

Supplementary Information for the article:

Assessment of biomass utilization pathways: a German case study

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This supporting information provides assumptions and data inventories for the life cycle assessment and techno-economic assessment.

Please note:

- Assumptions, equations and inventories are based on (Ruett et al., 2025).
- Alterations and additional assumptions for processes are explained in footnotes.
- For the environmental processes:
 - Ecoinvent version 3.10 (Wernet et al., 2016) was used.
 - The reference flow of each process is marked in bold.
 - When possible, ecoinvent provider processes were adjusted to German or European markets.
 - Reference ‘own process’ refers to processes that were created by the authors and have already been documented in this document.
- For all technological processes linear scale effects were assumed.

1 Calculations of the techno-economic assessment

1.1 Annuity

When data was given as levelized costs, we corrected to the present value based on (Chan & Tse, 2021).

Equation S-1: Annuity

$$PVA = x \cdot \left(\frac{1 - (1 + r)^{-t}}{r} \right)$$
$$x = \frac{PVA}{\left(\frac{1 - (1 + r)^{-t}}{r} \right)}$$

where

PVA: Present Value of Annuity
x: Annual Payment (undiscounted)
r: discount rate (e.g. 0.05 for 5%)
t: year of project lifetime, $t = 1, \dots, 20$

1.2 Levelized Profit

The calculation for the levelized profit was based on procedures by (Homagain et al., 2016; Langhorst et al., 2022) (see SI2).

Equation S-2: Levelized Profit

$$\text{Levelized Profit} = \frac{\sum_{t=1}^{20} [(C_t - R_t) \cdot (1 - \tau)] \cdot \frac{1}{(1 + r)^t}}{\sum_{t=1}^{20} B_t \cdot \frac{1}{(1 + r)^t}}$$

$$\forall t \in N = \{0, 1, 2, \dots, 20\}$$

where

C_t : total costs in year t
 R_t : total revenues in year t
 B_t : biomass input in year t (e.g. tonnes)
 r : discount rate (e.g. 0.05 for 5%)
 τ : tax rate on profits (e.g. 0.30 for 30%)
 t : year of project lifetime, $t = 1, \dots, 20$

Table S-1: Base data for the techno-economic assessment

Category	Position	Amount	Unit	Reference
General data				
Financial data	Discount rate r	5	%	(Cheng et al., 2021; Friedl et al., 2023)
	Tax	25	%	(Fawzy et al., 2022; Haeldermans et al., 2020)
	Costing period	20	years	(Arfan et al., 2023; Azzi et al., 2022; Fawzy et al., 2022; Oreggioni et al., 2017; Pyreg, personal communication, 2024)
	Producer Price Indices, applied when no data available for 2024	variable per year		(Destatis, 2025)
Technical data	Operation hours	8,000	hours year ⁻¹	(Azzi et al., 2022; Pyreg, personal communication, 2024; S. G. Subraveti, personal communication, 2025)
	Lifetime	20	years	acc. to technical plant specifications (Oreggioni et al., 2015; Pyreg, 2024) or adjusted accordingly.

2 Inventories for the life cycle and techno-economic assessment

2.1 Biomass-related processes (for all technologies)

Table S-2: Biomass production, straw

Biomass production, straw				per kg biomass
Input	Process	Amount	Unit	Reference
Inputs from	wheat grain production straw Cutoff, U OBU			(Wernet et al., 2016)
Output				
straw		1.00	kg	
Other outputs from	wheat grain production straw Cutoff, U OBU			(Wernet et al., 2016)

Table S-3: Storage, straw

Storage, straw				per MJ heat
Input	Process	Amount	Unit	Reference
building, hall	market for building, hall building, hall Cutoff, U - GLO	1	m2	(Wernet et al., 2016)
straw	wheat grain production straw Cutoff, U OBU - DE	1.058 ²	kg	(Wernet et al., 2016)
transport	market for transport, tractor and trailer, agricultural transport, tractor and trailer, agricultural Cutoff, U - RoW	0.002	t*km	Own assumption, (Wernet et al., 2016)
occupation	3	3	m2*a	(Wernet et al., 2016)
transformation	3	3	m2	(Wernet et al., 2016)
Output				
straw, stored		1.00	kg	

¹ For approximation of the biomass amount stored ecoinvent process 'building construction, hall, steel construction | building, hall, steel construction | Cutoff, U' was used.

² Accounting for 5.5% dry matter loss (Emery & Mosier, 2012; Tonini et al., 2012)

³ Amounts and processes taken from ecoinvent 3.10 process 'drying of maize straw and whole-plant | drying of maize straw and whole-plant | Cutoff, U'

Table S-4: Straw at market

Straw at market				per kg biomass
Input	Process	Amount	Unit	Reference
straw, stored	Storage, straw	1.02 ⁴	kg	(Wernet et al., 2016)
transport	Market for transport, freight, lorry 16-32 metric ton, EURO6 transport, freight, lorry 16-32 metric ton, EURO6 Cutoff, U - RER	0.05	t*km	(Pyreg, 2024; Ruett et al., 2024; Wernet et al., 2016)
Output				
Straw at market		1.00 ⁵	kg	

Table S-5: Data inventory for the techno-economic analysis.

Category	Position	Amount	Unit	Reference
Biomass	Straw	103 ⁶	€ t ⁻¹	(Greifenberg, Oliver, 2025)
	Ash treatment ⁷	99.65	€ t ⁻¹	(Eberhardinger et al., 2009)

2.2 Bioenergy (BE)

Table S-6: Combustion process, straw

Combustion process, straw				per MJ heat
Input	Process	Amount	Unit	Reference
Other inputs from	heat production, straw, at furnace 300kW heat, district or industrial, other than natural gas Cutoff, U – RER ⁸			(Wernet et al., 2016)
Straw at market	Straw at market	0.057	kg	Own process
Output				
Other outputs from	heat production, straw, at furnace 300kW heat, district or industrial, other than natural gas Cutoff, U - RER			(Wernet et al., 2016)
heat	avoids: market for heat, district or industrial, other than natural gas heat, district or industrial, other than natural gas Cutoff, U - Europe without Switzerland	1.00	MJ	(Wernet et al., 2016)

⁴ Accounting for 2% transport loss (Caixeta-Filho & Péra, 2018)

⁵ Biomass inputs and outputs for all technologies modelled on a dry mass basis

⁶ The average price over the quarters in 2024 was calculated. Since prices are market prices, we assumed that the biomass price includes delivery and pre-drying in the temporary storage facility.

⁷ For treating the ash residues it was conservatively assumed that the ash would be disposed of in a landfill and not possibly used as a more cost-effective option as a fertilizer (Eberhardinger et al., 2009).

⁸ The process ‘heat production, straw, at furnace 300kW’ has been adapted to German electricity mix. Biomass inputs/heat outputs calculated from furnace calorific efficiency (Fröling, 2024; Wernet et al., 2016) and biomass’ lower heating values. Ash outputs from combustion has been adjusted based on biomass’ ash content (Pyreg, 2024).

