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Enrichment of Integrated Steel Plant Process Gases with Implementation of Renewable Energy

Integration of power-to-gas and biomass gasification system in steel production

Ana Roza Medved, Markus Lehner*
Chair for Process Technology and Industrial Environmental Protection, Montanuniversität Leoben, Franz-Josef-Strasse 18, Leoben, Austria

Daniel C. Rosenfeld, Johannes Lindorfer
Energieinstitut an der Johannes Kepler Universität Linz, Altenberger Straße 69, 4040 Linz, Austria

Katharina Rechberger
K1-MET GmbH, Stahlstraße 14, 4020 Linz, Austria

***Email:** markus.lehner@unileoben.ac.at

The steel industry is one of the most important industry sectors, but also one of the largest greenhouse gas emitters. The process gases produced in an integrated steel plant, blast furnace gas (BFG), basic oxygen furnace gas (BOFG) and coke oven gas (COG), are due to high shares of inert gas (nitrogen) in large part energy poor but also providing a potential carbon source (carbon monoxide and carbon dioxide) for the catalytic hydrogenation to methane by integration of a power-to-gas (P2G) plant. Furthermore, by interconnecting a biomass gasification, an additional biogenic hydrogen source is provided. Three possible implementation scenarios for a P2G and a biomass gasification plant, including mass and energy balances were analysed. The scenarios stipulate a direct conversion of BFG and BOFG resulting in high shares of nitrogen in the feed gas of the methanation. Laboratory experimental tests have shown that the methanation of BFG and BOFG is technically possible without prior separation of CO_2. The methane-rich product gas can be utilised in the steel plant and substitutes for natural gas (NG). The implementation of these renewable energy sources results in a significant reduction of CO_2 emissions between 0.81 million tonnes CO_{2eq} and 4.6 million tonnes CO_{2eq} per year. However, the scenarios are significantly limited in terms of available electrolysis plant size, renewable electricity and biomass.

1. Introduction

In 2011 the European Commission presented "A Roadmap for Moving to a Competitive Low Carbon Economy in 2050" outlining the milestones, among them also the 83–87% CO_2 reduction of the industry sector (1, 2). Primary steel production *via* the blast furnace/basic oxygen furnace (BF/BOF) route or so-called integrated steel plant, is a predominant and well-established process, contributing 70.8% of the world's 1807 million tonnes of crude steel production in 2018 (3). The reduction process of the iron ore to crude steel is linked to CO_2 emissions, resulting in 2016 for a total of 7% (160 million tonnes of CO_{2eq}) of EU-28's greenhouse gas emissions (4). The energy efficiency potential of a modern integrated steel plant has already been exploited to a great extent through conventional process optimisations. It is, therefore, necessary to transfer steel production to climate-friendly processes through new and innovative approaches. Hydrogen-based direct reduction processes and electrolytic reduction methods are alternatives for the reduction of iron ore, but they require on the one hand huge amounts of renewable energy, for instance for green hydrogen production in water electrolysis, and cause on the other hand significant investment demand as the existing production infrastructure has to be replaced (5). Carbon capture and utilisation (CCU) processes are a second option which are near-term actionable, as they can be added to the existing infrastructure without a significant change in the steel production itself (6). The first step of a CCU process chain is the energy intensive separation of CO_2 from diluted exhaust or process gases. If these gases also contain carbon monoxide, as is the case in the steel industry (**Table I**), carbon monoxide is avoided of utilisation since the carbon capture processes selectively separate CO_2 (8). The separated CO_2 is then either biologically or catalytically converted to usable products (6).

The process gases in a steel plant, BFG, BOFG and COG, contain high shares of carbon monoxide and CO_2 (**Table I**). These low-calorific gases are currently utilised in an integrated steel plant as an energy carrier, i.e. in heating processes, and as fuel in the power plant. In **Figure 1** the energy flows in an integrated steel plant are depicted. The main part of the BFG (white letter **A** in **Figure 1**) is directed to the enrichment process where it is mixed with BOFG (white letter **B** in **Figure 1**). The main share of the enriched gas fuels the power plant. COG (white letter **C** in **Figure 1**) is mainly used in internal processes and in the power plant as well. The power plant covers almost the total electricity demand of the steel mill. NG (white letter **D** in **Figure 1**) is used for heating in downstream processes, like in the hot strip mill, and in the power plant as well. The quantity of the process gases BFG, BOFG and COG covers up to 40% (9) of the steel plant's energy demand, where the remaining part is provided by electrical energy and fossil fuels, like NG.

The Sankey diagram of **Figure 2** indicates the composition of the different byproduct gases and their internal use. It is obvious that a withdrawal of these low-calorific gases has to be compensated by the supply of other energy carriers, either synthetic natural gas (SNG) or external electricity, since the main part of the gases are used in the power plant downstream of the enrichment process. In the enrichment process, the byproduct gases are mixed and buffered in gasometers.

However, due to their high carbon monoxide and CO_2 concentrations, the process gases may be conceived for further use as a carbon source for catalytic conversions. As summarised in the review from Frey *et al*. (10) the alternative utilisation of steel plant process gases for the production of ammonia, methanol or recovery of its derivatives has already been under examination since the early 1950s. The latest review from Uribe-Soto *et al*. (11) outlined three alternatives: (a) thermal use of the process gases (state-of-the-art); (b) recovery of the valuable compounds (hydrogen, methane and carbon monoxide) *via* different separation technologies; and (c) thermochemical synthesis to high-added value products (methanol, dimethyl ether, urea), with the focus on the latter. The consideration of their utilisation as a potential carbon source and coupling it with renewable energy within the context of power-to-X technology, has gained attention in the last years especially in Europe, resulting in various theoretical studies as well as research projects. The largest German steel producer, thyssenkrupp, is leading the "Carbon2Chem" project (12), where different scenarios for the synthesis of methanol (13, 14), ammonia or urea (15), as well as higher alcohols and polymers (16) from BFG, COG and BOFG are being investigated. In an ongoing research project the possibilities of converting BOFG and BFG into methanol and methane are explored under dynamic conditions (17, 18).

