Supporting Information

Supporting information for article *Should Residual Biomass be used for Fuels, Power and Heat, or Materials? Assessing Costs and Environmental Impacts for China in 2035* by Sara Shapiro-Bengtsen, Lorie Hamelin, Lars Møllenbach Bregnbæk, Lele Zou, and Marie Münster. DOI: 10.1039/D1EE03816H

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Bio3E

The Bio3E spreadsheet model is uploaded to Figshare repository and can be accessed using the following link: https://doi.org/10.6084/m9.figshare.17143151.v1

In Bio3E the scenarios are selected in the *Dashboard Current Scenario* sheet and set-up in the *Assumptions* sheet. Here the Reference scenario and rates are defined as well as monetary assumptions (such as discount rate for investments), current use as well as environmental coefficients for these uses. The resource sheets; *CR*, *FR*, *AM*, *FW*, and *SS* list resource availability and projections by province. The *Biogas_total* sheet summarizes the projected output of biogas using methane yield factors described in the Anaerobic Digestion part of Section 2b in this document. The resources available to EDO for combustion is calculated in sheets *CR_EDO_Input*, *FR_EDO_Input*, and *Biogas_EDO_Input*. As sorting of FW for biogas utilization affects the available residual municipal solid waste (MSW) availability, this is calculated in the *MSW_EDO_Input* sheet. Provincial CR, FR, and Biogas potential defines the provincial distribution of power demand for electrolysis to produce hydrogen for biogas upgrading and excess heat production from these processes, specified in the *El_dem_DH_prod* sheet with data exported to EDO. Output from EDO is gathered in the *EDO_output* sheet and includes dynamic electricity and heating prices as well as production. The *Technology_data* sheet summarized the background information for conversion technologies. Hydrogen is generated through electrolysis, where the electrolysis input, output as well as production capacity and hydrogen storage is calculated in the *Electrolysis* sheet. Produced biogas can either be upgraded to biomethane through CO_2 removal or methanation, defined in the *Assumptions* sheet with input and output calculated in the *CO_2 removal* and *Methanation* sheets. Output from pyrolysis of CR and FR is calculated in the *Pyrolysis* sheet. Results are summarized in the *Current Scenario Table*. The *Background technology data* sheet shows the source of technology information.

Scenario system boundaries

Figure S1 shows the scenario system boundaries for quantifying environmental impacts.

