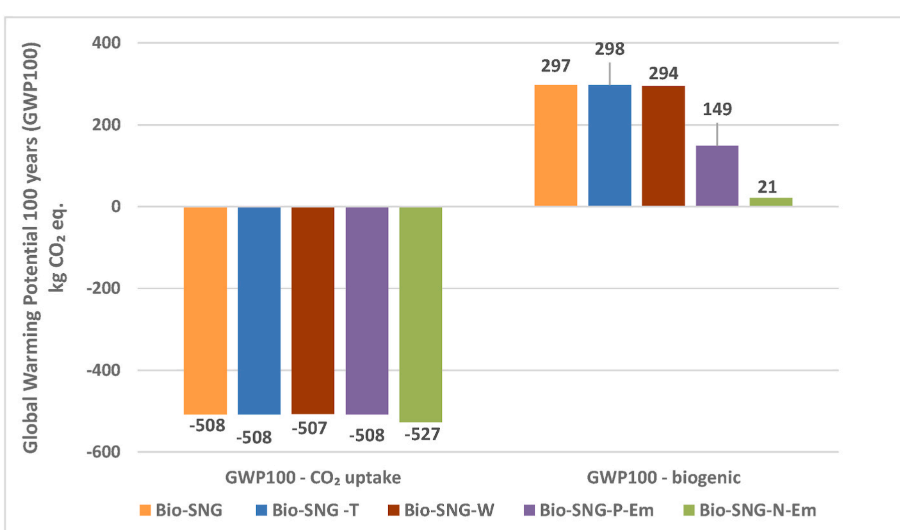

Fig. 5. Biogenic CO_2 uptake and emissions according to IPCC, 2021 GWP100 (incl. CO_2 uptake) method (−1/+1 approach. T-transport, W- wind, P-Em – Partial direct CO2 emissions, N-Em – No direct CO2 emissions, NG-P – Natural gas production.

Kolb et al. (2021) assumed GHG emissions ranging from −86.9 to 224.7 $kg_{CO2\ eq.}/MWh_{SNG}$ for wood-based bio-SNG, with an average of 44.5 $kg_{CO2\ eq.}/MWh_{Bio\text{-}SNG}$, which is comparable with the net GWP100 impacts presented in Fig. 6. As for natural gas production, the emissions from the present study (16 $kg_{CO2\ eq.}/MWh_{NG)}$ are equally lower than 214 to 380 $kg_{CO2\ eq.}/MWh_{NG}$ reported by the same author. However, since combustion in the power plant is also included in the reported ranges, applying the same approach in the present study would increase emissions to 242 $kg_{CO2\ eq.}/MWh_{NG}$ (Fig. 4), which still falls within the reported range. Concerning alternative feedstocks for gasification, the same author reports emissions varying from −25.9 to 804.7 $kg_{CO2\ eq.}/MWh_{SNG}$ for waste and 52.2 to 580.4 $kg_{CO2\ eq.}/MWh_{SNG}$ for straw (Kolb et al., 2021). However, it is not clear whether the difference in emissions comes from the assumptions in each study considered in the review or the type of feedstock.

Using feedstocks such as waste and straw may impact feedstock provision due to varying feedstock composition. As a result, there could be changes in the feedstock preparation and cleaning processes, as well as the supply chain, including transportation distances and methods. The composition also affects the energy content of biomass and gas production, due to agglomerate formation from alkali components (Ram et al., 2022). The DFB behaviour could differ, requiring adjustments to parameters or even to the process setup to keep the same product quality, still affecting the yield. These changes cannot be represented by the simulation and LCA models investigated in this study.

3.2.3. Electricity source variation

The Austrian market electricity mix dataset, used as the process electricity source in the base case (Bio-SNG), is based on 2020 statistics, comprises around 48 % hydropower, 11 % natural gas 8 % wind, 2 % bioenergy and imports from Germany and the Czech Republic. In total, at least 60 % of the mix is renewable.

To explore the effect of alternative electricity source assumptions, two additional scenarios were introduced. In the “Unsere Energiewelt 2040” case proposed by the Austrian Energy Agency (Bio-SNG-UEW), the renewable shares in the electricity mix increase to 97 %, with wind (35 %), hydropower (33 %), solar (22 %), and 10 % thermal power. In addition, a 100 % solar power case (Bio-SNG-S) is included for comparison, though this option is less realistic in the Austrian context. Combined with the 100 % wind power scenario (Bio-SNG-W), there is a broader basis for the sensitivity analysis of the electricity source.

Among the assessed impact categories, climate change, particulate matter, and water use are the most sensitive to the electricity mix. Variations in the electricity source would therefore impact these categories the most, while effects on the remaining impact categories are negligible. For climate change and fossil resource use, reductions of up to 40 % and 44 %, respectively, are observed in the alternative scenarios (Fig. 7). These improvements are due to lower fossil emissions, since all three scenarios (Bio-SNG-W, UEW and S) have a reduced or non-existent fossil-based electricity source in their mixes. As for water use, surprisingly, the emissions of the solar energy scenario are similar to the base case, due to the higher water demand related to the components of the solar panels, while Bio-SNG-W presents the lowest emissions for this impact category.

4. Conclusion

In this study, a simulation model was developed to describe the gasification of woody biomass and its subsequent processing into biosynthetic natural gas (Bio-SNG). The mass and energy balances derived from the model were used as inputs for a life cycle assessment (LCA) to evaluate the environmental impacts of producing Bio-SNG from wood chips, including scenarios involving CO_2 capture, transport, and different electricity sources. Generally, the Bio-SNG scenarios exhibited higher environmental impacts in several categories, except for fossil resource consumption. Increased non-climate-change-related impacts, partly due to background processes, highlight the need for sustainable agricultural and forestry practices, renewable electricity sources, and less strict gas cleaning compared to conventional natural gas production.

