ECONOMIC ASSESSMENT OF CO_2 UTILIZATION FOR WASTE BIOMASS CONVERSION INTO TRANSPORT FUELS

Frank RADOSITS, Amela AJANOVIC, Reinhard HAAS

Technische Universität Wien, Gusshausstraße 25/E370-3, 1040 Wien, +43 1 58801 - 370 367, radosits@eeg.tuwien.ac.at, http://eeg.tuwien.ac.at/

Abstract:

The utilization of waste biomass and lignocellulosic residues for conversion into energy carriers is proposed to contribute to the decarbonization of the transport sector. Advanced and waste-based biofuel production is estimated to lie in the ranges of 46-97 Mtoe (2030) and 71-176 Mtoe (2050). The core objective of this paper is an economic assessment of synthetic natural gas (SNG) and bio-methanol (bio-MeOH) production through biomass conversion and CO_2 utilization. Two different investment costs for each conversion technology and three feedstocks were compared. Production costs for SNG are between 7.9-10 €ct/ kWh and for bio-MeOH 7.1-13 €ct/ kWh. Feedstock costs have a larger share in bio-MeOH than in SNG production.

The major issue of advanced biofuels is still the economic competitiveness as prices for NG and fossil-based MeOH are lower. Further research is necessary because some economic assumptions were based on steam gasification and these parameters will change for the CO_2 gasification. A sensitivity analysis could be applied to determine the influence of technological learning on the investment cost of SNG and bio-MeOH production.

Keywords: CO_2 utilization, synthetic natural gas, Bio-methanol, transport sector

1 Introduction

The transport sector is a major contributor to greenhouse gas (GHG) emissions in Austria and the EU. Figure 1 shows GHG emissions in Austria from 1990-2019 in Mio. t CO2 eq. per sector. The emissions in the transport sector strongly increased by around 75%, in the EU by around 25%. Other sectors showed decreasing or stagnating trends since 1990.

The utilization of biowastes and lignocellulosic biomass for conversion into energy carriers is proposed to contribute to the decarbonization of the energy system and progress towards a circular economy [1]. These kinds of feedstocks gained more attention in recent years because the EU restricts the use of food crops for biofuel production to 7% of all renewable fuels [2]. Lignocellulosic biomass has a greater potential than energy crops towards a decrease of GHG emissions, because biomass cultivation, harvesting and transport have a substantial influence on environmental impact. The usage of local biomass is suggested to be the most environmentally friendly and economically feasible way of producing biofuels [3].

Energy crops are currently widely used for biofuel production in Europe. However, conversion of residues and waste streams should be promoted in the future, because of conflicts with agricultural land and material utilization [4]. Furthermore, it is also expected that fuels derived from waste streams will earlier reach economic competitiveness with fossil fuels than fuels from energy crops [5].