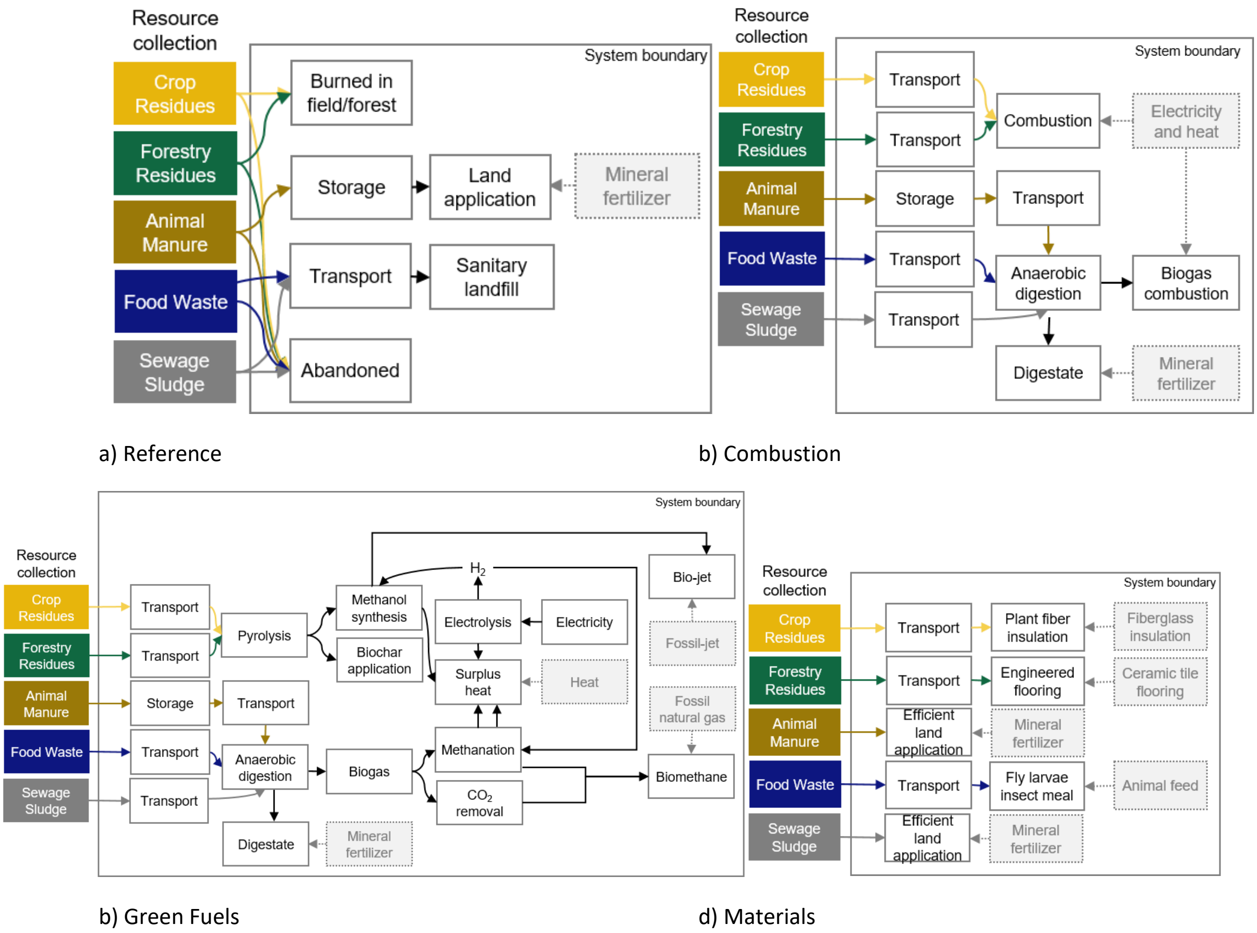

Figure S1: Overview of system boundaries for the different scenarios with the avoided energy and material products in grey. White boxes represent processes. Only flows considered within the system scope are shown.

Technology parameters, costs, and efficiencies

Table S1 presents an overview of main data points on costs and efficiencies used in the Bio3E model.

	Anaerobic digestion	Biogas upgrading CO_2 removal	Biogas upgrading methanation	Electrolysis	Hydrogen storage	Pyrolysis to methanol	Upgrading of methanol
Capacity	9 MW	6 MW	12 MW			20 MW	
Lifetime	20 years	15 years	25 years	25 years	30	25 years	20 years
Investment costs	12 MRMB/MW output	3 MRMB/MW output	5.5 MRMB/MW	0.88 MRMB/MW	0.3 MRMB/MWh	5.7 MRMB/MW	1.8 MRMB/MW
Fixed O&M	1.6 MRMB/MW/year	0.07 MRMB/MW/year	0.22 MRMB/MW/year	5% of CAPEX		4% of CAPEX	4% of CAPEX
Variable O&M	38 RMB/t input/year		26 RMB/MWh Biomethane			133 RMB/MWh	
Input	8 kWh electricity/t input	3% electricity of biogas input	1% electricity/Biomethane output (energy content)	100% electricity			
	365,000 tons biomass/year	100% biogas	53% biogas/Biomethane output (energy content) 46% hydrogen/Biomethane output (energy content)			100% biomass 40% hydrogen	

	Anaerobic digestion	Biogas upgrading CO_2 removal	Biogas upgrading methanation	Electrolysis	Hydrogen storage	Pyrolysis to methanol	Upgrading of methanol
Output	0.42 Nm3 CH_4/t input/year	100% biomethane 3% heat	89% biomethane 10% heat	67% hydrogen 11% heat		60% bio-jet 40% biochar 30% heat	
Data source	1	1	1	1, 2	3	4	5
1	(Danish Energy Agency and Energinet, 2017)						
2	(Bloomberg New Energy Finance, 2020)						
3	(Danish Energy Agency and Energinet, 2018)						
4	(Ea Energianalyse, 2020)						
5	(Dimitriou, Goldingay and Bridgwater, 2018)						

Table S1: Overview of main costs and efficiencies assumptions.