Fossil emissions arose mainly from electricity and biomass provision, while biogenic emissions reached up to 298 $kg_{CO2\ eq.}/MWh_{Bio\text{-}SNG}$ due to a low carbon utilisation rate of 34 % and heat demand covered by biochar combustion. CO_2 capture can reduce over 90 % of these emissions, and combining it with wind-powered electricity presents a viable pathway for Bio-SNG to contribute to future low-carbon energy systems. Further integration of heat and material streams could enhance process development and enable it to achieve a technology readiness level (TRL) comparable to that of the conventional natural gas route.

The study also shows the high carbon intensity of biomass-based processes, which is often overlooked in net GWP calculations, raising concerns about a potential burden shifting. While wood represents a best-case feedstock scenario, using residues could provide a more sustainable option, if process efficiency is maintained.

For future research, it is essential to assess the uncertainty inherent in this model and perform a sensitivity analysis to evaluate its accuracy and robustness. This is particularly important because the model relies on experimental data from a pilot-scale plant, so uncertainties related to upscaling should be carefully considered. Additionally, since the system

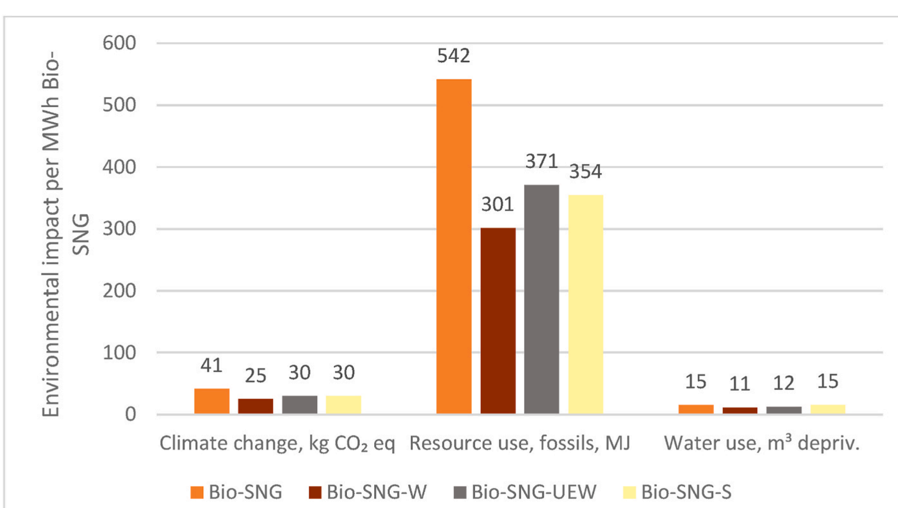

Fig. 7. Impact of electricity source variation. W - Wind, UEW – Unsere Energiewelt, S – Solar.

is based on the Austrian market, incorporating considerations of transport distances and background processes reflecting the Austrian context would greatly improve our understanding of the overall environmental footprint. As a further step, coupling LCA with data envelopment analysis could optimise both the resource and environmental efficiency of the process, thereby eliminating the need for environmental weighting factors.

CRediT authorship contribution statement

Diana Dimande: Writing – review & editing, Writing – original draft, Visualization, Validation, Methodology, Investigation, Formal analysis, Data curation, Conceptualization. **Bettina Mihalyi-Schneider:** Writing – review & editing, Supervision, Formal analysis, Conceptualization. **Michael Harasek:** Software, Resources, Project administration, Funding acquisition. **Walter Wukovits:** Writing – review & editing, Validation, Supervision, Software, Resources, Formal analysis, Conceptualization.

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.

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List of abbreviations

ALCA Attributional life cycle assessment
AP Acidification potential
APOS Allocation at point of substitution
Bio-SNG Biomass to synthetic natural gas
Bio-SNG-N-Em Bio-SNG with total CO_2 capture
Bio-SNG-P-Em Bio-SNG with CO_2 captured only from the SNG upgrading
Bio-SNG-S Bio-SNG considering electricity generated from photovoltaic
Bio-SNG-T Bio-SNG, including 200 km average transport distance for wood supply
Bio-SNG-UEW Bio-SNG case, assuming the 2040 electricity mix from the Unsere Energiewelt scenario by the Austrian energy agency
Bio-SNG-W Bio-SNG considering wind-generated electricity
CGE Cold gas efficiency
CLCA Consequential life cycle assessment
CTUe Comparative toxic unit for ecosystems
Db dry basis
EP Eutrophication potential
eq equivalents
fU Functional unit
GHG Greenhouse gas
GLO Global
GWP100 Global warming potential 100
LCA Life cycle assessment
MEA Monoethanol Amine
NG Natural gas
NG-P Natural gas production
Pt Dimensionless unit, expressed as points (Pt)
ReR Europe
RoW Rest of the world (Global without Switzerland)
SNG Synthetic or substitute natural gas
Syngas Synthesis gas
TEG Triethylene glycol
U Unit
η_C Carbon utilisation factor: $\frac{\text{Mass of carbon in product (SNG)}}{\text{Mass of carbon in solid fuel (Biomass)}}$

Appendix A. Supplementary data

Supplementary data to this article can be found online at https://doi.org/10.1016/j.cesys.2025.100359.

Data availability

Data will be made available on request.

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