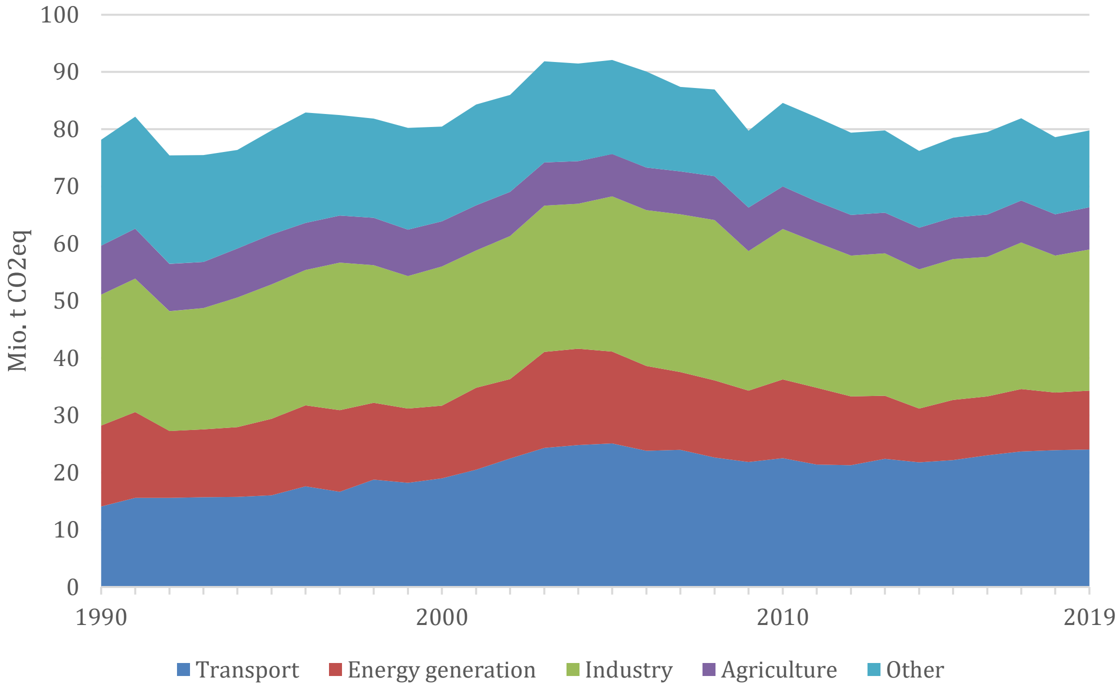

Figure 1. Sectoral emssions in Austria from 1990-2019, Other: Waste, Residential heating, F-gases (Data sources: Umweltbundesamt [6], [7]*)*

The core objective of this paper is an economic assessment of synthetic natural gas (SNG) and bio-methanol (bio-MeOH) production through biomass conversion and CO_2 utilization. Both fuels have the potential to contribute to the decarbonization of the transport sector. The usage of CO_2 as a renewable carbon source is an innovative approach in recent years. CO_2 can be utilized via conversion or non-conversion, e.g. as a solvent or for material processing. In carbon capture and utilization (CCU) as seen in Figure 2, CO_2 becomes converted into valuable products for example fuels, chemicals, etc.

Power-to-fuels technologies using renewable electricity are currently under intensive research. Other technologies for example photocatalytic CO_2 reduction have a lower technology readiness level (TRL). It is also possible to cultivate algae, which directly transform CO_2 into biomass, but there are still many challenges for implementation on a large scale existing [8]. The currently most studied process for combined biomass conversion with CO_2 utilization is gasification e.g., in the dual fluidized bed gasification (DFB) reactor with CO_2 as gasifying agent [9]. The DFB is a combination of two reactors. In the combustion reactor, which is fluidized with air, full oxidation of char and extra biomass, when required, takes place and provides heat to the gasification reactor. The gasification reactor can be separated into two parts: a lower part with heterogeneous reactions between solid and gas substances and an upper part with homogenous reforming reactions between gaseous compounds. The product gas composition is strongly influenced by the gasifying agent, temperature and elemental composition of the fuel. High C content showed higher CO yields, more oxygen in the feedstock lead to increased

CO_2 formation in experiments [10]. An important reaction in this process is the Boudouard-reaction:

$$CO_2 + C \leftrightarrow 2\,CO,\ \Delta H = +\ 172{,}5\ kJ/mol \quad (1)$$

The reaction of gaseous CO_2 with solid C from biomass is supposed to form carbon monoxide (CO), which is more favorable for certain fuel synthesis reactions.