Section 1. Resource availability

Data on residual biomass availability to the energy sector is found in literature. Data is collected for 31 Chinese provinces, autonomous regions, and municipalities, referred to as provinces and the total referred to as China. Hong Kong, Macao and Taiwan is excluded due to limitation in primary data sources. For data availability reasons, 2016 is set as a base year to assess ecologically sustainable resource availability, this is then projected to 2035. Fang et al. (2019) developed a detailed overview of crop residues (CR) uses at provincial granularity, resulting in 353 Mt of CR wet basis available for energy use in China. This corresponds to 5,069 GJ, using energy conversion rates and provincial availability by crop type and province from Kang et al. (2020). Fang et al. (2019) takes point of departure in the harvested grain yields and divides the ecologically sustainable resource potential in current use. In the resource assessment used for this study the quantities retained in field for soil improvement, used for feed or industrial purposes are excluded from the ecologically sustainable potential used, totaling at 544 Mt in 2016. CR are projected using crop yield development scenarios from the Food and Agriculture Organization of the United Nations (FAO, 2018), reaching 5,928 PJ by 2035. Forestry residues (FR) are assessed in provincial level using data from Kang et al. (2020). Here a wide range of FR are included totaling 5,034 PJ in 2016, of which protected forests stand for one fourth of available resources. When limiting forestry residues to what could be interpreted as timber forest where forestry management is assumed to occur, timber forests, shrubbery, sipang and sparse forest, available forestry residues amount to 3,089 PJ. These are the quantities assessed to be ecologically sustainable to collect and are the annually available forestry residues used in this study. It is assumed that the annual level is unchanged to 2035.

Potential animal manure (AM) is assessed for cattle, sheep, pigs, and chickens using methodology and data from Kang et al., (2020) resulting in 1,060 Mt animal manure wet basis. Number of heads for each livestock category by province was retrieved from the National Bureau of Statistics (NBS, 2018), which is also used to decide the provincial distribution of AM. Animal manure is projected by province using development scenarios from FAO (2018) by type of livestock. As the composition of livestock is subject to change, the levels of manure by province varies over time, totaling at 5,908 PJ by 2035. Food waste amounts to 114 Mt wet basis assuming 56% share of food waste from Zhou et al. (2014) (MoHURD, 2018). This is projected on provincial level using projections from Shapiro-Bengtsen et al. (2020) resulting in 168 Mt food waste by 2035.

Sewage sludge (SS) is a by-product from wastewater treatment. Data on wastewater treatment can therefore be used for assessing sludge quantities. Wastewater treatment has improved dramatically, but there is significant room for improvement as one fourth of wastewater treatment plants are under dimensioned (J. Y. Lu *et al.*, 2019). Using data from 1,605 urban wastewater treatment plants, (X. Lu *et al.*, 2019) characterize sludge parameters and relationships, showing that the sludge production 0.59 kg sludge per m^3 wastewater reported by Wei et al., 2020 is within the range of 0.48-0.63 kg sludge per m^3 of wastewater. The SS availability based on wastewater treatment capacity results in 39.04 Mt sludge in 2019 with 80% water content (Wei *et al.*, 2020). According to MoHURD statistics 95% of wastewater was treated in 2018. Assuming the same treatment ratio, the sludge potential in 2019 was 40.9 Mt. This is projected to 2035 using urban population projections (UN, 2018) by province as described by Shapiro-Bengtsen *et al.* (2020). Capacity to treat SS in anaerobic digestion was 2.68 Mt with the potential to generate 132 million m3 CH_4 in 2019 (Wei *et al.*, 2020). With a volatile solids (VS) content of 66% of total solids (TS) (Liu *et al.*, 2012), this results in 0.37 m3 CH_4/kg VS SS.

Section 1a. Utilization rates

Resource potentials listed in this study are assessed to be environmentally sustainable to collect and utilize. However, practical and economic implications are not included. To account for these limitations, utilization rates are used to reach utilizable potentials. These are based on planned potential utilization for the energy sector (Kang *et al.*, 2020), see Table S2. We assume FW from municipal solid waste (MSW) to be utilized at the same rate as mixed MSW. These shares are used to determine the share of potential resources that are actually collected for modern utilization, either for energy purposes or non-energy use. The unutilized materials are treated with minimal effort as described in Table S12. As the case year for this study is 2035, the midway point between 2030 and 2040 is used.

	2020	**2030**	***2035***	**2040**	**2050**
CR	42%	65%	***70%***	74%	75%
FR	42%	65%	***70%***	74%	75%
AM	33%	58%	***62%***	66%	72%
MSW	54%	72%	***76%***	80%	84%
SS	33%	58%	***62%***	66%	72%

Table S2: Energy utilization coefficients from Kang et al. (2020) values for 2020 and every 10 years to 2050.

Section 1b. Collection and transportation costs

Biomass feedstock prices is an important input parameter as it is assessed that these can make up around half of the cost for biofuel production (Kargbo, Harris and Phan, 2021). As this study investigates residual biomass the cost is made up by collection and transportation costs. Depending on resource use, costs are made up by neither collection or transportation costs, either or both. Residual biomass collection and transportation costs in China are calculated by adding collection cost and transport cost (multiplied by transport distance). The used data is listed in Table S3 and the final costs in Table S4. Residual biomass collection and transportation costs vary geographically. Due to limited detailed data, national averages are used for each resource, summarized in Table S4. These costs as well as associated emissions are included when the resources are assumed to be collected and transported for treatment, see Table S5. Total costs for biogas feedstock in 2035 average at 21 RMB/GJ biogas yield potential. There is no additional transportation cost associated with biogas as it is assumed that the biogas plants are built with access to gas distribution networks by year 2035.