Table S-7: Data inventory for the techno-economic analysis for BE

Category	Position	Amount	Unit	Reference
Costs				
BE	Combustion plant ⁹	140,000	€ unit ⁻¹	(Fröling, personal communication, February 4, 2025)
	Combustion plant, operating costs	17,500	€ year ⁻¹	(Bolhår-Nordenkamp et al., 2003)
	Electricity	0.17	€ kWh ⁻¹	(BDEW, 2024)
Revenues				
	District heat	0.05	€ kWh ⁻¹	(Green Innovations, 2024)
	Electricity	0.15	€ kWh ⁻¹	(Bundesnetzagentur, 2024a)
Technical data				
Technical data	Operation hours	8,000	hours year ⁻¹	(Azzi et al., 2022; Pyreg, personal communication, 2024; S. G. Subraveti, personal communication, 2025)
	Lifetime	20	years	acc. to technical plant specifications (Oreggioni et al., 2015; Pyreg, 2024) or adjusted accordingly.

2.3 Biochar Carbon Removal (BCR)

Table S-8: Straw pelletizing

Straw pelletizing				per kg biomass
Input	Process	Amount	Unit	Reference
Other inputs from straw	wood pellet production wood pellet, measured as dry mass Cutoff, U - RER			(Wernet et al., 2016)
	straw at market	1.00	kg	Own process
Output				
straw, pelletized		1.00	kg	
Other outputs from	wood pellet production wood pellet, measured as dry mass Cutoff, U - RER			(Wernet et al., 2016)

⁹ For the combustion process, a CHP plant with an energy output of 320 kW (Fröling, 2024) applied in the ecoinvent 3.10 process ‘heat production, straw, at furnace 300kW, Cutoff, U - RER’ (Wernet et al., 2016) was used. Only thermal energy is produced. We assume operational expenses of 12.5% of the plant costs (Bolhår-Nordenkamp et al., 2003).

Table S-9: Biochar production, straw (based on (Ruett et al., 2024))

Biochar production, straw				per t biochar
Input	Process	Amount	Unit	Reference
electricity	market for electricity, low voltage electricity, low voltage Cutoff, U – DE	10	kWh	(Pyreg, 2024; Wernet et al., 2016)
liquefied petroleum gas	liquefied petroleum gas [market for liquefied petroleum gas liquefied petroleum gas Cutoff, U - Europe without Switzerland	10	kg	(Pyreg, 2024; Wernet et al., 2016)
straw, pelletized	Straw, pelletized	4366.31	kg	Own process (Pyreg, personal communication, 2024; Wernet et al., 2016)
pyrolysis furnace	PX1500 plant production – DE ¹¹	10	Item	(Pyreg, 2024; Wernet et al., 2016)
water	Water, cooling, unspecified natural origin, RER	10	l	(Pyreg, 2024; Wernet et al., 2016)
big bag	big bag 1t, polypropylene, production – RER ¹²	5.00	kg	(Colomb et al., 2015; Marzeddu et al., 2021)
Output				
biochar, packed		1,000.00	kg	
heat	heat, district or industrial, other than natural gas [market for heat, district or industrial, other than natural gas heat, district or industrial, other than natural gas Cutoff, U - Europe without Switzerland]	10	kWh	(Pyreg, 2024)
ash	market for wood ash wood ash [mixture, pure wood ash mixture, pure Cutoff, U - Europe without Switzerland] ¹³	174.65	kg	(Wernet et al., 2016)
arsenic	elementary flow – to air	0.0035	kg	(Azzi et al., 2022; Wernet et al., 2016)
cadmium	elementary flow – to air	5.4E-4	kg	(Azzi et al., 2022; Wernet et al., 2016)
carbon dioxide, fossil	elementary flow – to air	0.00804	kg	(Azzi et al., 2022; Wernet et al., 2016)
carbon dioxide, non-fossil	elementary flow – to air	4400.0	kg	(Azzi et al., 2022; Wernet et al., 2016)
carbon monoxide, fossil	elementary flow – to air	0.0311	kg	(Azzi et al., 2022; Wernet et al., 2016)
carbon monoxide, non-fossil	elementary flow – to air	8.4	kg	(Azzi et al., 2022; Wernet et al., 2016)
chromium	elementary flow – to air	0.0096	kg	(Azzi et al., 2022; Wernet et al., 2016)
copper	elementary flow – to air	0.002	kg	(Azzi et al., 2022; Wernet et al., 2016)
lead	elementary flow – to air	0.00108	kg	(Azzi et al., 2022; Wernet et al., 2016)
mercury	elementary flow – to air	1.4E-4	kg	(Azzi et al., 2022; Wernet et al., 2016)
molybdenum	elementary flow – to air	5.7E-4	kg	(Azzi et al., 2022; Wernet et al., 2016)
nickel	elementary flow – to air	0.0018	kg	(Azzi et al., 2022; Wernet et al., 2016)

¹⁰ Calculated based on (Pyreg, 2024), including lower heating values of biomass and thermal efficiency/output of the pyrolysis plant. Data may be made available upon request.

¹¹ the process ‘pyrolysis plant production’ was linearly interpolated from the ecoinvent 3.10 process *furnace wood chips, with silo* between the process options 1000 and 5000 kW according to (Azzi et al., 2022); specific properties were adjusted according to (Pyreg, personal communication, 2024), in particular in percentage terms to the material mix of structural steel, stainless steel, polyethylene and rock wool and the total plant weight of 60t as well as corresponding waste processes and treatments. Includes transport of the plant over 300km from the construction to the production site by *transport, freight, lorry >32 metric ton, EURO6* in Germany (Wernet et al., 2016).

¹² Original process: *Big bag 1t, polypropylene, production – FR. Packing 1000 kg biochar requires 5 kg big bag material* (Marzeddu et al., 2021)

¹³ Proxy for straw, adjusted to amount of ash contained in straw (4%) on a dry mass basis (Pyreg, 2024).

nitrogen oxides, DE	elementary flow – to air	0.5	kg	(Azzi et al., 2022; Wernet et al., 2016)
NMVOC, non-methane volatile organic compounds	elementary flow – to air	0.25	kg	(Azzi et al., 2022; Wernet et al., 2016)
PAH, polycyclic aromatic hydrocarbons	elementary flow – to air	4.5E-5	kg	(Azzi et al., 2022; Wernet et al., 2016)
Particulates, > 10 um	elementary flow – to air	1.75	kg	(Azzi et al., 2022; Wernet et al., 2016)
tin	elementary flow – to air	3.0	kg	(Azzi et al., 2022; Wernet et al., 2016)
water	elementary flow – to air	499.06	l	(Azzi et al., 2022; Wernet et al., 2016)
water	elementary flow – to water	788.19	l	(Azzi et al., 2022; Wernet et al., 2016)

Table S-10: Biochar application to soil, straw

Biochar application to soil, straw				per t biochar
Input	Process	Amount	Unit	Reference
biochar, packed	Biochar production, straw	1.00	t	Own process
solid manure loading and spreading	Hydraulic loader and spreader [solid manure loading and spreading, by hydraulic loader and spreader solid manure loading and spreading, by hydraulic loader and spreader Cutoff, U – CH]	1000.0	kg	(Marzeddu et al., 2021; Wernet et al., 2016)
tillage	Rotary cultivator [tillage, rotary cultivator tillage, rotary cultivator Cutoff, U - RoW]	2000.0	m2	(Marzeddu et al., 2021; Wernet et al., 2016)
transport	Transport, freight, lorry 16-32 metric ton, EURO6 transport, freight, lorry 16-32 metric ton, EURO6 Cutoff, U - RER	20.0	t*km	(Ruett et al., 2024; Wernet et al., 2016)
Output				
biochar, to soil		1.00	t	
waste polyethylene ¹⁴	Market for waste polyethylene waste polyethylene Cutoff, U - DE	5.00	kg	(Wernet et al., 2016)
carbon dioxide	Elementary flow, to soil or biomass stock	2161.45 ¹⁵	kg	(Wernet et al., 2016)

¹⁴ Waste from biochar big bag

¹⁵ Carbon in biochar was assumed 75% permeable on average (Azzi et al., 2024). Carbon content in biochar was 78.5% for straw (Pyreg, 2024).