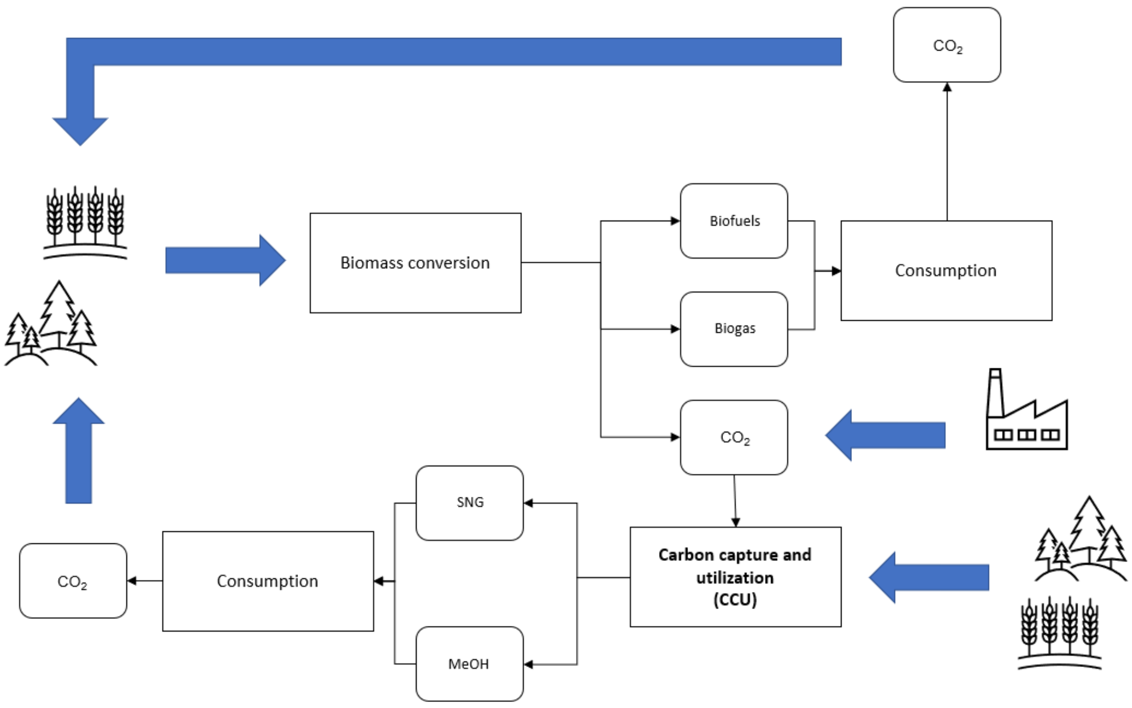

Figure 2. Scheme of biomass conversion and carbon capture and utilization (CCU) to produce CO_2-derived products

2 Material and methods

Our approach is based on: (i) an extensive literature research of state-of-the-art technologies for CO_2 utilization and biomass conversion; (ii) an assessment of feedstock potentials with a focus on Europe; (iii) an economic discussion regarding production cost of renewable fuels compared to fossil fuels.

There is a distinction between bio-waste and residues made in the literature. Bio-waste refers to garden waste, park waste, food and kitchen waste [11]. However, waste biomass is a broader term and asses agricultural wastes e.g. crop stalks, roots, leaves, etc. and processing waste of trees, e.g. bark, trimmings, sawdust [12]. Straw and forest thinnings are mostly called residues and energy wood is also not seen as biomass waste. However, since there is much data available for straw and forest residue prices, productions costs for these two feedstocks are also calculated. Following feedstocks are counted to waste biomass: rice husks, nutshells, roots, leaves, sawdust, bark, garden and park waste, food waste, trimmings at the sawmill, corn stover, etc.

Production costs for SNG and bio-methanol (MeOH) were calculated by using the Levelized-cost-of-energy approach, which is commonly used for the comparison of unit production cost of various energy carriers [13]. The operating period and interest rate are considered within the capital recovery factor.

Total fuel production costs in €ct/ kWh were calculated with following formulas:

$$CRF = \frac{(1+r)^n r}{(1+r)^n - 1} \tag{2}$$

$$C_{fuel} = I_C * \frac{CRF}{FLH} + p_{Biomass} * \frac{z}{LHV} + c_{var} \tag{3}$$

CRF=capital recovery factor, r=interest rate, n=project lifetime, $p_{Biomass}$= biomass price [€/ t FS], z = conversion factor [t FS/ t fuel], c_{var}=variable cost including: operating and maintenance (O&M), heat & electricity, labor [€/ MWh], FLH = full load hours, LHV = lower heating value [MWh/t], FS=Feedstock

Feedstock prices for wood and straw were taken from Statistik Austria 2020 [14] and “Holzmarktbericht 01/2022” [15] Corn stover prices are from [16] and values for conversion efficiencies and specific heat and electricity input from ALTETRÄ [17].

Production capacities of SNG and bio-MeOH plants were chosen to be around 200 MWth regarding the comparability of production cost. Cost data were derived from the GoBiGas project because there was the DFB technology used too. Thunman et al. [18] give a detailed list of cost parameters and scaling factors. The average investment costs for bio-methanol plants were taken from [19]. The lifetime of the project was assumed to be 20 years, interest rate 7.5% [20] and electricity price 120 €/MWh.

3 Results and discussion

The first part of the results is an overview of biomass waste and residues in the EU based on literature research. The second part presents a comparison of SNG and bio-MeOH production costs.