	Value	**Unit**	**Source**	**Note**
CR collection cost	190	RMB/t	(Wang *et al.*, 2019) SI	Purchase cost 235 RMB/t of which 0.9 RMB * 50 km = 45 RMB/t
FR collection cost	190	RMB/t	(Wang *et al.*, 2019) SI	Purchase cost 235 RMB/t of which 0.9 RMB * 50 km = 45 RMB/t
AM collection cost	23	RMB/t	(Li *et al.*, 2021)	Manure management cost made up by annualized capital costs. Weighted average based on AM solid/slurry ratio
FW collection cost	250	RMB/t	Own assumption	Based on interview with consultancy. 300 RMB to cover source sorting and transportation.
SS collection cost	0			As sewage sludge is a byproduct from wastewater treatment no additional collection cost is added to sewage sludge utilization
CR transport cost	0.9	RMB/tkm	(Wang *et al.*, 2019) SI	Typo in source, checked with author. It should be 0.9 and not 0.09 RMB/km/t

	Value	Unit	Source	Note
FR transport cost	0.9	RMB/tkm	(Wang *et al.*, 2019) SI	Typo in source, checked with author. It should be 0.9 and not 0.09 RMB/km/t
AM transport cost	0.5	RMB/tkm	(Li *et al.*, 2021)	Weighted average based on AM solid/slurry ratio
FW transport cost	1	RMB/tkm	Own assumption	Based on interview with consultancy. 300 RMB to cover source sorting and transportation.
SS transport cost	0.5	RMB/tkm		Assumed to be the same operational costs as slurry AM transport
CR transport distance	50	km	(Wang *et al.*, 2019) SI	
FR transport distance	50	km	(Wang *et al.*, 2019) SI	
AM transport distance	40	km	(Li *et al.*, 2021)	Assumption based on Li et al., 2021
FW transport distance	50	km	Own assumption	Based on interview with consultancy. 300 RMB to cover source sorting and transportation.
SS transport distance	40	km		Assumed to be the same as AM

Table S3: Overview of collection and transportation costs for residual biomass in China.

	RMB/t (collected and transported)	GJ/t ww	RMB/GJ	GJ CH_4 potential/t ww	RMB/GJ CH_4 potential
Crop Residues	235	14.4	16		
Forestry Residues	235	18.6	13		
Animal Manure	80	5.1	16	2.2	36
Food Waste	300	1.9	158	2.8	107
Sewage Sludge	80	3.3	25	1.8	45

Table S4: Overview of costs and main resource parameters using LHV for food waste 13.4 GJ/t TS (Yang et al.*, 2012).*

Pathway	Used in scenario	Collection	Transport
CR Burnt in field	Reference	No	No
CR Abandoned	Reference	No	No
FR Burnt in field	Reference	No	No
FR Abandoned	Reference	No	No
AM Applied on field	Reference	Yes	No
AM Abandoned	Reference	No	No
FW Abandoned	Reference	No	No
FW Landfilled	Reference	No	Yes
SS Abandoned	Reference	No	No

Pathway	Used in scenario	Collection	Transport
SS Landfilled	Reference	No	Yes
CR Pyrolysis	Green Fuels	Yes	Yes
CR Combustion	Combustion	Yes	Yes
FR Pyrolysis	Green Fuels	Yes	Yes
FR Combustion	Combustion	Yes	Yes
Biogas Combustion	Combustion	No	No
Biogas CO_2rem	Green Fuels	No	No
Biogas Methanation	Green Fuels	No	No
AM Biogas	Green Fuels /Combustion	Yes	Yes
FW Biogas	Green Fuels /Combustion	Yes	Yes
SS Biogas	Green Fuels /Combustion	No	Yes
CR Building materials	Materials	Yes	Yes
FR Building materials	Materials	Yes	Yes
AM Efficient land application	Materials	Yes	No
FW Feed	Materials	Yes	Yes
SS Efficient land application	Materials	No	No

Table S5: Overview of assumptions for collection and transport of resources by use.