Table S-11: Data inventory for the techno-economic analysis for BCR

Category	Position	Amount	Unit	Reference
Costs				
BCR	Pyrolysis plant	2,000,000 ¹⁶	€ unit ⁻¹	(Pyreg, personal communication, 2024)
	Pelletizing machine ¹⁷	290,000	€ unit ⁻¹	(Ecokraft, personal communication, 2024)
	Plant maintenance	2.5 ¹⁶	% of plant price	(Pyreg, personal communication, 2024)
	Plant insurance	0.5 ¹⁶	% of plant price	(Pyreg, personal communication, 2024)
	Property rent	6.43	€ m ² - ¹	(Statista & German Property Partners, 2024)
	Labor rate	40.54	€ h ⁻¹	(Destatis, 2024)
	Electricity	0.17	€ kWh ⁻¹	(BDEW, 2024)
	Gas	0.06	€ kWh ⁻¹	(Bundesnetzagentur, 2024b)
	Water	4.68	€ m ³ - ¹	(VEA, 2024)
	LPG gas	1.05	€ l ⁻¹	(myLPG, 2024)
	Big bag	10.87	€ unit ⁻¹	(MyPellets, 2024)
	Transport biochar to application side (20km)	7.99	€ t biochar ⁻¹	(Sahoo et al., 2021), scaled to 20 km according to (Ruett et al., 2024)
	Soil application, loading	6.75 ¹⁸	€ t biochar ⁻¹	(KTBL, 2025)
	Tillage, rotary cultivator	1.206 ¹⁸	€ t biochar ⁻¹	(KTBL, 2025)
Revenues				
Process output	Biochar	500	€ t ⁻¹	(BZL, 2023; Campion et al., 2023)
	District heat	0.05	€ kWh ⁻¹	(Green Innovations, 2024)
	CRC biochar	155.21	€ tCO ₂ - ¹	(Höglund & Niparko, 2024)
Technical data				
	Operation hours	8,000	hours year ⁻¹	(Azzi et al., 2022; Pyreg, personal communication, 2024; S. G. Subraveti, personal communication, 2025)
	Lifetime	20	years	acc. to technical plant specifications (Oreggioni et al., 2015; Pyreg, 2024) or adjusted accordingly.

¹⁶ We used data of a pyrolysis plant of the established German manufacturer PYREG (Pyreg, personal communication, 2024, 2024) with a capacity of 1500kW. Data as well as heat outputs for straw may be made available via request.

¹⁷ It was taken into account that biomass is pelletized after delivery, incurring additional costs. A pelletizing plant (Ecokraft, 2024) corresponding to the biomass input of the pyrolysis plant that processes straw was identified (pelletizing rate of up to 255 kg biomass/h (Ecokraft, personal communication, 2024)).

¹⁸ The costs for biochar application to soil were calculated using (KTBL, 2025) cost data on solid manure loading and tillage by rotary cultivator.

2.4 Bioenergy with Carbon Capture and Storage (BECCS)

Table S-12: Gasification process, straw

Gasification process, straw ¹⁹				per 1.565 kg of CO ₂
Input	Process	Amount	Unit	Reference
heat and power co-generation unit	heat and power co-generation unit, 160kW electrical, common components for heat+electricity Cutoff, U – RER ²⁰	1.21	item	(Wernet et al., 2016)
heat and power co-generation unit	heat and power co-generation unit, 160kW electrical, components for electricity only Cutoff, U - RER	1.21	item	(Oreggioni et al., 2017; Wernet et al., 2016)
heat and power co-generation unit	heat and power co-generation unit, 160kW electrical, components for heat only Cutoff, U – RER ²¹	1.21	item	(Wernet et al., 2016)
straw	Biomass production, straw	0.92 ²²	kg	Own process
water	market for water, completely softened water, completely softened Cutoff, U - RER	27.1	kg	(Oreggioni et al., 2017; Wernet et al., 2016)
Output				
CO ₂ , output		1.57 ²³	kg	
electricity	avoids: market for electricity, low voltage electricity, low voltage Cutoff, U - DE	0.78 ²⁴	kWh	(Oreggioni et al., 2017; Wernet et al., 2016)
heat	avoids: market for heat, district or industrial, other than natural gas heat, district or industrial, other than natural gas Cutoff, U - Europe without Switzerland	2.02 ²⁵	kWh	(Oreggioni et al., 2017; Wernet et al., 2016)
ash	market for wood ash mixture, pure wood ash mixture, pure Cutoff, U - Europe without Switzerland	0.04 ¹³	kg	(Oreggioni et al., 2017; Wernet et al., 2016)

¹⁹ Process created according to (Oreggioni et al., 2017), including adjustments as indicated in footnotes. Two-zone 10 MW input/ 2.8 MWe output fast internally circulating fluidized bed gasification combined heat and power plant with pre-combustion adsorptive unit.

²⁰ Added to consider the entire combined heat and power plant

²¹ Added to consider the entire combined heat and power plant

²² Biomass input calculated based on lower heating value of biomass and gasification process data (Oreggioni et al., 2017).

²³ Adjusted according to carbon content in straw (46.2%) dry mass (Pyreg, 2024).

²⁴ Calculated electricity produced based on lower heating value of biomass and gasification process data (Oreggioni et al., 2017). Subsequently, calculated excess electricity to feed into the market by subtracting electricity requirements for gasification, carbon capture and compression processes from electricity produced (Burger et al., 2024; Oreggioni et al., 2015). No electricity inputs in gasification, pre-combustion and compression processes due to electricity surplus. Thus, 2.29 MW of the plant's 2.74 MW potential electrical energy is fed into the grid (Oreggioni et al., 2015).

²⁵ Calculated heat produced based on lower heating value of biomass and gasification process data (Oreggioni et al., 2017). Subsequently, calculated excess heat to feed into the market by subtracting heat requirements for gasification, carbon capture and compression processes from electricity produced (Burger et al., 2024; Oreggioni et al., 2015). No heat inputs in gasification, pre-combustion and compression processes due to heat surplus.