3.1 Feedstock potentials

Estimations of feedstock potentials show large variations in the literature. In the Biofrontiers 2016 report [21], 140 Mio. tonnes of waste and residues were assessed for the EU [11].

In a study of the Imperial College London [22] were feedstock potentials of residues and waste biomass in the former EU-28 were assessed. Thereof, the types of biomasses, which are seen as waste in a production process or usually are leftovers at the agricultural fields than as by-products, are presented in Figure 3. A large potential is seen for secondary forest residues, consisting of sawmill by-products and other forestry industry by-products, bark sawdust, etc. including post-consumer wood. Primary forest residues consist also of leaves/ needles, which should remain in the forest, because otherwise there can be a withdrawal of nutrients. This potential refers to all ways of utilization: products, chemicals and energy. Cereal straw is often investigated for different biomass conversion technologies e.g., bioethanol. Therefore, it is also added to the feedstock potentials in this paper, but utilization conflicts due to its importance for animal farming should be considered in supply chain management for biomass conversion plants.

The total estimated biomass for biofuel production refers to 126-262 Mtoe in 2030 and 101-252 Mtoe in 2050. Advanced and waste-based biofuel production is estimated to lie in the ranges of 46-97 Mtoe (2030) 71-176 Mtoe (2050).

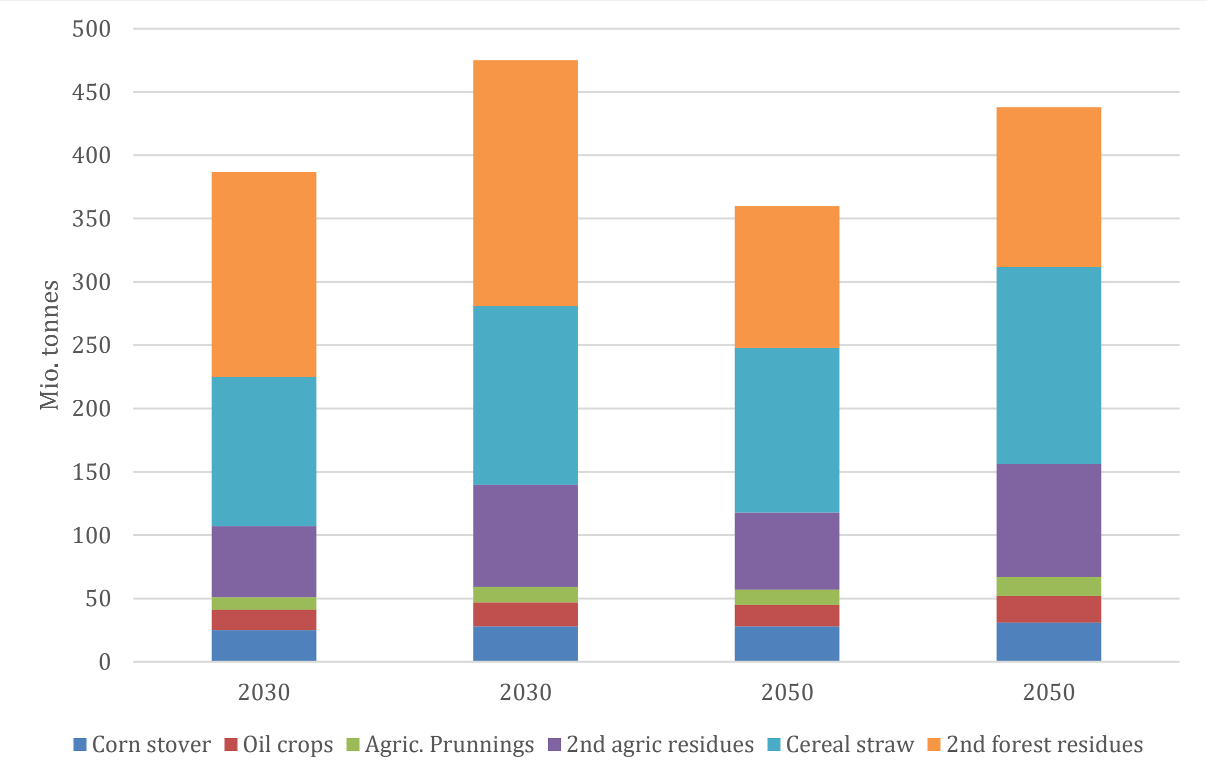

Figure 3. Feedstock potentials in the EU-28 with a focus on biomass waste and residues. (Data source: [22]*)*

The IEA assessed an overall global technical potential for biomethane production by anaerobic digestion and biomass gasification for the year 2018 in a bottom-up study, considering only feedstocks with no food or agricultural land competition. It is estimated at around 730 Mtoe (30.54 EJ) and corresponds to 20% of worldwide gas demand. Biomass gasification accounts for 160 Mtoe of the total biomethane potential Between this potential and the actual production of 35 Mtoe in 2018 shows a huge gap [23].