Average AM transport distance is 40km, if optimized this could be reduced to 20km (Li *et al.*, 2021). We assume transport distance of 40km for AM in this study. With 75% or AM in 2035 being categorized as slurry (from cattle and pigs) and the remainder as solid (from poultry and sheep), the weighted transportation cost is 1 RMB/tkm (Li *et al.*, 2021). Costs for collecting food waste is substantially higher than the costs for collecting and transporting other residual biomass fractions. This can be attributed to the additional costs of sorting systems. The assumed transport distance, listed in Table S3, is based on energy utilization but is used for all utilization scenarios, making the price of residual biomass the same for all utilization cases. In the case for unutilized biomass collection cost is set to zero in most cases, see Table S5 for details.

Environmental Impacts from Transport

All residual biomass is assumed to be transported using diesel trucks. Transport emissions are added when the resource is assumed to be transported for treatment, see Table S6. This is the case for all resources in the Combustion, Green Fuels and Materials scenarios. In the Reference scenario transportation is assumed to only occur when resources are landfilled in sanitary landfills.

	kg/tkm
CO_2e	1.48E+00
$PM_{2.5}$	3.70E-11
P	8.82E-05
N	1.50E-02

Ecoinvent process used (from Ecoinvent v.3.5): Municipal waste collection service by 21 metric tonne lorry {RoW}| processing | Conseq,U

Table S6: Environmental impact of transport.

Section 2. Environmental impacts

Climate change

In this study, lifecycle aspects of the three main GHG contributors, CO_2, CH_4 and N_2O emissions are included and converted to CO_2-equivialents using 100 year global warming potential factors (UNEP-SETAC, 2016). The biomass included in this article is residual biomass and is in itself assumed to be carbon neutral, thus carbon uptake during growth and CO_2 emissions to air as residues degrade is not included. However, CH_4 and N_2O emissions, as well as sequestrated carbon, are included in the GHG emissions factor (GHGF).

Equation S1:

$$GHGF_{r,a} = -CC_r * SC_{r,a} + (CH4_{r,a} * GWP_{CH4}) + (N2O_{r,a} * GWP_{N2O}) - AC_{r,a}$$

GHGF is calculated for each resource and treatment method using Equation S1, where $GHGF_{r,a}$ denotes the CO_2e emissions in kg per t of total solids in resource *r* by treatment method a. CC_r denotes carbon content for resource r and $SC_{r,a}$ the share of sequestrated carbon for resource *r* by treatment method *a.* The carbon content for each resource is hence converted to CO_2, using the ratio of the molecular weight of carbon dioxide to carbon, and the sequestered carbon is deducted, enabling negative CO_2 emissions. Emitted CH_4 and N_2O is converted to CO_2e using global warming potential (GWP) factors for 100 years of 28 and 265, respectively (UNEP-SETAC, 2016). Finally $AC_{r,a}$ denotes avoided fossil and biogenic emissions in kg CO_2e per t of total solids by resource *r* and treatment method *a* from emissions avoided due to substituted fossil fuels, materials or feed, when applicable.

When used for materials, the carbon is sequestrated for the lifetime of the material. In the case for CR and FR, building materials are the application in the Materials scenario. Building lifetimes vary depending on the building quality and materials used. Chinese buildings are for example expected to stand for 30 years, compared to 64-133 years in European countries (Wang, Zhang and Wang, 2018). The year for the study is 2035 and the lifetime of building materials from CR and FR is estimated to 30 years. After 30 years of use, the carbon is emitted at the earliest in 2065, and is hence not included within the timeframe of this study. There is a benefit[1] of delaying carbon emissions due to the urgency of climate change and assumed development of carbon storage and utilization technology.

Air pollution

Air pollution causes extensive health issues and burning of residual biomass adds to this (Chen *et al.*, 2017). There are complex relationships resulting in air pollution, which are not represented in this study but direct $PM_{2.5}$ emissions are included for each treatment pathway. We use a lifecycle perspective in emissions assessment and $PM_{2.5}$ emissions are quantified and included to serve as an indicator for air pollution.

Eutrophication

Phosphorous losses and nitrate leaching cause eutrophication. How much nitrate and phosphorous is lost in water depend on local soil conditions and is difficult to generalize. Despite these limitations, the high importance of eutrophication motivates including even a rough assessment of the issue.

Section 2a. Combustion and Green Fuels Scenarios

Energy emissions factors

CO_2e emission from required electricity in the Green Fuels scenario and avoided electricity and heat in the Combustion scenario are calculated in the EDO model and N, P, and $PM_{2.5}$ impacts are from Ecoinvent v.3.5, processes described in Table S7. The table also shows the emissions impacts for fossil fuels.