Table S-13: Pre-combustion carbon capture, straw

Pre-combustion carbon capture ²⁶			per 1,880 kg of CO ₂ captured	
Input	Process	Amount	Unit	Reference
CO ₂ output	Gasification process, straw	3,860.00	kg	Own process
metal working	metal working, average for steel product manufacturing metal working, average for steel product manufacturing Cutoff, U - RER	0.005	kg	(Oreggioni et al., 2017; Wernet et al., 2016)
water	market for water, completely softened water, completely softened Cutoff, U - RER	862.92	kg	(Oreggioni et al., 2017; Wernet et al., 2016)
zeolite	market for zeolite, powder zeolite, powder Cutoff, U - GLO	0.75	kg	(Oreggioni et al., 2017; Wernet et al., 2016)
nitrogen	elementary flow – in air	10,100.00	kg	(Oreggioni et al., 2017; Wernet et al., 2016)
nitrogen	elementary flow – in air	4,560.00	kg	(Oreggioni et al., 2017; Wernet et al., 2016)
oxygen	elementary flow – in air	1,380.00	kg	(Oreggioni et al., 2017; Wernet et al., 2016)
oxygen	elementary flow – in air	3,040.00	kg	(Oreggioni et al., 2017; Wernet et al., 2016)
occupation	elementary flow – industrial area	17.58	m ² *a	(Burger et al., 2024; Wernet et al., 2016)
transformation	elementary flow – to industrial area	0.88	m ²	(Burger et al., 2024; Wernet et al., 2016)
water	elementary flow - cooling	455.00	l	(Oreggioni et al., 2017; Wernet et al., 2016)
Output ²⁷				
CO ₂ , captured		1,880.00 ²⁸	kg	
waste zeolite	treatment of waste zeolite, inert material landfill waste zeolite Cutoff, U - RoW	0.75	kg	(Oreggioni et al., 2017; Wernet et al., 2016)
ammonia	elementary flow – to air	0.07	kg	(Oreggioni et al., 2017; Wernet et al., 2016)
benzene	elementary flow – to air	33.76	kg	(Oreggioni et al., 2017; Wernet et al., 2016)
carbon dioxide, non-fossil	elementary flow – to air	1,980.00	kg	(Oreggioni et al., 2017; Wernet et al., 2016)
carbon monoxide, non-fossil	elementary flow – to air	2.38	kg	(Oreggioni et al., 2017; Wernet et al., 2016)

²⁶ Process from (Oreggioni et al., 2017) (Two-zone 10 MW input/ 2.8 MWe output fast internally circulating fluidized bed gasification combined heat and power plant with pre-combustion adsorptive unit), added estimation for occupation and transformation from (Burger et al., 2024) for the entire BECCS plant. No energy inputs as sourced from gasification process (see ^{18,19}).

²⁷ All elementary flow outputs were scaled according to the different amounts of syngas produced during gasification in relation to wood chips (biomass used in (Oreggioni et al., 2017)). (Erlach et al., 2012; Qin et al., 2012) find similar exhaust gases for gasification of wood chips and lignocellulosic biomasses.

²⁸ Capture rate for pre-combustion pressure swing adsorption: 49% (Oreggioni et al., 2017).

carbon monoxide, non-fossil	elementary flow – to air	0.08	kg	(Oreggioni et al., 2017; Wernet et al., 2016)
chlorine	elementary flow – to air	0.03	kg	(Oreggioni et al., 2017; Wernet et al., 2016)
hydrochloric acid	elementary flow – to air	0.002	kg	(Oreggioni et al., 2017; Wernet et al., 2016)
hydrogen	elementary flow – to air	4.16	kg	(Oreggioni et al., 2017; Wernet et al., 2016)
hydrogen	elementary flow – to air	0.02	kg	(Oreggioni et al., 2017; Wernet et al., 2016)
hydrogen sulfide	elementary flow – to air	0.02	kg	(Oreggioni et al., 2017; Wernet et al., 2016)
hydrogen sulfide	elementary flow – to air	0.71	kg	(Oreggioni et al., 2017; Wernet et al., 2016)
naphthalene	elementary flow – to air	9.41	kg	(Oreggioni et al., 2017; Wernet et al., 2016)
nitrogen	elementary flow – to air	2.11	kg	(Oreggioni et al., 2017; Wernet et al., 2016)
nitrogen oxides	elementary flow – to air	1.63	kg	(Oreggioni et al., 2017; Wernet et al., 2016)
oxygen	elementary flow – to air	2,597.04	kg	(Oreggioni et al., 2017; Wernet et al., 2016)
PAH, polycyclic aromatic hydrocarbons	elementary flow – to air	0.22	kg	(Oreggioni et al., 2017; Wernet et al., 2016)
Particulate Matter, > 2.5 um and < 10um	elementary flow – to air	0.03	kg	(Oreggioni et al., 2017; Wernet et al., 2016)
Particulate Matter, > 2.5 um and < 10um	elementary flow – to air	0.08	kg	(Oreggioni et al., 2017; Wernet et al., 2016)
sulfur oxides	elementary flow – to air	0.96	kg	(Oreggioni et al., 2017; Wernet et al., 2016)
water	elementary flow – to air	3,621.42	l	(Oreggioni et al., 2017; Wernet et al., 2016)
water	elementary flow – to water	393.00	l	(Oreggioni et al., 2017; Wernet et al., 2016)

Table S-14: CO₂ compression, straw

CO ₂ compression, straw ²⁹		per 1,000 kg of CO ₂ liquefied		
Input	Process	Amount	Unit	Reference
CO ₂ , captured	Pre-combustion carbon capture, straw	1,000.00	kg	Own process
metal working	metal working, average for chromium steel product manufacturing metal working, average for chromium steel product manufacturing Cutoff, U - RER	0.976	kg	(Burger et al., 2024; Wernet et al., 2016)
water	water, cooling DE	774.20	MJ	(Burger et al., 2024; Wernet et al., 2016)
air compressor	air compressor production, screw-type compressor, 300kW air compressor, screw-type compressor, 300kW Cutoff, U - RER	1.17E-6	Item	(Burger et al., 2024; Wernet et al., 2016)
ammonia	market for ammonia, anhydrous, liquid ammonia, anhydrous, liquid Cutoff, U - RER	0.0001	kg	(Burger et al., 2024; Wernet et al., 2016)
concrete block	market for concrete block concrete block Cutoff, U - DE	0.056	kg	(Burger et al., 2024; Wernet et al., 2016)
concrete block	market for concrete block concrete block Cutoff, U - DE	0.012	kg	(Burger et al., 2024; Wernet et al., 2016)
refrigeration machine	refrigeration machine production, ammonia, liquid as refrigerant refrigeration machine, carbon dioxide, liquid as refrigerant Cutoff, U ³⁰	3.11E-5	Item	(Burger et al., 2024; Wernet et al., 2016)
steel	steel production, electric, chromium steel 18/8 steel, chromium steel 18/8 Cutoff, U - RER	0.976	kg	(Burger et al., 2024; Wernet et al., 2016)
steel	market for steel, chromium steel 18/8 steel, chromium steel 18/8 Cutoff, U - GLO	0.01	kg	(Burger et al., 2024; Wernet et al., 2016)
water pump operation	water pump operation, electric water pump operation, electric Cutoff, U - DE	0.72	MJ	(Burger et al., 2024; Wernet et al., 2016)
zeolite	market for zeolite, powder zeolite, powder Cutoff, U - GLO	0.00017	kg	(Burger et al., 2024; Wernet et al., 2016)
water	elementary flow - cooling	455.00	l	(Burger et al., 2024; Wernet et al., 2016)
water	elementary flow - in water	1.00	m3	(Burger et al., 2024; Wernet et al., 2016)
Output				
CO ₂ , liquefied		1,000.00	kg	
waste zeolite	treatment of waste zeolite, inert material landfill waste zeolite Cutoff, U - RoW	0.00017	kg	(Burger et al., 2024; Wernet et al., 2016)
hazardous waste	treatment of hazardous waste, hazardous waste incineration hazardous waste, for incineration Cutoff, U - Europe without Switzerland	0.00014	kg	(Burger et al., 2024; Wernet et al., 2016)
scrap steel	market for scrap steel scrap steel Cutoff, U - Europe without Switzerland	0.976	kg	(Burger et al., 2024; Wernet et al., 2016)