3.2 Economic assessment

Feedstock prices, conversion efficiencies and plant capacities among other factors have a strong influence on the overall production cost of SNG from biomass. The bars in Figure 4 indicate variations in the production cost related to different investment capacities for 100 MW_{th} and 200 MW_{th} SNG plants and low/high investment cost from the Innovation Outlook: Renewable Methanol report [19]. Production costs for SNG production for forest wood residues are approximately 8.3-9.4 €ct/ kWh and for straw 8.9-10.0 €ct/. Feedstock prices of straw account for 15.6%-17.5 % of total production cost, whereas in the case of forest wood residues for only 10.2-11.5 %. Waste biomass, for example, corn stover shows lower production costs of 7.9 €ct/ kWh for the 200 MW_{th} plant, because of lower feedstock prices, although the conversion efficiency is lower than for wood, meaning that more FS per ton output is necessary. The feedstock costs account for approximately 6.7 % of the total production cost. This is a surprising result, because the feedstock costs have usually a higher share in bioenergy. The highest share of production costs is related to capital cost. Natural gas (NG) prices, adapted to inflation and with taxes, for the first half of 2021 were approximately 4 €ct/ kWh for non-household consumers [24]. The NG prices increased significantly in the second half of 2021 and reached an average yearly value of approximately 7.7 €ct/ kWh [25]. However, it is unclear how these high NG prices will develop in the near future.

Bio-MeOH production costs are in a similar range for forest wood residues and corn stover, but wheat straw-derived methanol production costs are higher per kWh than for SNG. Corn stover-based bio-methanol production is approximately 2-4 times higher than fossil methanol. Fossil-based methanol has lower production costs of 1.5-3.8 €ct/ kWh. By using low-cost feedstocks and applying carbon credits, bio-methanol costs will decrease.