All studies referenced above utilise pure CO_2 which is separated in a first step from the process gases,

Table I Typical Gas Composition of Process Gases in an Integrated Steel Plant[a]

Parameter	Units	BFG	COG	BOFG mean
CO	vol%	19–27	3.4–5.8	60.9
H_2	vol%	1–8	36.1–61.7	4.3
CO_2	vol%	16–26	1–5.4	17.2
N_2	vol%	44–58	1.5–6	15.5
CH_4	vol%	–	15.7–27	0.1
C_xH_y	vol%	–	1.4–2.4	–
Lower heating Value	kJ Nm^{-3}	2600–4000	9000–19,000	8184

[a] Data taken from (7)

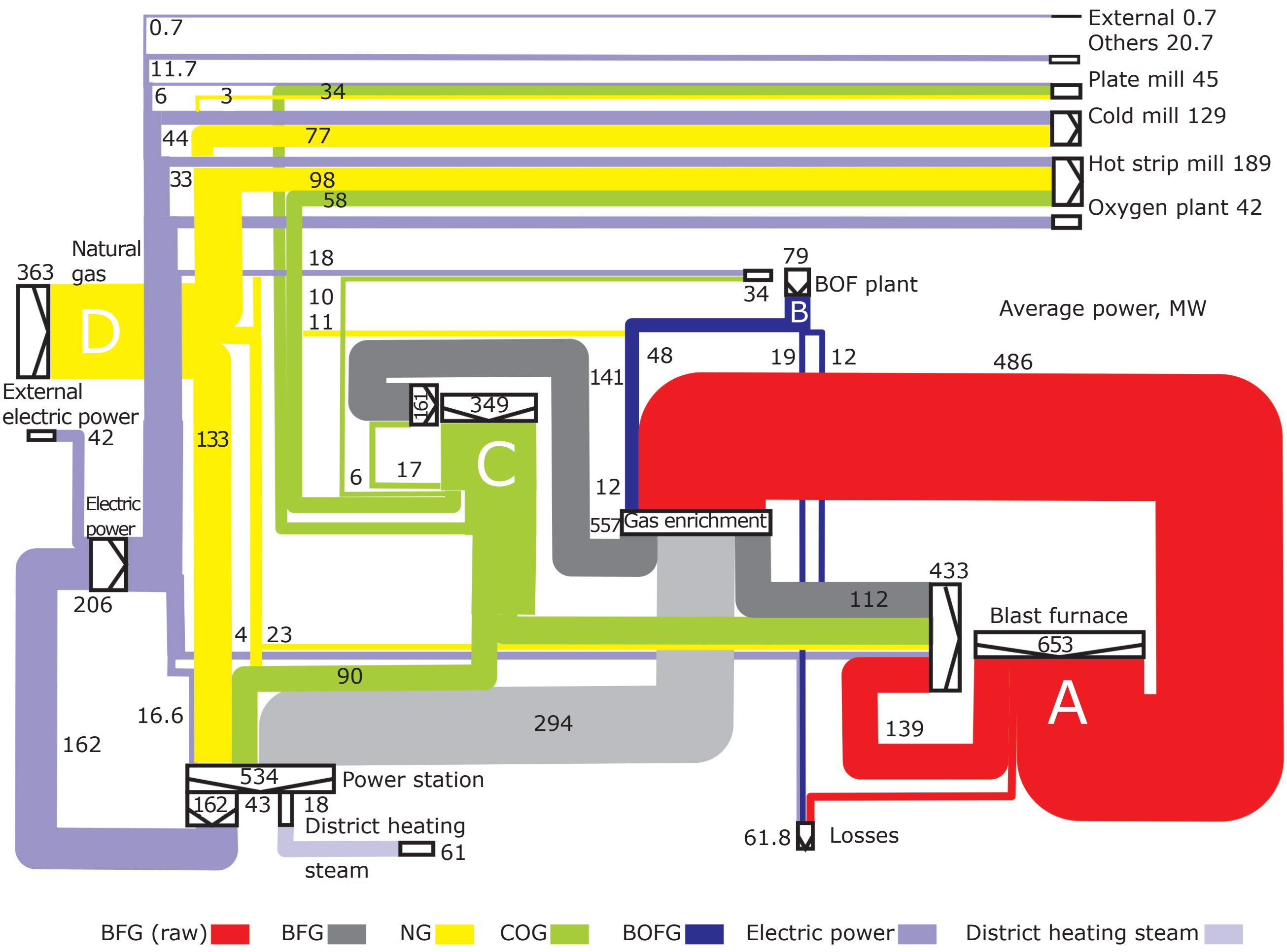

Fig. 1. Energy flow in an integrated steel plant, simplified from (7)

and is subsequently converted with hydrogen in a catalytic synthesis. In this study, the catalytic conversion of BFG and BOFG to methane is investigated without a prior separation of CO_2. The process gases of the steel plant are only pre-cleaned upstream of the catalytic conversion by dust removal (i.e. by a venturi scrubber and a bag house filter) and separation of the sulfur compounds sulfur dioxide, carbonyl sulfide, mercaptans (i.e. in a series of two adsorbers in order to remove the catalyst poisons), see **Figure 3**. Consequently, the catalytic conversion is carried out with significant shares of nitrogen in the feed gas. Therefore, the following advantages arise:

- The energy-intense CO_2-separation is avoided, and thus the energy efficiency of the CCU process chain is improved
- The additional carbon source, carbon monoxide, present in high concentrations in the process gases BFG and, particularly, BOFG (**Table I**), can be utilised for the catalytic process
- Hydrogenation of carbon monoxide requires one mole of hydrogen less than the hydrogenation of CO_2 to methane, giving another economic advantage in view of the high cost of green hydrogen production.

The aim of the present study is the assessment of different process chains for the direct utilisation of BFG and BOFG in catalytic methanation without a prior CO_2 separation. Since the conversion of CO_2 and carbon monoxide to methane requires renewable hydrogen, the hydrogen supply is ensured by a water electrolysis powered by renewable electricity (P2G plant) as well as by an additional biomass gasification plant (**Figure 3**). Therefore, a variety of possible implementation scenarios arise, and the following fundamental research questions have to be answered:

- **Question 1**: (a) What process gases should be used; and (b) in what amount?
- **Question 2**: What is the required size of the P2G plant and the biomass gasification plant and in what share do they provide the required renewable hydrogen?