²⁹ Process from (Burger et al., 2024)³⁰ In the original ecoinvent 3.10 process refrigeration machine production, carbon dioxide, liquid as refrigerant (Ecoinvent, 2023), carbon dioxide was replaced by ammonia (NH₃) in accordance with (Burger et al., 2024).

scrap steel	market for scrap steel scrap steel Cutoff, U - Europe without Switzerland	0.01	kg	(Burger et al., 2024; Wernet et al., 2016)
waste concrete	market for waste concrete waste concrete Cutoff, U - Europe without Switzerland	0.012	kg	(Burger et al., 2024; Wernet et al., 2016)
waste concrete	treatment of waste concrete, inert material landfill waste concrete Cutoff, U - Europe without Switzerland	0.056	kg	(Burger et al., 2024; Wernet et al., 2016)
wastewater	treatment of wastewater, average, wastewater treatment wastewater, average Cutoff, U - Europe without Switzerland ³¹	0.008	m3	(Burger et al., 2024; Wernet et al., 2016)
ammonia	elementary flow – to air	0.0001	kg	(Burger et al., 2024; Wernet et al., 2016)
occupation	elementary flow – industrial	0.0031	m2*a	(Burger et al., 2024; Wernet et al., 2016)
transformation	elementary flow – to industrial area	0.00016	m2	(Burger et al., 2024; Wernet et al., 2016)
carbon dioxide, non-fossil	elementary flow – to air	6.67	kg	(Burger et al., 2024; Wernet et al., 2016)

Table S-15: CO₂ transport via truck and ship, straw

CO ₂ transport ³²		per 1,000 kg of CO ₂		
Input	Process	Amount	Unit	Reference
CO ₂ , liquefied	CO ₂ compression, straw	1,000.00	kg	Own process
metal working	market for metal working, average for chromium steel product manufacturing metal working, average for chromium steel product manufacturing Cutoff, U - GLO	1.38	kg	(Burger et al., 2024; Wernet et al., 2016)
steel	market for steel, chromium steel 18/8 steel, chromium steel 18/8 Cutoff, U - GLO	1.38	kg	(Burger et al., 2024; Wernet et al., 2016)
transport	transport, freight, lorry with refrigeration machine, 7.5-16 ton, EURO6, carbon dioxide, liquid refrigerant, cooling transport, freight, lorry with refrigeration machine, 7.5-16 ton, EURO6, carbon dioxide, liquid refrigerant, cooling Cutoff, U - GLO	51.0 ³³	t*km	(Burger et al., 2024; Wernet et al., 2016)
transport	transport, freight, lorry with refrigeration machine, 7.5-16 ton, EURO6, carbon dioxide, liquid refrigerant, cooling transport, freight, lorry with refrigeration machine, 7.5-16 ton, EURO6, carbon dioxide, liquid refrigerant, cooling Cutoff, U - GLO	236.00 ^{33,34}	t*km	(Burger et al., 2024; Wernet et al., 2016)
transport	transport, freight, sea, tanker for liquefied natural gas transport, freight, sea, tanker for liquefied natural gas Cutoff, U - GLO	803.5 ³³	t*km	(Burger et al., 2024; Wernet et al., 2016)
Output				
CO ₂ , transported		1,000.00	kg	

³¹ The process 'treatment of wastewater, average, wastewater treatment | wastewater, average | Cutoff, U - Europe without Switzerland' (Wernet et al., 2016) was adjusted to the German electricity grid.

³² Process from (Burger et al., 2024).

³³ Adjusted to one-way transport distances

³⁴ In the scenario for the geological storage in Germany, only 236 km land transport were considered.

Table S-16: CO₂ storage, geological injection, straw

CO ₂ storage, geological injection, straw				per 1,000 kg of CO ₂
Input	Process	Amount	Unit	Reference
CO ₂ storage, injection well	offshore well production, CO ₂ offshore well, CO ₂ Cutoff, U - GLO	0.00014	m	(Burger et al., 2024; Wernet et al., 2016)
electricity	market for electricity, medium voltage electricity, medium voltage Cutoff, U - NO ³⁵	33.83	kWh	(Burger et al., 2024; Wernet et al., 2016)
CO ₂ , transported	CO ₂ transport, straw	1,000.00	kg	Own process
CO ₂ storage, subsea facility	defined in supporting information of Burger et al. (2024)	5.33E-8	Item	(Burger et al., 2024; Wernet et al., 2016)
CO ₂ storage, pipeline	defined in supporting information of Burger et al. (2024)	2.68E-6	Item	(Burger et al., 2024; Wernet et al., 2016)
CO ₂ storage, onshore facilities	defined in supporting information of Burger et al. (2024)	2.67E-8	Item	(Burger et al., 2024; Wernet et al., 2016)
Output				
Straw at market		1,173.84	kg	
CO ₂ , geological stored		1,000.00	kg	
Other outputs	defined in supporting information of Burger et al. (2024)			(Burger et al., 2024; Wernet et al., 2016)

³⁵ In the scenario for the geological storage in Germany, electricity mix was changed to the German market mix.

Table S-17: Data inventory for the techno-economic analysis for BECCS

Category	Position	Amount	Unit	Reference
Costs				
BECCS	Gasification plant ³⁶	13,403,159	€ unit ⁻¹	(Bolh�r-Nordenkampf et al., 2003)
	Gasification plant, operational cost ³⁷	1,340,316	€ year ⁻¹	(Bolh�r-Nordenkampf et al., 2003)
	CO ₂ capture CAPEX ³⁸	26.91	€ t _{CO₂} ⁻¹	(Subraveti et al., 2022)
	CO ₂ capture OPEX ³⁷	8.24	€ t _{CO₂} ⁻¹	(Subraveti et al., 2022)
	CO ₂ conditioning ³⁷	8.12	€ t _{CO₂} ⁻¹	(Subraveti et al., 2022)
	CO ₂ transport, land	0.1	€*(t _{CO₂} *km) ⁻¹	(Becattini et al., 2024)
	CO ₂ transport, ship	0.03	€*(t _{CO₂} *km) ⁻¹	(d'Amore & Bezzo, 2017)
	CO ₂ injection into geological storage	0.67	€ t _{CO₂} ⁻¹	(d'Amore & Bezzo, 2017)
Revenues				
Process output	District heat	0.05	€ kWh ⁻¹	(Green Innovations, 2024)
	Electricity	0.15	€ kWh ⁻¹	(Bundesnetzagentur, 2024a)
	CRC BECCS	209.72	€ tCO ₂ ⁻¹	(H�glund & Niparko, 2024)
Technical data				
Technical data	Operation hours	8,000	hours year ⁻¹	(Azzi et al., 2022; Pyreg, personal communication, 2024; S. G. Subraveti, personal communication, 2025)
	Lifetime	20	years	acc. to technical plant specifications (Oreggioni et al., 2015; Pyreg, 2024) or adjusted accordingly.