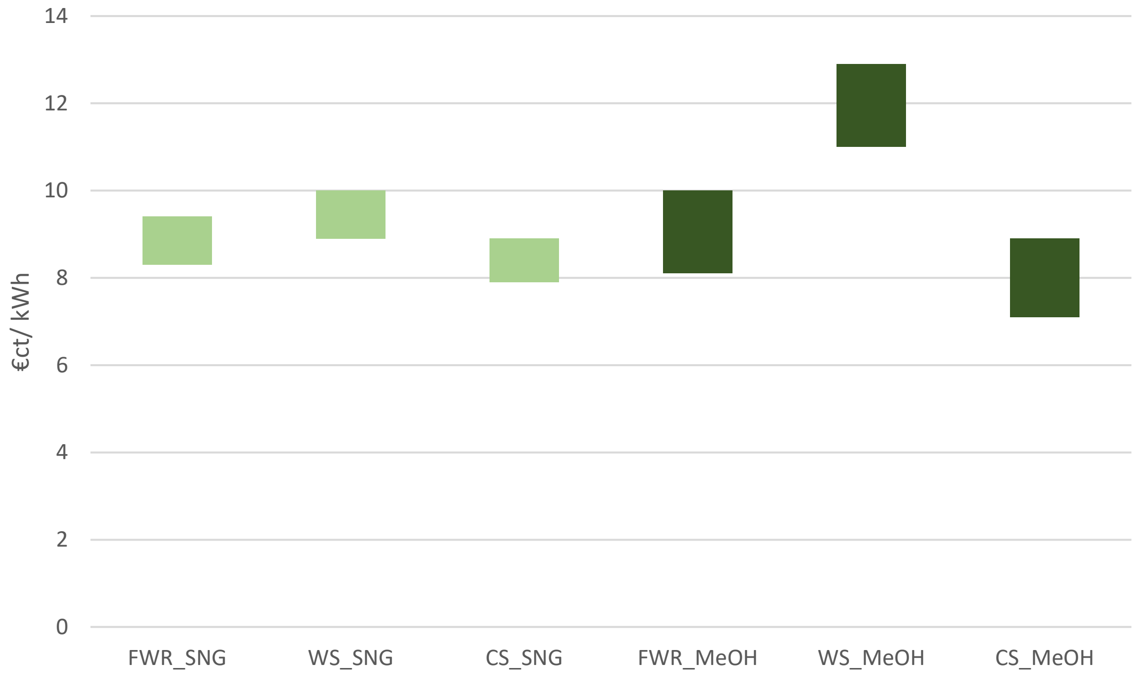

Figure 4. Production cost for SNG and MeOH for three different feedstocks. FWR=forest wood residues, WS=wheat straw, CS=corn stover, SNG=synthetic natural gas, MeOH=methanol

Feedstock prices can vary significantly in certain years as consequences of droughts, occurrence of damaged wood, etc. Climate change is a major challenge for forests, because of changes in precipitation and beetle infestation e.g., in some parts of AT like the “Waldviertel”. This is interesting because the feedstock prices have an influence on the production cost as seen in Figure 5. The feedstock prices for MeOH production with forest wood resides and corn stover account for 29.2 and 18.6% respectively. The share of the feedstock prices on the total SNG production cost is much lower.

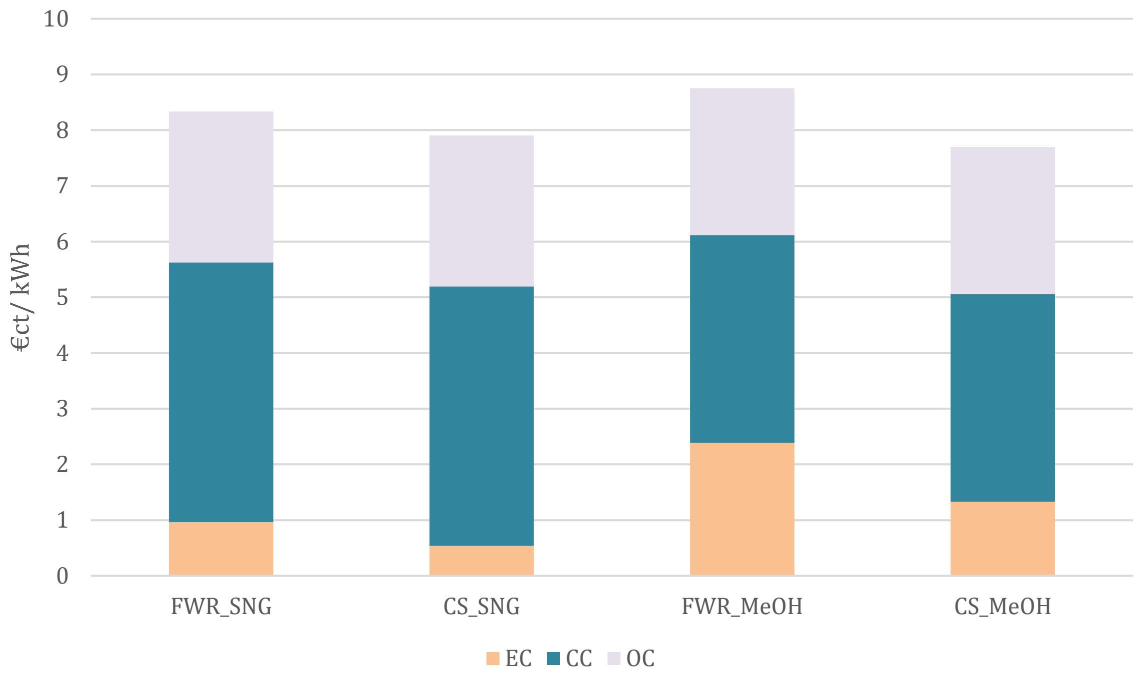

Figure 5. Differentiated production costs [€ct/ kWh] for SNG= synthetic natural gas and MeOH=methanol for FWR=forest wood residues and CS=corn stover

4 Conclusions

Large quantities of waste biomass and residues will be available in 2030 and 2050. These are potential feedstocks for conversion into energy carriers, which can contribute to the emission reduction goals set by the EU. Gas-powered cars play currently a minor role in the transport sector, but SNG shows lower unit production costs under some conditions than MeOH in this paper. SNG production in the context of CCU is therefore also an opportunity to contribute to the decarbonization of the transport sector. However, these technologies are not cost-competitive with fossil fuels at the moment and rely on policy mechanisms for example carbon credit and CO_2 tax for fossil fuels.