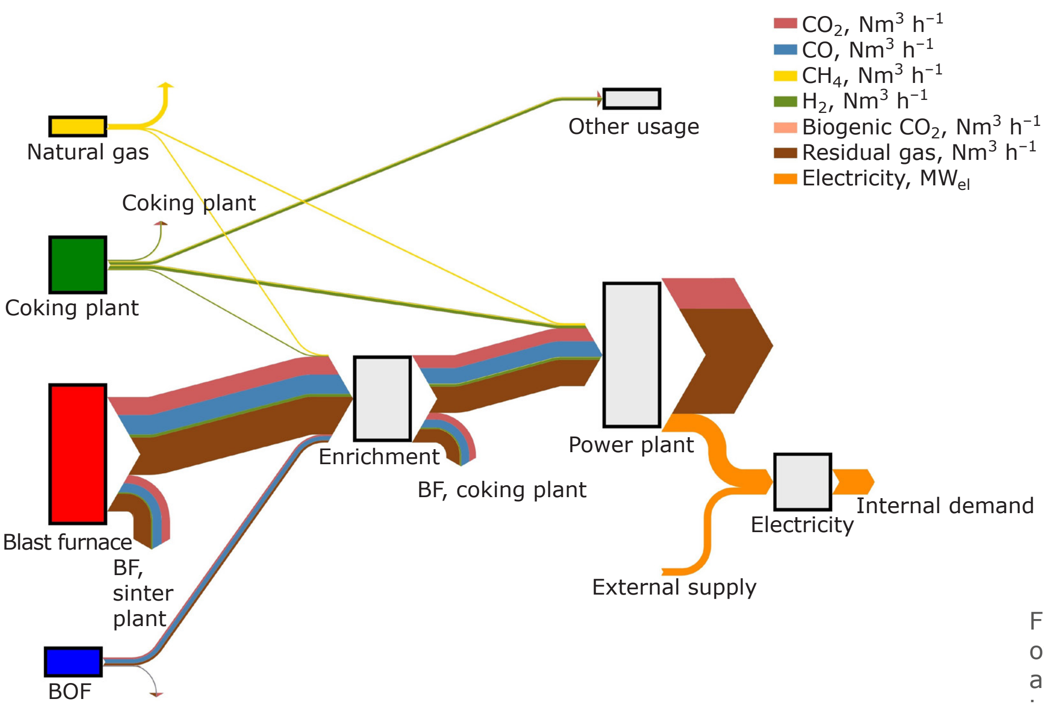

Fig. 2. Composition of byproduct gases and their use in an integrated steel plant

- **Question 3**: How is the produced SNG, which is diluted by nitrogen, utilised?
- **Question 4**: What is the technoeconomic optimum, and what is the CO_2 abatement potential?
- **Question 5**: Is a sound operation of a catalytic methanation with high shares of nitrogen in the feed gas possible?

A withdrawal of process gases, particularly of the comparatively high calorific COG, would result in a shortage of internal energy supply in the integrated steel plant (**Figure 1**) which has to be substituted by NG or electric energy sourced externally. Therefore, in order to avoid significant changes of the existing steel production infrastructure, in this study COG was not considered, and BFG as well as BOFG are solely used as a carbon source for a potential utilisation process (Question 1(a)). Furthermore, it has been deliberately decided that the product gas from the methanation, nitrogen diluted SNG, substitute fossil NG currently used in the integrated steel plant, mainly for heating processes. Alternatively, it is used as reducing agent in the blast furnace, for example as substitute for pulverised coal injection (PCI). An injection into the NG grid is not possible since the required specifications are not met (Question 3). The technoeconomic and ecological questions (Questions 1(b), 2 and 4) have been treated by Rosenfeld *et al.* (19). Supporting laboratory experiments for biomass gasification have been published by Müller *et al.* (20). The focus of this study is on Questions 5 and 1(b).

2. Integration Scenarios

Figure 3 provides an overview of the possible integration of a P2G plant (**Figure 3(b)**) as well as a dual fluidised biomass gasification plant (**Figure 3(c)**) into the integrated steel plant (**Figure 3(a)** in dashed lines). By integrating a P2G plant, renewable energy is used for the production of hydrogen by water electrolysis and subsequently for the catalytic methanation of the process gases BFG and BOFG. The combination with a dual fluidised biomass gasification (20–22) provides an additional biogenic hydrogen source. The biogenic CO_2 is vented to the atmosphere. Alternatively, it could be stored in a carbon capture and storage (CCS) process resulting in negative CO_2 emissions (bioenergy with carbon capture and storage (BECCS)) which is not further considered here (23). In addition, the oxygen from the water electrolysis has the potential for utilisation in steel production as well as in the biomass gasification process. The produced nitrogen diluted SNG is directly utilised in the steel plant as a substitute for NG in various processes, and PCI in the blast furnace.

To explore the integration potential, a number of different scenarios has been defined and three of

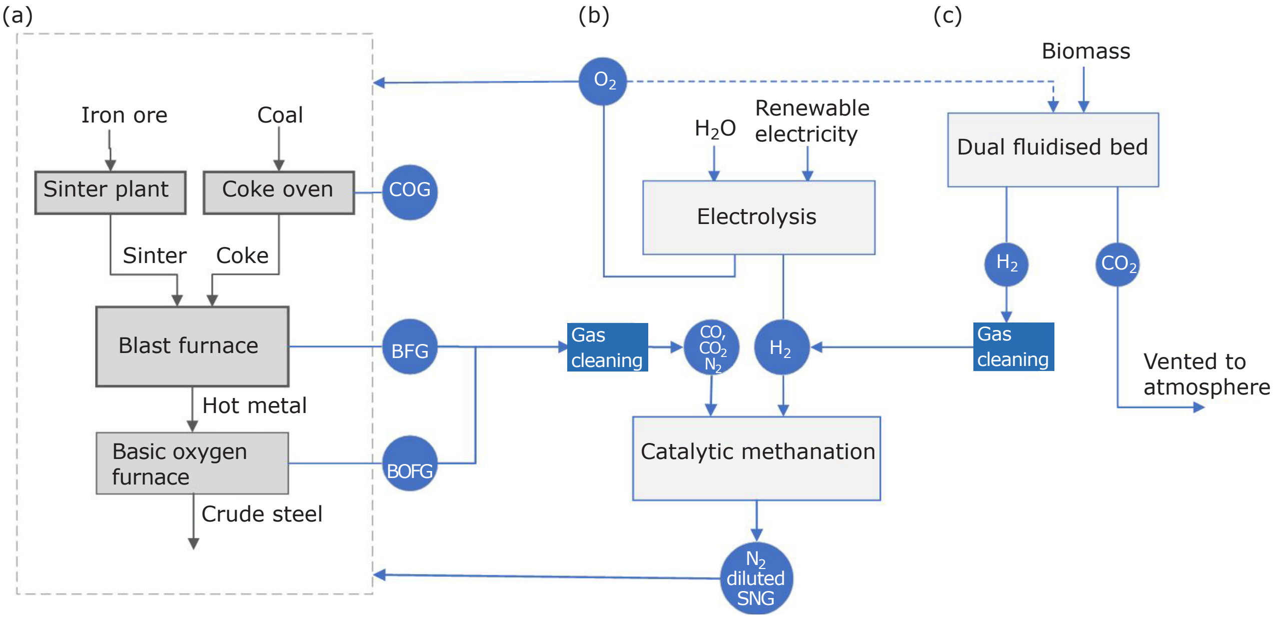

Fig. 3. P2G and biomass gasification integration variations in the integrated steel plant: (a) Integrated steel plant; (b) P2G plant; (c) dual fluidised biomass gasification plant

them, supported by the experimental results at a laboratory catalytic methanation plant, will be presented in detail in the present work. The three chosen scenarios provide a good overview of the order of magnitude of the required renewable energy, as well as the resulting CO_2 reduction potential.