³⁶ We used cost data of 10MW gasification plant (Bolh r-Nordenkampf et al., 2003; Oreggioni et al., 2015) that has been used in the study of (Oreggioni et al., 2015). The gasification plant generates a net electrical output (already deducting the consumption of the machine and carbon capture process) of 2.29 MW and net district heat of 4.86 MW (Oreggioni et al., 2015). These technological specifications were used lateron in the study we used for the environmental life cycle inventory (Oreggioni et al., 2017).

³⁷ We assume operational expenses of 12.5% of the plant costs (Bolh r-Nordenkampf et al., 2003).

³⁸ The costs data according to (Subraveti et al., 2021, 2022) were used for the carbon capture and the CO₂-conditioning processes and scaled to match the plant of (Oreggioni et al., 2017). When possible, we applied available data from (Oreggioni et al., 2017), e.g. adsorbent amount, cooling water) within cost calculation. The process runs on a four-stage vacuum swing adsorption unit with a capacity of 2004 texhaust gas/h. Zeolite 13X is used as the absorbent. In addition, the machine operates 8000 h/year with a lifetime of 25 years (Subraveti et al., 2022). To enable a comparative assessment, costs were adjusted based on their discount rate and the lifetime of the operation (see 1.1 for annuity formula).

2.5 Scenario analyses

Table S-18: For the ‘renewable energy offsets’ scenario: Approximation of electricity production, low voltage, German energy mix 2045 approximated as projected by (Prognos et al., 2021). Applied to offset produced electricity in scenario “renewable energy”

Electricity production, low voltage, German energy mix 2045				per kWh of electricity
Input	Process	Amount	Unit	Reference
distribution network	market for distribution network, electricity, low voltage distribution network, electricity, low voltage Cutoff, U - GLO	8.74E-8	km	(Wernet et al., 2016)
electricity	heat and power co-generation, biogas, gas engine electricity, high voltage Cutoff, U - DE	0.01	kWh	(Wernet et al., 2016)
electricity	electricity production, hydro, reservoir, non-alpine region electricity, high voltage Cutoff, U - DE	0.02	kWh	(Wernet et al., 2016)
electricity	electricity production, wind, 1-3MW turbine, onshore electricity, high voltage Cutoff, U - DE	0.31	kWh	(Wernet et al., 2016)
electricity	electricity production, wind, 1-3MW turbine, offshore electricity, high voltage Cutoff, U - DE	0.25	kWh	(Wernet et al., 2016)
electricity	electricity production, hydrogen based on natural gas, conventional power plant electricity, high voltage Cutoff, U ³⁹	0.06	kWh	Own process based on (Wernet et al., 2016)
electricity	electricity production, natural gas, conventional power plant electricity, high voltage Cutoff, U - DE	0.002	kWh	(Wernet et al., 2016)
electricity	electricity production, photovoltaic, 3kWp slanted-roof installation, multi-Si, panel, mounted electricity, low voltage Cutoff, U - DE	0.36	kWh	(Wernet et al., 2016)
electricity	electricity voltage transformation from medium to low voltage electricity, low voltage Cutoff, U, only in-frastructure for conversion - DE	0.84	kWh	(Wernet et al., 2016)
electricity	market for electricity, medium voltage, renewable energy products electricity, medium voltage, renewable energy products Cutoff, U - CH	0.03	kWh	(Wernet et al., 2016)
sulfur hexafluoride	market for sulfur hexafluoride, liquid sulfur hexafluoride, liquid Cutoff, U - RER	6.27E-9	kg	(Wernet et al., 2016)
Output				
electricity, German energy mix 2045		1.00	kWh	
sulfur hexafluoride	elementary flow - emission to air	6.27E-9	kg	(Wernet et al., 2016)

Table S-19: For the ‘renewable energy offsets’ scenario: Approximation of heat production, German energy mix 2045 approximated as projected by (Prognos et al., 2021). Applied to offset produced (district) heat in scenario “renewable energy”

Heat production, German energy mix 2045				per kWh of heat
Input	Process	Amount	Unit	Reference
electricity	electricity production, low voltage, German energy mix 2045	0.067	kWh	own process
heat	heat production, at heat pump 30kW, allocation exergy heat, central or small-scale, other than natural gas Cutoff, U - Europe without Switzerland	0.024	kWh	(Wernet et al., 2016)

³⁹ Hydrogen (production process and hydrogen plant were modelled according to (Delpierre et al., 2021)) replaced natural gas inecoinvent 3.10 process ‘electricity production, hydrogen based on natural gas, conventional power plant | electricity, high voltage | Cutoff, U’ (Wernet et al., 2016).

heat	operation, solar collector system, evacuated tube collector, one-family house, for combined system heat, central or small-scale, other than natural gas Cutoff, U - RoW	0.079	kWh	(Wernet et al., 2016)
heat	heat, from municipal waste incineration to generic market for heat district or industrial, other than natural gas heat, district or industrial, other than natural gas Cutoff, U - CH	0.043	kWh	(Wernet et al., 2016)
heat	industrial waste heat ⁴⁰	0.073	kWh	
heat	heat production, untreated waste wood, at furnace 1000-5000 kW heat, district or industrial, other than natural gas Cutoff, U - RoW	0.067	kWh	(Wernet et al., 2016)
heat	heat production, hydrogen replaces natural gas, at industrial furnace >100kW heat, district or industrial, natural gas Cutoff, U - Europe without Switzerland	0.28	kWh	(Wernet et al., 2016)
heat	heat production based on electricity production, deep geothermal electricity, high voltage Cutoff, U - DE	0.03	kWh	(Wernet et al., 2016)
Output				
heat, German energy mix 2045		1.00	kWh	

Table S-20: For the 'lower and higher CRC prices' scenario: lower and upper value for CRC prices.

Category	Position	Amount	Unit	Reference
Process output	CRC BCR, lower value	104.40	€ tCO ₂ ⁻¹	(Höglund & Niparko, 2024)
	CRC BCR, upper value	286.05	€ tCO ₂ ⁻¹	(Höglund & Niparko, 2024)
	CRC BECCS, lower value	197.71	€ tCO ₂ ⁻¹	(Höglund & Niparko, 2024)
	CRC BECCS, upper value	323.37	€ tCO ₂ ⁻¹	(Höglund & Niparko, 2024)

⁴⁰ Describes a by-product from industrial processes which comes without a burden.