The assumptions for the economic calculation were based on the steam gasification at the GoBiGas plant. There was not enough data for CO2 gasification available, because it is a rather new approach for biomass conversion. However, as reported in the experiments of Mauerhofer et al., more heat is required and the syngas composition is actually not favorable for fuel synthesis. Therefore, the unit production cost would be eventually higher than stated in this paper.

No carbon credit was applied in this study as it was done, only the production costs were calculated and compared with two different investment costs. Other parameters were not modified in terms of a sensitivity analysis. This leaves room for further investigations on the key cost drivers for CO_2 gasification. For this paper, it was assumed that capital costs and operating costs are the same for different feedstock types, although there may be differences in the feedstock pre-treatment, gas treatment and related energy input. A sensitivity analysis could be applied to determine the influence of technological learning on the investment costs of SNG and bio-MeOH production.

5 Acknowledgements

This research was enabled by the doctoral college CO_2Refinery of the Vienna University of Technology (TU Wien).

6 References

[1] I. D'Adamo, P. M. Falcone, D. Huisingh, und P. Morone, „A circular economy model based on biomethane: What are the opportunities for the municipality of Rome and beyond?", *Renew. Energy*, Bd. 163, S. 1660–1672, Jan. 2021, doi: 10.1016/j.renene.2020.10.072.

[2] EU RED 2018, „DIRECTIVE (EU) 2018/2001 OF THE EUROPEAN PARLIAMENT AND OF THE COUNCIL of 11 December 2018 - on the promotion of the use of energy from renewable sources", 21. December 2018. https://eur-lex.europa.eu/legal-content/EN/TXT/HTML/?uri=CELEX:32018L2001&from=EN (zugegriffen 27. Juli 2021).

[3] H. Kargbo, J. S. Harris, and A. N. Phan, „"Drop-in" fuel production from biomass: Critical review on techno-economic feasibility and sustainability", *Renew. Sustain. Energy Rev.*, Bd. 135, S. 110168, Jan. 2021, doi: 10.1016/j.rser.2020.110168.

[4] M. Baumann *u. a.*, „Erneuerbares Gas in Österreich 2040", Wien, Juni 2021. Zugegriffen: 10. Juni 2021. [Online]. Verfügbar unter: https://www.bmk.gv.at/themen/energie/publikationen/erneuerbares-gas-2040.html

[5] A. Skorek-Osikowska, M. Martín-Gamboa, und J. Dufour, „Thermodynamic, economic and environmental assessment of renewable natural gas production systems", *Energy Convers. Manag. X*, Bd. 7, S. 100046, Sep. 2020, doi: 10.1016/j.ecmx.2020.100046.

[6] M. Anderl *u. a.*, *Emissionstrends 1990-2010 - Ein Überblick über die österreichischen Verursacher von Luftschadstoffen (Datenstand 2012)*. 2012.

[7] „Treibhausgas-Bilanz Österreichs 2019". https://www.umweltbundesamt.at/news210119 (zugegriffen 11. Februar 2022).

[8] M. Bagnoud-Velásquez, D. Refardt, F. Vuille, und C. Ludwig, „Opportunities for Switzerland to Contribute to the Production of Algal Biofuels: the Hydrothermal Pathway to Bio-Methane", *Chim. Int. J. Chem.*, Bd. 69, Nr. 10, S. 614–621, Okt. 2015, doi: 10.2533/chimia.2015.614.

[9] A. M. Mauerhofer *u. a.*, „Conversion of CO2 during the DFB biomass gasification process", *Biomass Convers. Biorefinery*, Bd. 11, Nr. 1, S. 15–27, Feb. 2021, doi: 10.1007/s13399-020-00822-x.

[10] A. M. Mauerhofer, S. Müller, F. Benedikt, J. Fuchs, A. Bartik, und H. Hofbauer, „CO2 gasification of biogenic fuels in a dual fluidized bed reactor system", *Biomass Convers. Biorefinery*, Sep. 2019, doi: 10.1007/s13399-019-00493-3.