The scenarios with different integration variations were based on Austria's biggest steel production sites. The integration of renewable energy by a P2G plant and a biomass gasification plant has been analysed by three extreme value scenarios and three constrained scenarios. The results are reported in (19). The three extreme value scenarios described a maximum utilisation of the process gases, either individually or in combination. The required hydrogen for the methanation was balanced, half from water electrolysis and half from biomass gasification. The constrained scenarios are realistic in the medium term. They are limited by the maximum plant size of the biomass gasification plant (100 MW_{th}), based on the current biomass fuel availability and already installed gasification capacity in Europe (21). The main cost influencing factor throughout all six scenarios is the energy supply cost, both for electricity and for biomass (19).

The aim of the aforementioned scenarios was the minimisation of, or complete substitution of, the integrated steel plant's demand for fossil fuels like NG and PCI. The steel plant process gases (BFG and BOFG) were used as carbon source for the methanation. The three scenarios which are the basis for the considerations in this paper are:

- **Scenario 1**: utilisation of the total carbon monoxide and CO_2 content of BFG and BOFG; hydrogen supply by electrolysis and biomass gasification in equal shares (extreme scenario)
- **Scenario 2**: complete substitution of the steel plant's NG and PCI demand *via* methanation of BFG and BOFG, hydrogen supply by electrolysis and biomass gasification where the biomass gasification is limited to 100 MW_{th} gasification power
- **Scenario 3**: complete substitution of the steel plant's NG demand *via* methanation of BOFG, hydrogen supply by electrolysis and biomass gasification where biomass gasification is limited to 100 MW_{th} gasification power.

For these three scenarios, the required amount of the renewable electricity, biomass as well as the withdrawal amount of the process gasses (BFG or BOFG) has been determined. The main evaluation criteria for all scenarios were set by the CO_2 reduction potential.

3. Fluidised Bed Biomass Gasification

Dual fluidised bed gasification systems consist of two reactors, the gasification reactor (650°C) and the combustion reactor (900°C). In contrast to the conventional systems, the presented system uses

Table II Product Gas Composition of Dual Fluidised Bed Gasification for OxySER Gasification (20, 21)

Parameter	Units	Product gas	Flue gas
CO	vol%	10	–
H_2	vol%	72	–
CO_2	vol%	5	91
N_2	vol%	–	–
CH_4	vol%	11	–
O_2	vol%	–	9
C_xH_y	vol%	2	–
Lower heating Value	kJ Nm^{-3}	14,100	–

the sorption enhanced reforming (SER) process. It allows selective transport of CO_2 between the gasification reactor and the combustion reactor, by the use of calcium oxide as bed material, resulting in a product gas with a high hydrogen (up to 75 vol%) and low CO_2 concentration. The hydrogen rich product gas of the biomass gasification substitute green hydrogen from the electrolysis, and thus reduces the demand of renewable electric power (22, 24). Additionally, when pure oxygen is used instead of air for the combustion (oxySER), an almost pure CO_2 stream can be obtained as an exhaust (flue) gas, suitable as biogenic CO_2 source (**Table II**). The data given in **Table II** are based on the gasification of wood chips. A thermal gasification power of 100 MW_{th} consumes 50,400 kg h^{-1} wood chips from Austria as fuel, and produces 28,800 Nm^3 h^{-1} product gas with the composition according to **Table II** (21).

4. Experimental Tests

The experimental tests were performed at a laboratory test plant, which consists of three fixed-bed reactors (R1–R3) connected in series with the purpose of achieving a multi-stage fixed-bed methanation. A detailed description of the test plant can be found in Kirchbacher *et al*. (25) and Medved (26). The conversion of CO_2 and carbon monoxide was investigated for synthetic gas compositions of BFG and BOFG under different flow rates, variation of hydrogen surplus and presence of nitrogen, with the focus on achieving a complete CO_x conversion.

A commercial bulk catalyst with 20 wt% nickel load was used. The operating pressure was set to 4 bar, which coincided with the steel producer's gas supply system. The reactor load was limited to gas hourly space velocity (GHSV) of 4000 h^{-1} (GHSV = $\dot{V}_{feedgas}/V_{catalyst}$) for the synthetic BFG and BOFG gas composition and added hydrogen. The temperature in the reactor was determined by multi-thermocouples (**Figure 4**).

Seven measuring points in each reactor, five in the catalyst bed and one below and above the catalyst zone, gave an understanding of the axial temperature profile in the catalyst bed. The methanation gas composition for BFG and BOFG for

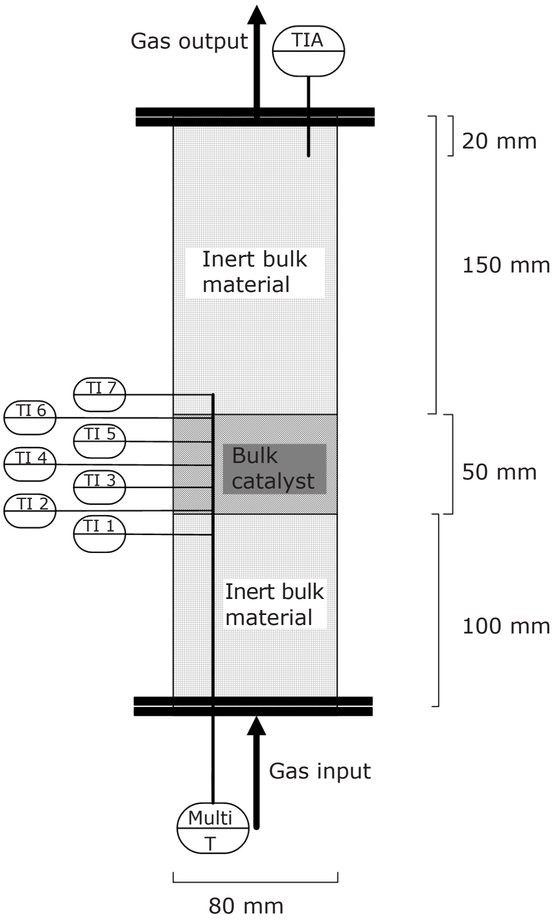

Fig. 4. Catalyst implementation and positioned multi-thermocouples in the reactor (26)

Table III Methanation Feed Gas Composition for BFG and BOFG

	Feed gas molar fraction			
	CO_2	CO	N_2	H_2
BFG	0.088	0.095	0.183	0.634
BOFG	0.06	0.155	0.082	0.703

the stoichiometric ratio with hydrogen according to Equations (i) and (ii) is listed in **Table III**.

$$\text{CO}_2\ \text{methanation: } CO_2 + 4H_2 \leftrightarrow CH_4 + 2H_2O \quad \Delta H_R^0 = -165\ \text{kJ mol}^{-1} \tag{i}$$

$$\text{CO methanation: } CO + 3H_2 \leftrightarrow CH_4 + H_2O \quad \Delta H_R^0 = -206\ \text{kJ mol}^{-1} \tag{ii}$$

5. Results and Discussion

The experimental results obtained from the methanation of BFG and BOFG were used as support for the further analysis of the three selected scenarios. In the following, the experimental results and the scenarios are presented separately in the subsections.