References

- Arfan, M., Eriksson, O., Wang, Z., & Soam, S. (2023). Life cycle assessment and life cycle costing of hydrogen production from biowaste and biomass in Sweden. *Energy Conversion and Management*, 291, 117262. <https://doi.org/10.1016/j.enconman.2023.117262>
- Azzi, E. S., Karlton, E., & Sundberg, C. (2022). Life cycle assessment of urban uses of biochar and case study in Uppsala, Sweden. *Biochar*, 4(1), 18. <https://doi.org/10.1007/s42773-022-00144-3>
- Azzi, E. S., Li, H., Cederlund, H., Karlton, E., & Sundberg, C. (2024). Modelling biochar long-term carbon storage in soil with harmonized analysis of decomposition data. *Geoderma*, 441, 116761. <https://doi.org/10.1016/j.geoderma.2023.116761>
- BDEW. (2024). *BDEW-Strompreisanalyse Februar 2024*. <https://www.bdew.de/impressum/>
- Becattini, V., Riboldi, L., Burger, J., Nöhl, J., Oeuvray, P., Reyes-Lúa, A., Anantharaman, R., Bardow, A., Frattini, L., Fu, C., Mazzotti, M., Roussanaly, S., & Zotică, C. (2024). Rolling-out pioneering carbon dioxide capture and transport chains from inland European industrial facilities: A techno-economic, environmental, and regulatory evaluation. *Renewable and Sustainable Energy Reviews*, 205, 114803. <https://doi.org/10.1016/j.rser.2024.114803>
- Bolh r-Nordenkampf, M., Rauch, R., Bosch, K., Aichernig, C., & Hofbauer, H. (2003). Biomass CHP Plant G ssing – Using Gasification for Power Generation. *Proceeding of the 2nd Regional Conference on Energy Technology Towards a Clean Environment*. 2nd Regional Conference on Energy Technology Towards a Clean Environment, 12-14 February 2003, Phuket, Thailand.
- Bundesnetzagentur. (2024a). *Einspeiseverg tungen Strom aus Biomasse 2024*. Ergebnisse Der Ausschreibungsrunden F r Biomasseanlagen 2024. <https://www.bundesnetzagentur.de/DE/Fachthemen/ElektrizitaetundGas/Ausschreibungen/Biomasse/BeendeteAusschreibungen/start.html>
- Bundesnetzagentur. (2024b). *Monitoringbericht 2024*. <https://data.bundesnetzagentur.de/Bundesnetzagentur/SharedDocs/Mediathek/Monitoringberichte/MonitoringberichtEnergie2024.pdf>
- Burger, J., N hl, J., Seiler, J., Gabrielli, P., Oeuvray, P., Becattini, V., Reyes-L a, A., Riboldi, L., Sansavini, G., & Bardow, A. (2024). Environmental impacts of carbon capture, transport, and storage supply chains: Status and the way forward. *International Journal of Greenhouse Gas Control*, 132, 104039. <https://doi.org/10.1016/j.ijggc.2023.104039>
- BZL. (2023). *Pflanzenkohle: Das Klima sch tzen und B den verbessern*. <https://www.praxis-agrar.de/pflanze/ackerbau/pflanzenkohle>
- Caixeta-Filho, J. V., & P ra, T. G. (2018). Post-harvest losses during the transportation of grains from farms to aggregation points. *International Journal of Logistics Economics and Globalisation*, 7(3), 209–247. <https://doi.org/10.1504/IJLEG.2018.093755>
- Campion, L., Bekchanova, M., Malina, R., & Kuppens, T. (2023). The costs and benefits of biochar production and use: A systematic review. *Journal of Cleaner Production*, 408, 137138. <https://doi.org/10.1016/j.jclepro.2023.137138>
- Chan, W.-S., & Tse, Y.-K. (2021). Annuities. In *Financial Mathematics for Actuaries* (3rd ed., pp. 39–72). WORLD SCIENTIFIC. https://doi.org/10.1142/9789811243288_0002

- Cheng, F., Small, A. A., & Colosi, L. M. (2021). The levelized cost of negative CO₂ emissions from thermochemical conversion of biomass coupled with carbon capture and storage. *Energy Conversion and Management*, 237, 114115. <https://doi.org/10.1016/j.enconman.2021.114115>
- Colomb, V., Amar, S. A., Mens, C. B., Gac, A., Gaillard, G., Koch, P., Mousset, J., Salou, T., Tailleur, A., & Werf, H. M. G. van der. (2015). AGRIBALYSE®, the French LCI Database for agricultural products: High quality data for producers and environmental labeling. *OCL*, 22(1), Article 1. <https://doi.org/10.1051/ocl/20140047>
- d'Amore, F., & Bezzo, F. (2017). Economic optimisation of European supply chains for CO₂ capture, transport and sequestration. *International Journal of Greenhouse Gas Control*, 65, 99–116. <https://doi.org/10.1016/j.ijggc.2017.08.015>
- Delpierre, M., Quist, J., Mertens, J., Prieur-Vernat, A., & Cucurachi, S. (2021). Assessing the environmental impacts of wind-based hydrogen production in the Netherlands using ex-ante LCA and scenarios analysis. *Journal of Cleaner Production*, 299, 126866. <https://doi.org/10.1016/j.jclepro.2021.126866>
- Destatis. (2024). *Arbeitskosten in Deutschland im EU-Vergleich im Jahr 2022*. https://www.destatis.de/DE/Presse/Pressemitteilungen/2023/04/PD23_164_624.html
- Destatis. (2025). *Producer Price Index Deutschland*. Erzeugerpreisindex Gewerblicher Produkte: Deutschland, Jahre. <https://www-genesis.destatis.de/datenbank/online/statistic/61241/table/61241-0001>
- Eberhardinger, A., Schardt, M., Zormaier, F., & Zimmer, B. (2009). *Prozessanalyse und Ökobilanzierung der Bereitstellung von Waldhackgut zur thermischen Verwertung*.
- Ecoinvent. (2023). *Ecoinvent 3.10* (LCI Database No. Ecoinvent; Version 3.10). <https://ecoinvent.org/ecoinvent-v3-10/>
- Ecokraft. (2024). *Ecokraft Pelletieranlage LP22*.
- Ecokraft. (2024). *Personal communication with Ecokraft: Email conversation with Christian Wagner (Sales Director, Ecokraft) on 11.03.2024* [Personal communication].
- Emery, I. R., & Mosier, N. S. (2012). The impact of dry matter loss during herbaceous biomass storage on net greenhouse gas emissions from biofuels production. *Biomass and Bioenergy*, 39, 237–246. <https://doi.org/10.1016/j.biombioe.2012.01.004>
- Erlach, B., Harder, B., & Tsatsaronis, G. (2012). Combined hydrothermal carbonization and gasification of biomass with carbon capture. *Energy*, 45(1), 329–338. <https://doi.org/10.1016/j.energy.2012.01.057>
- Fawzy, S., Osman, A. I., Mehta, N., Moran, D., Al-Muhtaseb, A. H., & Rooney, D. W. (2022). Atmospheric carbon removal via industrial biochar systems: A techno-economic-environmental study. *Journal of Cleaner Production*, 371, 133660. <https://doi.org/10.1016/j.jclepro.2022.133660>
- Friedl, G., Reichelstein, S., Bach, A., Blaschke, M., & Kemmer, L. (2023). Applications of the levelized cost concept. *Journal of Business Economics*, 93(6–7), 1125–1148. <https://doi.org/10.1007/s11573-023-01171-7>
- Fröling. (2024). *Technisches Datenblatt Turbomat TM 320-550*.
- Fröling. (2025, February 4). *Anfrage Daten Formling Turbomat 320kW* [Personal communication].