Energy service		Ecoinvent process
Electricity	Coal	Electricity, high voltage {CN-JS}| electricity production, hard coal | Conseq, U
Electricity	Wind	Electricity, high voltage {CN-NM}| electricity production, wind, >3MW turbine, onshore | Conseq, U
Electricity	Solar	Electricity, high voltage {RoW}| electricity production, solar thermal parabolic trough, 50 MW | Conseq, U
Electricity	Natural gas	Electricity, high voltage {CN-JS}| electricity production, natural gas, conventional power plant | Conseq, U
Electricity	MSW	Electricity, for reuse in municipal waste incineration only {TW}| electricity, from municipal waste incineration to generic market for electricity, medium voltage | Conseq, U

[1] The benefit of delaying emissions also applies to leaving straw on fields as it takes time for the carbon to decay. Most of the carbon, 77%, is emitted as CO_2 during the first three years after the straw is left on fields and 19% in subsequent years (Tonini, Hamelin and Astrup, 2016). It is assumed that CR left on fields to decay is not collected for utilization in a later stage and all CO_2 emissions are accounted for in the year the CR are left on fields.

Electricity	Nuclear	Electricity, high voltage {CN-ZJ}| electricity production, nuclear, pressure water reactor | Conseq, U
Heat	Natural gas	Heat, district or industrial, natural gas {RoW}| market for heat, district or industrial, natural gas | Conseq, U
Heat	Coal	Heat, district or industrial, other than natural gas {RoW}| heat production, at coal coke industrial furnace 1-10MW | Conseq, U
Heat	Electric	Heat, air-water heat pump 10kW {CH}| production | Conseq, U
Heat	MSW	Heat, for reuse in municipal waste incineration only {RoW}| Conseq, U
Fuel	Natural gas	Natural gas, low pressure {RoW}| market for | Conseq, U
Fuel	Jet kersosene	Kerosene {RoW}| market for | Conseq, U
Fuel	Diesel	Diesel {RoW}| market for | Conseq, U

Table S7: Overview of Ecoinvent processes used for environmental impact of energy services. All from Ecoinvent v.3.5

CR & FR

In this study fast pyrolysis is used with a following upgrading process to produce bio-jet. It is assumed that 40% of the energy in bio-jet from pyrolysis stems from hydrogen and 60% from biomass (Clausen, 2015). Half of the carbon content in biomass ends up as biochar. Of the total carbon in biochar, 80% is sequestered in the soil (Brassard, Godbout and Hamelin, 2021). N and P losses as well as $PM_{2.5}$ emissions are assumed to zero. From 100 PJ biomass 40 PJ ends up as biochar and 60 PJ as gas and oil, which is assumed to be converted into bio 60 PJ jet fuel and 30 PJ excess heat by adding 40 PJ hydrogen (Clausen, Butera and Jensen, 2019). The excess heat is made available for district heating. For pyrolysis of CR and FR the same efficiency is assumed. These overall estimated efficiencies are associated with uncertainty and results should be interpreted accordingly. Costs for pyrolysis and subsequent upgrading to bio-jet are listed in Table S1.

Anaerobic Digestion

The potential methane yield from anaerobic digestion is expressed as methane per mass of volatile solids (VS) or the chemical oxygen demand (COD). A set factor, expressed in in m^3 CH_4 per kg VS or COD for each resource is used to assess the biogas methane yield. The energy content of CH_4 is 35.9 MJ/ m^3 CH_4. For AM is the volatile solids content varies in different types of manure and the composition of types of livestock changes over time. For 2016 the potential methane yield from anaerobic digestion of AM is 0.28 m^3 CH_4 / kg VS. For FW this is 0.47 m^3 CH_4 / kg VS. Output from SS is calculated from COD content using the factor 0.35 m^3 CH_4 / kg COD. There is an overall assumption of 2% fugitive methane emissions from anaerobic digestion. There is some carbon sequestration from the produced digestate from the anaerobic digestion process (Hamelin, Naroznova and Wenzel, 2014). Digestate storage is associated with some CH_4 emissions, resulting in 0.19 kg CH_4/t digestate and N_2O emissions of 0.008 kg N_2O per kg N in digestate; the spreading of digestate is associated with 0.016 kg N_2O per kg N applied on fields (Hamelin, Naroznova and Wenzel, 2014).

AM

The methane yield from AM is calculated from the volatile solids content of manure and with a fixed factor of m^3 CH_4 per kg volatile solids by livestock species and found using Equation S2 and parameters in Table S8. Parameters for the bioenergy potential estimation of animal manure, breeding cycle, daily excretion coefficient, dry matter content, and collection coefficient from Kang et al. (2020). Number of heads of livestock from National Bureau of Statistics, year 2016 (NBS, 2018). Using number of livestock - annual by province (Cows and Sheep). This is also used to decide the provincial distribution of AM.