5.1 Methanation

The methanation of process gases is a combination of CO_2 and carbon monoxide conversion according to Equations (i) and (ii).

A suitable parameter for the description of the stoichiometry is the ratio r_{H_2} of molar hydrogen flow and molar flows of CO and CO_2, respectively, in the feed gas given in the Equation (iii):

$$r_{H_2} = \frac{n_{H_2}}{4n_{CO_2} + 3n_{CO}} \tag{iii}$$

r_{H_2} equals 1 for stoichiometric mixtures, r_{H_2} <1 for sub- and r_{H_2} >1 for over-stoichiometric mixtures, respectively.

Achieved CO_x conversion rates for each reactor (R1–R3), with variation of hydrogen surplus (r_{H_2} = 1; 1.02; 1.04; 1.05) with and without nitrogen for a synthetic BFG and BOFG feed gas compositions, can be seen in **Figures 5** and **6**. On the right y-axis, the mean reactor temperature represents the average of the measured catalyst bed temperatures, as well as the calculated heating values of the product gas in each reactor. For experiments without nitrogen in the feed gas, marked with -N_2, the H_2:CO_x ratio and the amount of the reactive gas in the experimental series remained the same, meaning that the GHSV was reduced to 3260–3280 h^{-1} for BFG and 3680–3690 h^{-1} for BOFG due to the absent inert gas flow.

5.1.1 Methanation of Blast Furnace Gas

Complete CO_x conversions are achieved downstream of the third reactor with an over-stoichiometric ratio of 1.05, both with and without the nitrogen in the feed gas (**Figure 5**). The mean reactor temperatures are approximately 50°C lower with nitrogen present, which is a result of the additional heat capacity of the inert gas. Despite these lower temperatures, approximately 4% better conversions are reached in R1 for all ratios in the absence of nitrogen. The withdrawal of nitrogen from the feed gas resulted in lower GHSV, consequently prolonging the residence time in the reactor leading to slightly better CO_x conversions. The temperature decrease in R2 and R3 was expected, since the majority of the reactive gas converted in R1, resulting in lower release of the exothermic reaction heat. Therefore, nitrogen in the feed gas only has a significant influence on the heating value of the product gas. In the case of the product gas (R3) with nitrogen the heating values vary from 19.4–19.8 MJ m^{-3} (r_{H_2} = 1.05–1), whereas without nitrogen the values almost double (36.0–37.9 MJ m^{-3}). Although with the higher hydrogen surplus better conversions are achieved, the unconverted hydrogen decreases the heating value of the product gas, due to its lower volumetric heating value compared to methane.

5.1.2 Methanation of Basic Oxygen Furnace Gas

As for BFG, similar test series were conducted for the methanation of BOFG. As shown in **Figure 6**, on account of lower nitrogen share in the feed gas (8.2%), no noticeable effect on the temperature and consequently conversion can be recognised. Furthermore, a complete CO_x conversion at 4% hydrogen surplus is achieved with or without nitrogen in the feed gas. When comparing the mean reactor temperatures and CO_x conversion in R1 of BOFG with the BFG test series, temperatures are 50–100°C higher and conversions 5–10% lower, respectively. This can be attributed to the higher carbon monoxide share in BOFG, resulting in higher reaction heat release. Therefore, the conversion in the first reactor (R1) is clearly thermodynamically limited. Since its lower share in BOFG compared to BFG, the influence of nitrogen on the heating value

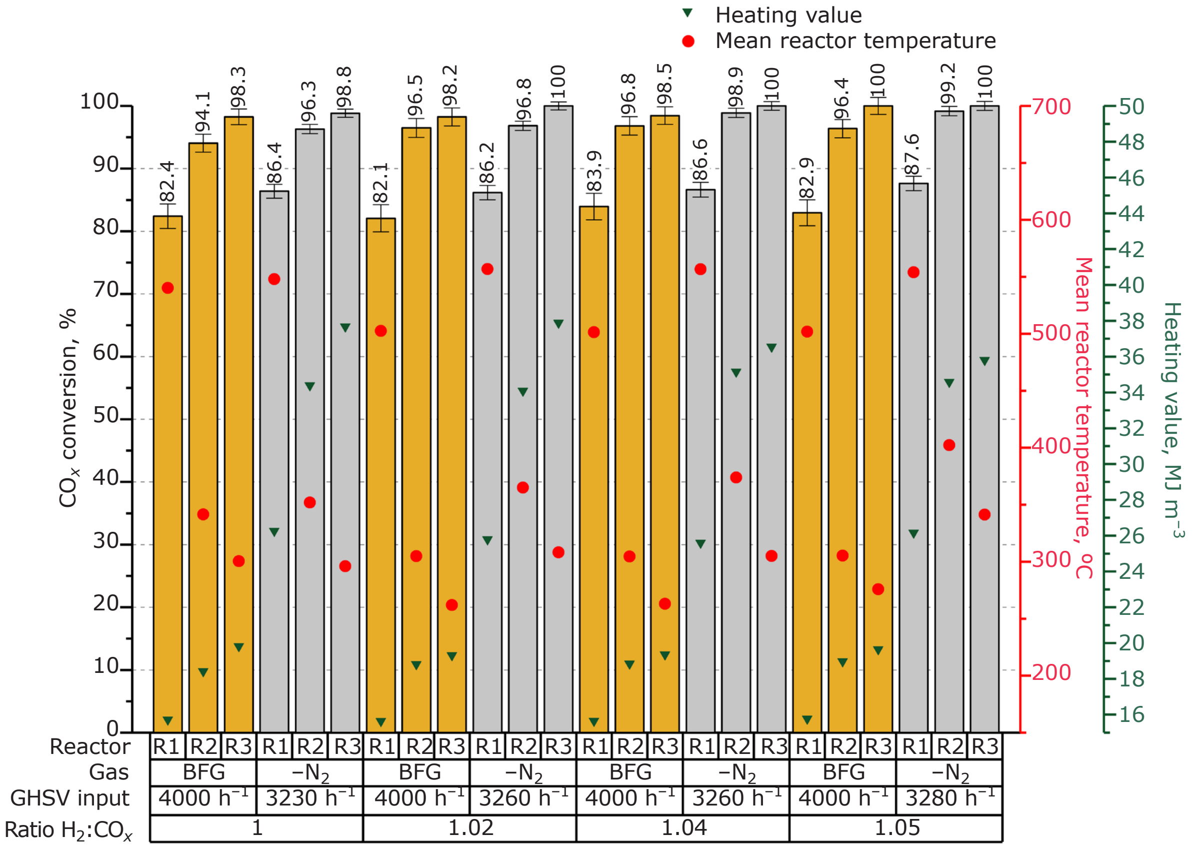

Fig. 5. Methanation of BFG with and without nitrogen and hydrogen-surplus variation

