Supplementary material to the paper

Evaluation of biomass utilization pathways – a methodological framework

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Modeling notes and conventions:

- Any assumptions applied to processes are documented in footnotes.
- Environmental inventories rely on ecoinvent version 3.10 (Wernet et al., 2016).
- For each unit process, the reference flow is highlighted in bold.
- When feasible, provider datasets from ecoinvent were regionalized to German or European markets.
- Entries labeled “own process” indicate processes created by the authors and documented herein.
- Linear scale effects are assumed for all technological unit

1 Techno-economic assessment: calculations

Levelized Profit

Levelized profit is computed following (Homagain et al., 2016; Langhorst et al., 2022).

Equation 1: Levelized Profit

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

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

where

C_{t} : total costs in year *t*
R_{t} : total revenues in year *t*
B_{t} : biomass input in year *t*
r : discount rate (e.g. 0.05 for 5%)
τ : profit tax rate (e.g. 0.30 for 30%)
t : year (*t* = 1,...,20)

Table 1: Global parameters and assumptions for the techno-economic model

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	a	(Arfan et al., 2023; Azzi et al., 2022; Fawzy et al., 2022; Oreggioni et al., 2017; Pyreg, 2024a)
	Producer Price Indices, applied when 2024 data missing	variable per year		(Destatis, 2025)
Technical data	Operation hours	8,000	$h*a^{-1}$	(Azzi et al., 2022; Pyreg, 2024a; Subraveti, 2025)
	Lifetime	20	a	acc. to technical plant specifications (Oreggioni et al., 2015; Pyreg, 2024b) or adjusted accordingly.

2 Life cycle inventories and techno-economic inputs

2.1 Biomass supply chain (applied to both technologies)

Table 2: Miscanthus biomass production

Biomass production, miscanthus				per kg biomass
Input	**Process**	**Amount**	**Unit**	**Reference**
Inputs from	Miscanthus production, as in (Schulte et al., 2021)			(Schulte et al., 2021; Wagner et al., 2017, 2019)
Output				
miscanthus, chopped		**1.00**	**kg**	
Other outputs from	Miscanthus production, as in (Schulte et al., 2021)			(Schulte et al., 2021; Wagner et al., 2017, 2019)

Table 3: Miscanthus storage

Storage, miscanthus				per MJ heat
Input	**Process**	**Amount**	**Unit**	**Reference**
building, hall	market for building, hall | building, hall | Cutoff, U - GLO	[1]	m^2	(Wernet et al., 2016)
miscanthus	Biomass production miscanthus	1.058[2]	kg	(Schulte et al., 2021; Wagner et al., 2019, 2017)
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]	m^2*a	(Wernet et al., 2016)
transformation	[3]	[3]	m^2	(Wernet et al., 2016)
Output				
miscanthus, stored		**1.00**	**kg**	

[1] To estimate onsite storage capacity for biomass, we used the ecoinvent 3.10 proxy 'building construction, hall, steel construction | building, hall, steel construction | Cutoff, U'.
[2] We include a 5.5% loss of dry matter (Emery and Mosier, 2012; Tonini et al., 2012)
[3] Drying-related inputs and factors are proxied by the ecoinvent 3.10 process 'drying of maize straw and whole-plant | drying of maize straw and whole-plant | Cutoff, U'

Table 4: Miscanthus at market

Miscanthus at market				per kg of biomass
Input	**Process**	**Amount**	**Unit**	**Reference**
miscanthus, stored	storage, miscanthus	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, 2024c; Ruett et al., 2024; Wernet et al., 2016)
Output				
Miscanthus at market		**1.00**[5]	**kg**	

Table 5: Techno-economic inputs for miscanthus production and handling

Category	Position	Amount	Unit	Reference
COSTS				
Biomass	Miscanthus	147	$€*t^{-1}$	(Sieverdingbeck, 2023)
	Ash treatment[6]	99.65	$€*t^{-1}$	(Eberhardinger et al., 2009)

2.2 Bioenergy (BE): miscanthus combustion

Table 6: Miscanthus combustion

Combustion process, miscanthus				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[7]			(Wernet et al., 2016)
Miscanthus at market	Miscanthus at market	0.056	kg	Own process
Output				
Other outputs from	heat production, straw, at furnace 300kW | heat, district or industrial, other than natural gas | Cutoff, U - RER[6]			(Wernet et al., 2016)
heat	**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] A 2% loss during transportation is considered (Caixeta-Filho and Péra, 2018).
[5] All biomass balances across technologies are expressed on a dry-mass basis.
[6] Ash management is modeled conservatively as disposal in landfill (Eberhardinger et al., 2009).
[7] The 'heat production, straw, at furnace 300kW' dataset is used as a proxy for miscanthus. Herein, electricity mix is adapted and biomass mass balances are derived from calorific efficiency (Fröling, 2024; Wernet et al., 2016); key parameters such as ash content are aligned with the modeled biomass (Pyreg, 2024c).