Slaughtered poultry and slaughtered pig (pigs and chickens), volatile solids content as share of total solids, and data from methane potential by livestock species for cattle, chicken, and pig manure is from Fen et al. (2017). The VS share of TS in sheep manure is comparable to cattle manure, while sheep manure has a methane yield potential that is 80% of that of cattle manure (Kozłowski *et al.*, 2019). This ratio is used to reach sheep manure characteristics.

	Breeding cycle (day)[a]	Daily excretion coefficient (kg/day) [a]	Dry matter content (%)[a]	Collection coefficient [a]	LHV (kJ/kg)	Number of heads in 2016 [b]	Volitile solids of dry matter (%)[c]	Methane yield (m^3 CH_4 / kg VS)[c]

i	B_i	E_i	D_i	R_i		N_i	V_i	M_i
Cows	365	25.93	0.19	0.6	13799	1.1E+08	75%	0.29
Sheep	365	2.1	0.5	0.6	15472	3.0E+08	74%	0.23
Pigs	199	3.12	0.2	0.9	12545	6.9E+08	60%	0.27
Chickens	210	0.12	0.5	0.6	18817	1.2E+10	64%	0.27

Table S8: Parameters for AM. Sources: [a] (Kang *et al.*, 2020) [b] (NBS, 2018) [c] *for cows, pigs, and chickens* (Fen *et al.*, 2017). *For sheep compared to cow manure* (Kozłowski *et al.*, 2019).

Equation S2:

$$MY_{AM} = \sum_{i=1}^{n} N_i * E_i * B_i * D_i * R_i * V_i * M_i$$

The methane potential from animal manure MY_{AM} is projected to 2050 using FAO scenarios for livestock development, here the business as usual scenario is used (FAO, 2018).

FW

Methane yield from food waste is found by Equation S3, where FW is the wet weight food waste in kg, T is the total solids share, 20% (Negri *et al.*, 2020), V is the share volatile solids in total solids, 83% (Negri *et al.*, 2020), and M is the potential methane yield from anaerobic digestion of food waste per kg volatile solids (VS), 0.474 m3 CH_4 / kg VS (Negri *et al.*, 2020).

Equation S3:

$$MY_{FW} = FW * T_{FW} * V_{FW} * M_{FW}$$

SS

Methane yield from SS is found by using a fixed factor 12.57 GJ CH_4/t COD for SS (350 m3 CH_4 per t COD and 0.0359 GJ/m3 CH_4 = 12.57 GJ CH_4/t COD).

Biogas upgrading

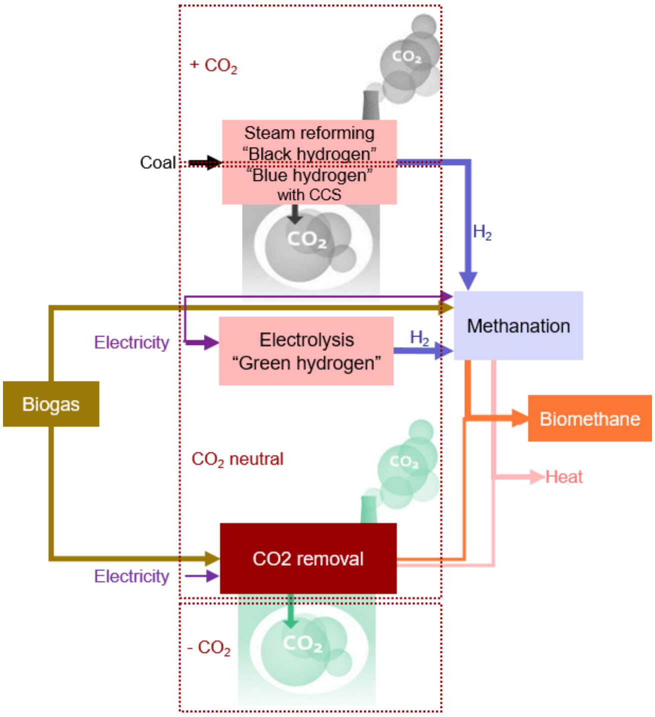

Figure S2: Biogas upgrading pathways

Biogas typically consists of around 60% CH_4 and 40% CO_2 by volume, as well as other compounds. To enable substitution of fossil natural gas, biogas can be upgraded to increase the share of CH_4 content of the gas. This can be done by either removing the CO_2 content and contaminating gasses or by methanation of the CO_2 in the biogas with H_2, see Figure S2. In this study half of the biogas is upgraded through CO_2 removal and the remaining half is upgraded through methanation.