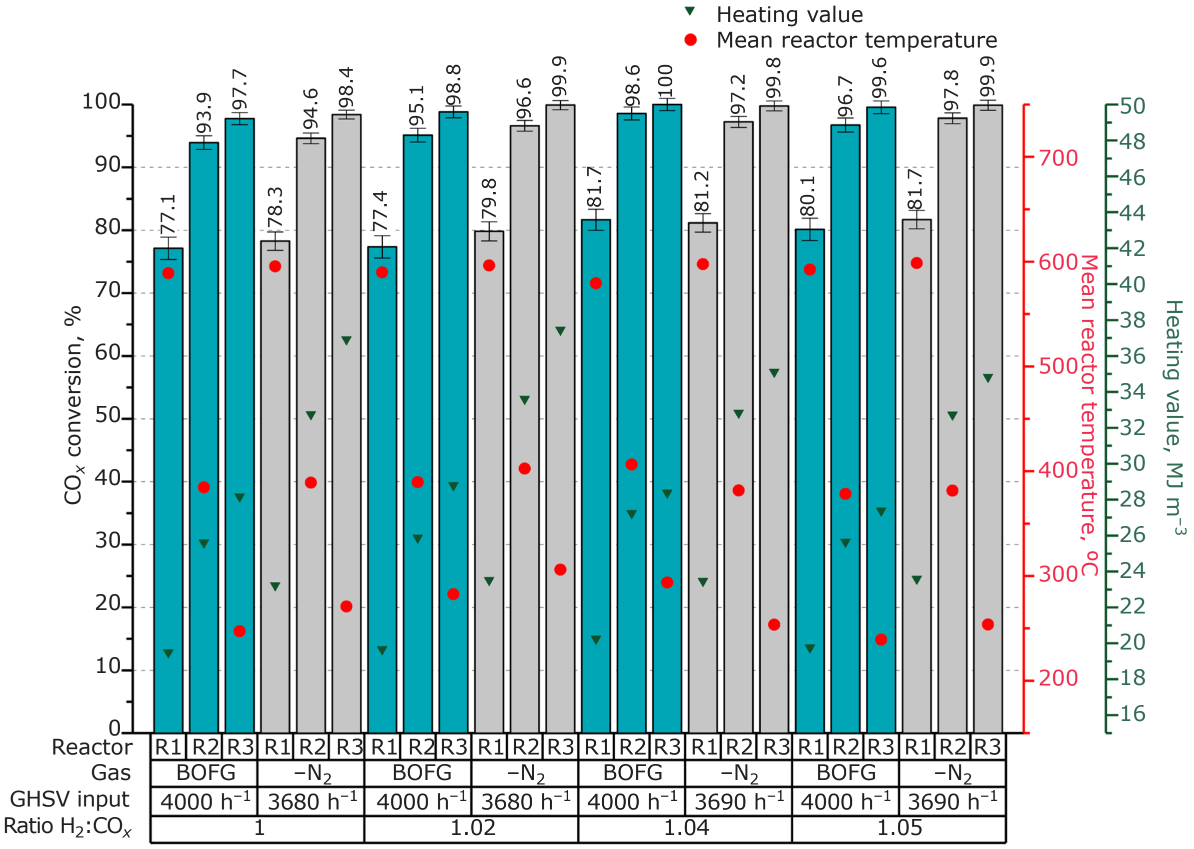

Fig. 6. Methanation of BOFG with and without nitrogen and hydrogen-surplus variation

of the product gas is lower, and values vary from 27.2–28.8 MJ m^{-3} (r_{H_2} = 1.05–1) with nitrogen and between 34.9–37.7 MJ m^{-3} (r_{H_2} = 1.05–1) without nitrogen.

The product gas composition downstream of the methanation is given in **Table IV**. A complete conversion is achieved at 5% hydrogen surplus for BFG and at 4% hydrogen surplus for BOFG, where the unconverted hydrogen is a result of its over-stoichiometric addition.

5.2 Results for the Selected Scenarios

The performance overview of the three selected scenarios (Scenarios 1, 2 and 3) can be found in **Table V**. The required hydrogen for the methanation was calculated with 4–5% surplus, based on the experimental results for a complete CO_x conversion for BFG as well BOFG. For the evaluation of these scenarios, a hydrogen content of 72 vol% in the biogenic-rich hydrogen stream from the biomass gasification (**Table II**), and a specific power consumption of 5 kWh Nm^{-3} hydrogen in the electrolyser were assumed (25).

The extreme value Scenario 1 was defined with a complete CO_x (CO_x:CO and CO_2) conversion of the content in BFG and BOFG, and the hydrogen demand is covered by electrolysis (50%) and biomass gasification (50%). For a complete CO_X conversion, an electrolyser with 2.88 GW_{el} and 3.16 GW_{th} biomass gasification would be required (**Figure 7**). Due to the enormous amount of available BFG and BOFG gas, the methane-rich product gas would cover up to three times the NG demand of the steel plant and result in 4.6 million tonnes of CO_{2eq} reduction potential per year. Additionally, the oxygen produced could replace the air separation unit of the steel mill and cover the steel plant's demand more than three times.

Scenario 2 was defined as methanation of BOFG without nitrogen for a complete substitution of the fossil fuels NG and PCI used as injection for the blast furnace. When partially withdrawing the BOFG from the steel production, a shortage of its currently used energy input in the power plant occurs that would consequently result in loss of electric power production. To compensate for the missing amount of BOFG, the BFG with nitrogen is additionally enriched *via* methanation (**Figure 8**). As demonstrated by the methanation experimental tests, the resulting product gas obtained the same lower heating value (19.4–19.8 MJ m^{-3}) as COG (19.0 MJ m^{-3}) and more than double that of the unrefined BOFG (8.2 MJ m^{-3}) (7). Additionally, when comparing the high specific global warming potential (GWP) based on the calorific value of the process gases, with 268 kg_{CO_2eq} $GJ^{-1}{}_{LHV}$, BFG has a much higher GWP in comparison to BOFG (182 kg_{CO_2eq} $GJ^{-1}{}_{LHV}$) and COG (49 kg_{CO_2eq} $GJ^{-1}{}_{LHV}$) (27). The product gas from the methanation of BFG could substitute for the withdrawal of BOFG and subsequently be sent to the enrichment process in the steel plant. Complete utilisation of the available BOFG and 8% of the available BFG amount would be necessary. With the required 901 MW_{el} electrolyser, the complete oxygen demand of the steel plant is covered.