[11] „Bio-waste – European Biomass Industry Association". https://www.eubia.org/cms/wiki-biomass/biowaste/ (zugegriffen 11. February 2022).

[12] N. Tripathi, C. D. Hills, R. S. Singh, and C. J. Atkinson, „Biomass waste utilization in low-carbon products: harnessing a major potential resource", *Npj Clim. Atmospheric Sci.*, Bd. 2, Nr. 1, Art. Nr. 1, Okt. 2019, doi: 10.1038/s41612-019-0093-5.

[13] D.-H. Lee, „Levelized cost of energy and financial evaluation for biobutanol, algal biodiesel and biohydrogen during commercial development", *Int. J. Hydrog. Energy*, Bd. 41, Nr. 46, S. 21583–21599, Dez. 2016, doi: 10.1016/j.ijhydene.2016.07.242.

[14] „Agrarpreise". https://www.statistik.at/web_de/statistiken/wirtschaft/preise/agrarpreise/index.html (zugegriffen 12. Februar 2022).

[15] „Jänner 2022: Holzmarktbericht der LK Österreich | Landwirtschaftskammer Österreich". https://www.lko.at/jänner-2022-holzmarktbericht-der-lk-österreich+2400+3563338 (zugegriffen 12. Februar 2022).

[16] I. Câmara-Salim, P. Conde, G. Feijoo, und M. T. Moreira, „The use of maize stover and sugar beet pulp as feedstocks in industrial fermentation plants – An economic and

environmental perspective“, *Clean. Environ. Syst.*, Bd. 2, S. 100005, Juni 2021, doi: 10.1016/j.cesys.2020.100005.

[17] A. Ajanovic, R. Haas, M. Beermann, G. Jungmaier, und C. Zeiss, „ALTETRÄ - Perspectives for Alternative Energy Carriers in Austria up to 2050 (Project Report)“, Wien, 815677, Feb. 2012. Zugegriffen: 28. November 2021. [Online]. Verfügbar unter: https://www.joanneum.at/life/publikationen/detail/altetrae-perspectives-for-alternative-energy-carriers-in-austria-up-to-2050-project-report

[18] H. Thunman, C. Gustavsson, A. Larsson, I. Gunnarsson, und F. Tengberg, „Economic assessment of advanced biofuel production via gasification using cost data from the GoBiGas plant“, *Energy Sci. Eng.*, Bd. 7, Jan. 2019, doi: 10.1002/ese3.271.

[19] IRENA and Methanol Institute, „Innovation Outlook: Renewable Methanol“, Abu Dhabi, 2021.

[20] L. Eisemann, *Transformationsprozess zum treibhausgasneutralen und ressourcenschonenden Deutschland - GreenEe*. Umweltbundesamt, 2020. Zugegriffen: 12. Februar 2022. [Online]. Verfügbar unter: https://www.umweltbundesamt.de/publikationen/transformationsprozess-treibhausgasneutrales-ressourcenschonendes-deutschland-greenee

[21] Directorate-General for Mobility and Transport (European Commission), I. Landälv, K. Maniatis, E. van den Heuvel, L. Waldheim, und S. Kalligeros, *Building up the future: sub group on advanced biofuels : final report*. LU: Publications Office of the European Union, 2017. Zugegriffen: 12. Februar 2022. [Online]. Verfügbar unter: https://data.europa.eu/doi/10.2832/494620

[22] Imperial College London, K. Maniatis, und C. Panoutsou, „Sustainable biomass availability in the EU, to 2050“, Aug. 2021. [Online]. Verfügbar unter: https://www.concawe.eu/publication/sustainable-biomass-availability-in-the-eu-to-2050/

[23] IEA, „Outlook for biogas and biomethane: Prospects for organic growth – Analysis“, *IEA*, 2020. https://www.iea.org/reports/outlook-for-biogas-and-biomethane-prospects-for-organic-growth (zugegriffen 1. November 2021).

[24] „Natural gas price statistics“. https://ec.europa.eu/eurostat/statistics-explained/index.php?title=Natural_gas_price_statistics (zugegriffen 12. Februar 2022).

[25] „EU Natural Gas - 2022 Data - 2010-2021 Historical - 2023 Forecast - Price - Quote“. https://tradingeconomics.com/commodity/eu-natural-gas (zugegriffen 12. Februar 2022).