Table 7: Techno-economic inputs for BE

Category	Position	Amount	Unit	Reference
COSTS				
BE	Combustion plant[8]	140,000	€*unit^{-1}	(Fröling, 2025)
	Combustion plant, operating costs	17,500	€*year^{-1}	(Bolhàr-Nordenkampf et al., 2003)
Revenues				
	District heat	0.05	€*kWh^{-1}	(Green Innovations, 2024)
	Electricity	0.15	€*kWh^{-1}	(Bundesnetzagentur, 2024a)

2.3 Biochar Carbon Removal (BCR): miscanthus pyrolysis

Table 8: Miscanthus pelletizing

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

[8] Combustion assumes a CHP configuration with an energy output split analogous to the proxy dataset from ecoinvent 3.10 (‘heat production, straw, at furnace 300kW, Cutoff, U - RER’) (Wernet et al., 2016). Annual operating costs are taken as 12.5% of plant CAPEX (Bolhàr-Nordenkampf et al., 2003).

Table 9: Miscanthus biochar production based on (Ruett et al., 2024)

Biochar production, miscanthus				per t biochar
Input	**Process**	**Amount**	**Unit**	**Reference**
Electricity	Electricity, low voltage [market for electricity, low voltage | electricity, low voltage | Cutoff, U – DE]	[9]	kWh	(Pyreg, 2024c; 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, 2024c; Wernet et al., 2016)
Miscanthus, pelletized	Miscanthus pelletizing	4159.80	kg	Own process
Pyrolysis furnace	PX1500 plant production - DE[10]	[10]	Item	(Pyreg, 2024a; Wernet et al., 2016)
Water	Water, cooling, unspecified natural origin, RER	[10]	l	(Pyreg, 2024c; Wernet et al., 2016)
big bag	big bag 1t, polypropylene, production - RER[11]	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, 2024c)
Ash	market for wood ash wood ash [mixture, pure | wood ash mixture, pure | Cutoff, U - Europe without Switzerland][12]	158.07	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	8.40	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)

[9] Energy outputs (heat/electricity) are derived from (Pyreg, 2024c), using the lower heating value of the feedstock and measured energy recovery from the PX1500; detailed data available on request.
[10] The ‘pyrolysis plant production’ dataset is scaled linearly to the appropriate plant size and expanded to include transport of the plant using a >32 t EURO6 lorry within Germany for 300km (Wernet et al., 2016). The dataset bases on the ecoinvent 3.10 process “furnace wood chips, with silo”, scaling is based on (Azzi et al., 2022) and the furnace’s material mix was adjusted along (Pyreg, 2024a).
[11] For packaging, we start from the “Big bag 1t, polypropylene, production – FR. Packing 1000 kg biochar requires 5 kg big bag material” dataset and assume 5 kg of big-bag material per tonne of biochar handled (Marzeddu et al., 2021).
[12] A straw ash dataset is used as a proxy and corrected to match ash content differences between miscanthus (3.8%) and straw (4%) on a dry-mass basis (Pyreg, 2024c).

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)
Nitrogen oxides, DE	Elementary flow – to air	0.50	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 10: Miscanthus biochar soil application

Biochar application to soil, miscanthus				per t of biochar
Input	**Process**	**Amount**	**Unit**	**Reference**
biochar, packed	Biochar production, miscanthus	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	m^2	(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[11]	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	2303.84[13]	kg	(Wernet et al., 2016)

Table 11: Techno-economic inputs for BCR

Category	Position	Amount	Unit	Reference
COSTS				
BCR	Pyrolysis plant	2,000,000[14]	€*unit^{-1}	(Pyreg, 2024a)
	Pelletizing machine[15]	290,000	€*unit^{-1}	(Ecokraft, 2024)
	Plant maintenance	2.5[16]	% of plant price	(Pyreg, 2024a)
	Plant insurance	0.5[16]	% of plant price	(Pyreg, 2024a)
	Property rent	6.43	€*m$^{2\ -1}$	(Statista and 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	€*Mg biochar^{-1}	(Sahoo et al., 2021), scaled to 20 km according to (Ruett et al., 2024)
	Soil application, loading	6.75[16]	€*Mg biochar^{-1}	(KTBL, 2025)
	Tillage, rotary cultivator	1.206[18]	€*Mg 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 and Niparko, 2024)

[13] The share of carbon considered stabilized in biochar is set at 75% on average (Azzi et al., 2024); measured carbon content of the resulting char is 83.7% (Pyreg, 2024b).
[14] Plant performance and yield data are based on a PX1500 pyrolysis line; detailed input-output data can be provided upon request (Pyreg, 2024a, 2024c).
[15] The model assumes pelletization after drying; the referenced pelletizer has a nominal throughput up to 255 kg biomass per hour (Ecokraft, 2024).
[16] Field application costs are compiled using the KTBL calculator, combining data for solid-manure loading/spreading and rotary cultivation operations (KTBL, 2025).

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