Table IV Product Gas Composition for the Methanation of BFG and BOFG

	Product gas molar fraction				
	CH_4	CO_2	CO	N_2	H_2
BFG (r_{H_2} = 1.05)	0.446	0	0	0.434	0.120
BOFG (r_{H_2} = 1.04)	0.679	0	0	0.215	0.106

Table V Performance Overview

	Unit	Scenario 1	Scenario 2	Scenario 3
Process gas utilisation	%	100 (BOFG+BFG)	100 (BOFG) 8 (BFG)	87 (BOFG)
Electrolyser	MW_{el}	2877	901	754
Methanation	MW_{th}	1496	119 (BFG) 349 (BOFG)	392
Biomass gasification	MW_{th}	3162	100	100
NG substitution	%	300	100	100
CO_{2eq}	million tonnes CO_{2eq} per year	4.6	0.81	0.81

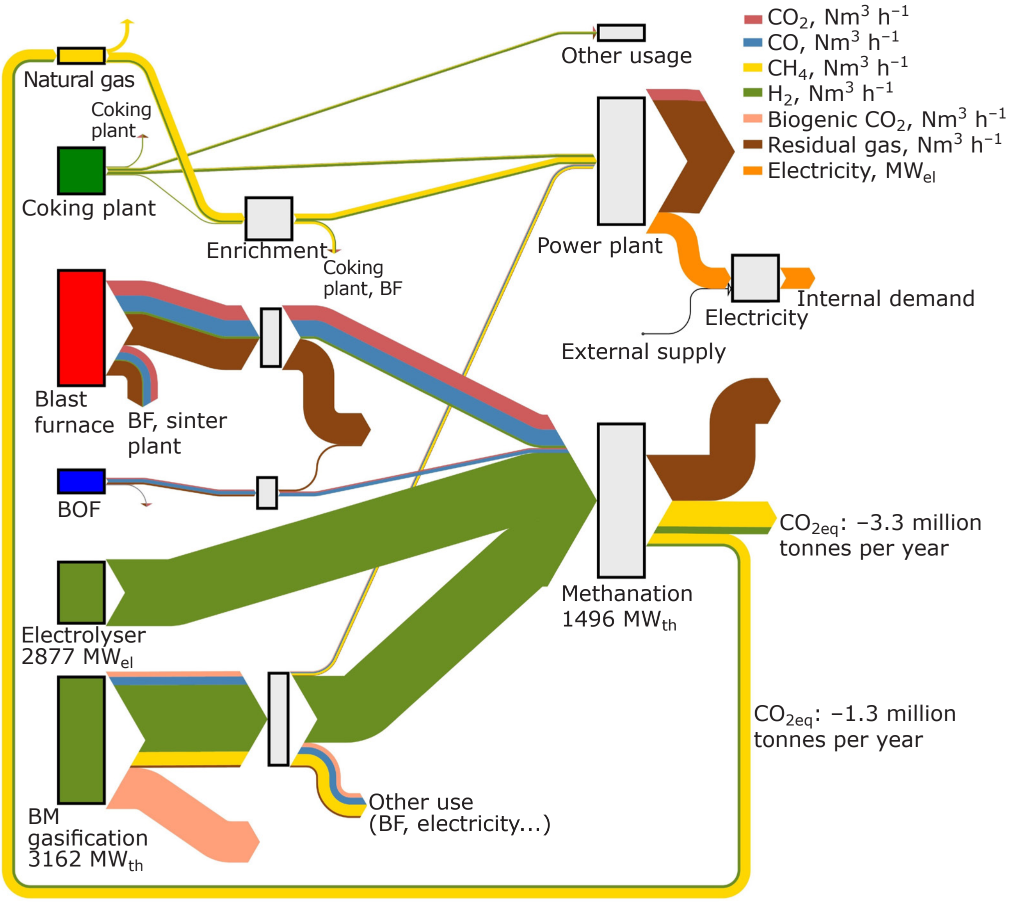

Fig. 7. Sankey diagram for the energy flows and the CO$_2$ reduction of an implementation of Scenario 1 in the integrated steel plant

Figure 7 shows a Sankey diagram of the energy flows for the implementation of Scenario 1 in the integrated steel plant of voestalpine Stahl GmbH at the production site Linz, Austria. The electrolyser (2877 MW$_{el}$) and the biomass gasification (3162 MW$_{th}$) provide the hydrogen for the methanation (1496 MW$_{LHV}$) of BFG and BOFG. A part of the produced SNG covers the total NG and PCI demand of the plant which accounts for a reduction of CO$_2$ emissions of 1.3 million tonnes CO$_{2eq}$ per year. The excess SNG substitutes, after an appropriate conditioning for the injection into the NG grid, another 3.3 million tonnes CO$_{2eq}$ per year.

As for Scenario 3, the scenario differs from Scenario 2 in the lower required electrolyser power of 754 MW$_{el}$. In this case, the withdrawn BOFG would not be substituted by the enriched BFG but with external electricity or other energy sources, due to the set framework conditions and system configurations. The CO$_2$ reduction potential of 0.81 million tonnes of CO$_{2eq}$ annually would be possible with a complete substitution of the NG demand.

6. Conclusions

In this study, three different scenarios for the implementation of a P2G plant and a biomass gasification in an integrated steel plant have been investigated. The aim was the quantification of the CO$_2$ emission reduction potential of steel production, avoiding significant modifications in the existing steel plant infrastructure. Furthermore, a carbon capture step shall be avoided as well, in order to improve the efficiency of the CCU process chain, resulting in a catalytic conversion of BFG and BOFG to methane in the presence of nitrogen.

Basic evaluation of the three chosen scenarios confirmed the possibility of CO$_2$ emission reductions between 0.81 and 4.6 million tonnes CO$_{2eq}$ per year without considerable interference with existing steel production. The required plant sizes and the necessary fuel demand (renewable power and biomass, respectively) substantially exceed the current realistic possibilities of a P2G plant (electrolyser power 784–2877 MW$_{el}$) as well of a biomass gasification (100–3162 MW$_{th}$). Even for the scenarios realistic in the medium term, the amount