- Green Innovations. (2024). *Klimapositiv—Mit Pyrolyse Wärmenetze dekarbonisieren, CO2 binden & Landwirtschaft stärken (Webseminar 27.02.2024)*. <https://green-innovations-gmbh.de>
- Greifenberg, Oliver. (2025). *Strohpreis Deutschland 2024*. Preiseverlauf Für Stroh Im Bundesdurchschnitt. <https://www.strohpreis.de>
- Haeldermans, T., Campion, L., Kuppens, T., Vanreppelen, K., Cuypers, A., & Schreurs, S. (2020). A comparative techno-economic assessment of biochar production from different residue streams using conventional and microwave pyrolysis. *Bioresource Technology*, 318, 124083. <https://doi.org/10.1016/j.biortech.2020.124083>
- Höglund, R., & Niparko, K. (2024). *Carbon Removal Certificate Prices by Method 2024*. CDR.Fyi 2024 Year in Review. <https://www.cdr.fyi/blog/2024-year-in-review>
- Homagain, K., Shahi, C., Luckai, N., & Sharma, M. (2016). Life cycle cost and economic assessment of biochar-based bioenergy production and biochar land application in Northwestern Ontario, Canada. *Forest Ecosystems*, 3(1), 21. <https://doi.org/10.1186/s40663-016-0081-8>
- KTBL. (2025). *KTBL-Feldarbeitsrechner*. KTBL-Feldarbeitsrechner. <https://daten.ktbl.de/feldarbeit/entry.html>
- Langhorst, T., McCord, S., Zimmermann, A., Müller, L., Cremonese, L., Strunge, T., Wang, Y., Zaragoza, A. V., Wunderlich, J., Marxen, A., Armstrong, K., Buchner, G., Kätelhön, A., Bachmann, M., Sternberg, A., Michailos, S., Naims, H., Winter, B., Roskosch, D., ... Sick, V. (2022). *Techno-Economic Assessment & Life Cycle Assessment Guidelines for CO2 Utilization (Version 2.0)*. <https://doi.org/10.7302/4190>
- Marzeddu, S., Cappelli, A., Ambrosio, A., Décima, M. A., Viotti, P., & Boni, M. R. (2021). A Life Cycle Assessment of an Energy-Biochar Chain Involving a Gasification Plant in Italy. *Land*, 10(11), Article 11. <https://doi.org/10.3390/land10111256>
- myLPG. (2024). *LPG Prices Germany 2024*. Chart of Fuel Prices in Germany. <https://www.mylpg.eu/stations/germany/prices/>
- MyPellets. (2024). *BigBag Preise 2024*. Big Bag Wiederverwendbar 90X90X140 1500 Kg. <https://www.mypalletsonline.com/de/big-bag-bauabfaelle-und-kies/372-big-bag-wiederverwendbar-sf-6-1-90x90x140-1500kg.html>
- Oreggioni, G. D., Brandani, S., Luberti, M., Baykan, Y., Friedrich, D., & Ahn, H. (2015). CO2 capture from syngas by an adsorption process at a biomass gasification CHP plant: Its comparison with amine-based CO2 capture. *International Journal of Greenhouse Gas Control*, 35, 71–81. <https://doi.org/10.1016/j.ijggc.2015.01.008>
- Oreggioni, G. D., Singh, B., Cherubini, F., Guest, G., Lausset, C., Luberti, M., Ahn, H., & Strømman, A. H. (2017). Environmental assessment of biomass gasification combined heat and power plants with absorptive and adsorptive carbon capture units in Norway. *International Journal of Greenhouse Gas Control*, 57, 162–172. <https://doi.org/10.1016/j.ijggc.2016.11.025>
- Prognos, Öko-Institut, & Wuppertal-Institut. (2021). *Klimaneutrales Deutschland 2045—Wie Deutschland seine Klimaziele schon vor 2050 erreichen kann*. https://www.agora-verkehrswende.de/fileadmin/Projekte/2021/KNDE_2045_Langfassung/Klimaneutrales_Deutschland_2045_Langfassung.pdf
- Pyreg. (2024). *Performance Tables PX1500*.

- Pyreg. (2024). *Personal communication with Pyreg: Meeting with Philipp Reichardt (Sales Manager, Pyreg) on 04.01.2024* [Personal communication].
- Qin, K., Lin, W., Jensen, P. A., & Jensen, A. D. (2012). High-temperature entrained flow gasification of biomass. *Fuel*, 93, 589–600. <https://doi.org/10.1016/j.fuel.2011.10.063>
- Ruett, J., Abdelshafy, A., & Walther, G. (2024). Using miscanthus and biochar as sustainable substrates in horticulture: An economic and carbon footprint assessment of their primary and cascading value chains. *Sustainable Production and Consumption*. <https://doi.org/10.1016/j.spc.2024.06.016>
- Ruett, J., Abdelshafy, A., & Walther, G. (2025). *Evaluation of biomass utilization pathways – a methodological framework*. Research Square. <https://doi.org/10.21203/rs.3.rs-7831805/v2>
- Sahoo, K., Upadhyay, A., Runge, T., Bergman, R., Puettmann, M., & Bilek, E. (2021). Life-cycle assessment and techno-economic analysis of biochar produced from forest residues using portable systems. *The International Journal of Life Cycle Assessment*, 26(1), 189–213. <https://doi.org/10.1007/s11367-020-01830-9>
- Statista, & German Property Partners. (2024). *Mietpreis für neu errichtete Industrie- und Logistikflächen*. <https://de.statista.com/statistik/suche/?q=Mietpreis+für+Industrie-+und+Logistikfläche&Suche=&p=1>
- Subraveti, S. G. (2025). *Personal communication with Sai Gokul Subraveti, CCS expert, regarding technical specifications of carbon capture facilities on 13.01.2024* [Personal communication].
- Subraveti, S. G., Roussanaly, S., Anantharaman, R., Riboldi, L., & Rajendran, A. (2021). Techno-economic assessment of optimised vacuum swing adsorption for post-combustion CO₂ capture from steam-methane reformer flue gas. *Separation and Purification Technology*, 256, 117832. <https://doi.org/10.1016/j.seppur.2020.117832>
- Subraveti, S. G., Roussanaly, S., Anantharaman, R., Riboldi, L., & Rajendran, A. (2022). How much can novel solid sorbents reduce the cost of post-combustion CO₂ capture? A techno-economic investigation on the cost limits of pressure–vacuum swing adsorption. *Applied Energy*, 306, 117955. <https://doi.org/10.1016/j.apenergy.2021.117955>
- Tonini, D., Hamelin, L., Wenzel, H., & Astrup, T. (2012). Bioenergy Production from Perennial Energy Crops: A Consequential LCA of 12 Bioenergy Scenarios including Land Use Changes. *Environmental Science & Technology*, 46(24), 13521–13530. <https://doi.org/10.1021/es3024435>
- VEA. (2024). *VEA-Wasserpreisvergleich 2024*. https://www.vea.de/files/user_upload/VEA-Hauptseite/Newsroom/Pressemitteilungen/2024/Februar/240305_Tabellen_zum_Wasserpreisvergleich.pdf
- Wernet, G., Bauer, C., Steubing, B., Reinhard, J., Moreno-Ruiz, E., & Weidema, B. (2016). The ecoinvent database version 3 (part I): Overview and methodology (ecoinvent v3.10 cut-off unit processes). *The International Journal of Life Cycle Assessment*, 21(9), 1218–1230. <https://doi.org/10.1007/s11367-016-1087-8>