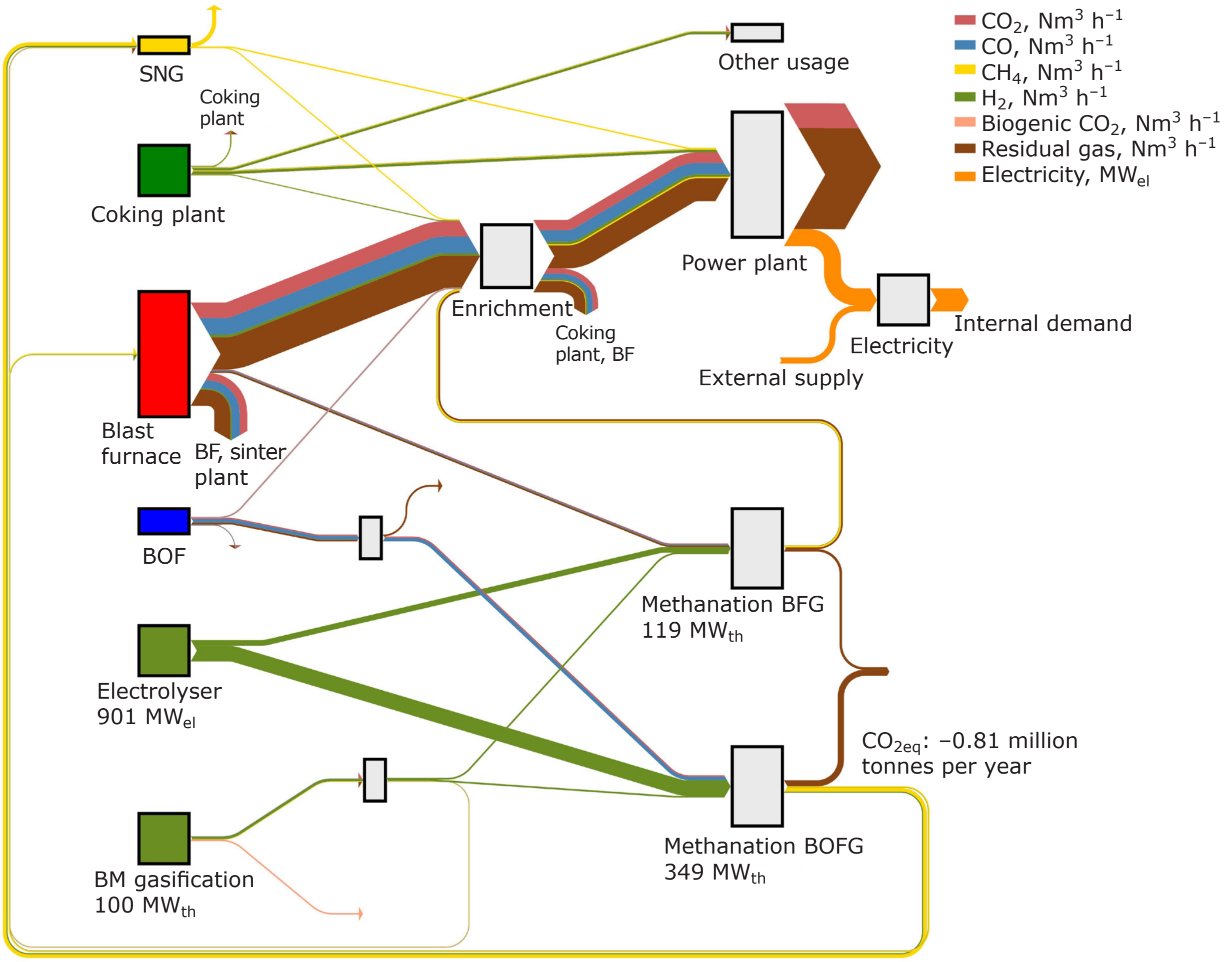

Fig. 8. Sankey diagram for the energy flows and the CO_2 reduction of an implementation of Scenario 2 in the integrated steel plant

of required renewable electricity beyond 700 MW_{el} cannot be provided in the foreseeable future. This underscores the need for new technologies for the production of CO_2-free hydrogen.

Experimental tests have shown that the methanation of BFG and BOFG is technically possible without separating the inert gas nitrogen, and thus saving the energy intensive carbon capture unit with the additional benefit of carbon monoxide utilisation contained in the process gases from the steel production. A complete conversion of CO_x was achieved with a 4–5% hydrogen surplus for both process gases, BFG and BOFG, with and without nitrogen, with three-stage methanation. The lower heating value enrichment of the unrefined BFG (up to 19.8 MJ m^{-3}) and BOFG (up to 28.8 MJ m^{-3}) *via* methanation without the necessity of nitrogen removal as lean product gas showed a utilisation potential in the integrated steel plant as a substitute for NG and PCI.

The first evaluation presented here provides a good overview on the order of magnitude of required renewable energy and biomass for the transition of the integrated steel plant towards renewable gas supply by adding a CCU process chain. Additionally, particularly for the utilisation of the product gases of catalytic methanation within the steel plant, intricate CO_2 separation is not required as has been shown by the experimental investigations.

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The Authors

Ana Roza Medved studied chemical engineering at the faculty for Chemistry and Chemical Technologies at the University of Ljubljana, Slovenia. Since 2015, she has been a part of the Energy Process Engineering research group at the Chair for Process Technology and Industrial Environmental Protection, Montanuniversität Leoben, Austria as research assistant, with a focus on catalytic methanation and P2G technologies.

Markus Lehner studied chemical process engineering at TU Munich, Germany. He achieved doctoral graduation in 1996 and held a postdoctoral position until 1998. He worked at RVT Process Equipment GmbH (previously Rauschert Verfahrenstechnik GmbH), Steinwiesen, Germany from 1999 to 2010. His last position was as area manager for sales, engineering and construction. Since October 2010 he is full professor and head of the chair of process technology, Montanuniversität Leoben. His fields of activity are energy process engineering, thermal cracking, catalytic processes for CO_2 utilisation and P2G.

Daniel Rosenfeld completed his master's studies in Chemical and Process Engineering at the Vienna University of Technology, Austria, in 2017. Since 2018 he is working as researcher at the Energy Institute at the Johannes Kepler University Linz, Austria. In July 2020, Rosenfeld completed his doctoral studies in energy technologies at the University of Natural Resources and Life Sciences, Vienna, Austria. After his graduation, he stayed at the Energy Institute as a senior researcher. The focus of his work is on the technical, economic and ecological evaluation of generation and application technologies of renewable gases.

Johannes Lindorfer studied environmental engineering at the University of Applied Sciences in Upper Austria. He worked as project engineer in the field of dispersion calculation of air pollutants and since 2007 Johannes is working as research associate and since 2009 as project manager at the Energy Institute at the Johannes Kepler University Linz, Austria. His research focus is on environmental and technoeconomic process evaluation in applied research and development projects.

Katharina Rechberger finished her studies in Industrial Environmental Protection at the Montanuniversität Leoben in 2010. After working as plant and process engineer in a cement producing company, she joined K1-MET GmbH, Austria in 2017. Her focus is on the investigation of technologies for CO_2 reduction in the steel industry as well as the utilisation of hydrogen as an alternative energy source in steelmaking processes.