Hydrogen

Hydrogen needed for upgrading of biogas through methanation and pyrolysis products can be produced in several ways, one of which being through water electrolysis, which is used in this study. Anaerobic digestion and methanation is assumed to be operate continuously and hydrogen generated flexibly through electrolysis. It is assumed that electrolysis is powered by grid-power, as opposed to stand-alone electrolysis parks. Therefor there is no control for which energy sources are used for electricity generation. The electrolysis units are modelled to run flexibly during 4000 full load hours per year in EDO to utilize the cheapest power prices.

Excess heat

Excess heat from the pyrolysis, electrolysis, and methanation processes can be used for district heating or process heat. Excess heat from pyrolysis process makes up the majority, 72% of available excess heat.

Avoided emissions

Fixed values for avoided fossil CO_2e emissions from produced biofuels. The avoided emissions from electricity and heat emissions are dynamic following output from EDO.

Avoided fossil CO_2e emissions are made up by indirect emissions from the fuel generation and direct emissions from the combustion of the fuels. Indirect emissions are taken from the Ecoinvent database Table S7 and avoided direct fossil emissions are calculated based on the carbon content in fossil fuel and oxidation factor using Equation S4, methodology from the IPCC guidelines for national greenhouse as inventories (IPCC, 2006).

Equation S4:

$$FC = CC_f * O_f * \frac{44}{12} * 1000$$

Where *FC* is the fossil CO_2 emission factor in t CO_2e/PJ and *CC* is the carbon content in fuel *f* in kg/GJ and O is the oxygenation factor in percent and 44/12 is the molecular weight ratio between CO_2 and carbon. IPCC uses default oxygenation factors of 100%, whereas the factors used in this study are China specific and vary by fuel (Shan *et al.*, 2017). Adding to CO_2e emissions – indirect N and P as well as indirect $PM_{2.5}$ emissions are also quantified using data from the Ecoinvent database, see Table S7. Resulting values are shown in Table S9. For indirect P, N, and $PM_{2.5}$ emissions, coal generated electricity and heat have substantial impact. P and N from other fuels are negligible, while indirect $PM_{2.5}$ emissions are small. Apart from emissions from unutilized resources, a substantial part of N and P emissions stem from the anaerobic digestion process of AM, FW and SS. In the materials scenario there are N and P emissions from the application of AM and SS on land.

Unit: ton/PJ	Electricity (Coal)	Heat (Coal)	Natural gas	Jet kerosene	Diesel
$PM_{2.5}$ (indirect)	8.49E+01	5.20E+01	3.43E-01	2.22E+00	2.28E+00
P	1.83E+02	1.73E+02	7.42E-10	5.01E-08	5.08E-08
N	5.50E+01	5.15E+01	2.82E-10	1.51E-08	1.53E-08
CO_2e (indirect)	3.14E+05	1.63E+05	1.70E+04	2.44E+04	2.48E+04
CO_2e (direct)			5.50E+04	6.90E+04	7.11E+04

Table S9: Overview of environmental impacts associated with fossil fuel generation and use. For processes considered see Table S7.

Section 2b. Materials Scenario

CR

Using plant fiber blocks for insulation in buildings is 2.6 times less GHG intensive compared to fiberglass (Revuelta-Aramburu *et al.*, 2020). Emissions are given per produced plant fiber block, 19.4kg CO_2e (Revuelta-Aramburu *et al.*, 2020). This corresponds to 1,954 kg CO_2 avoided emissions per t of CR TS when converted to kg CO_2e/t TS CR, assuming a TS content of 89% (Gao *et al.*, 2016) and an average density of 105 kg/m^3 plant fiber blocks (Revuelta-Aramburu *et al.*, 2020). The difference includes manufacturing emissions. Data on avoided emission flows are gathered from Ecoinvent v.3.5, considering the Glass fibre {GLO}| market for | Conseq, U process.

Avoided cost

The avoided costs for using CR for insulation is estimated to 648 RMB/t TS CR. Results from Revuelta-Aramburu et al., (2020) shows a cost saving of 3.33 €/m2 of wall when using plant fiber blocks compared to the least cost conventional alternative listed. Converted to RMB per t of TS CR used for PFB results in -6.48 RMB/t/year.

FR

It is assumed that FR can be used to produce engineered wood flooring to substitute ceramic tiles. To produce one m^3 of engineered wood flooring, 1,499 kg FR is used and the avoided CO_2e per m3 of engineered wood flooring compiles to 0.42 tons of CO_2e (Geng, Zhang and Yang, 2017). The avoided CO_2e emissions are therefore 280 kg CO_2e per t of FR dry matter. Data on avoided emission flows from ceramic tile production are gathered from the Ecoinvent database v.3.5, using the Ceramic tile {GLO}| market for | Conseq, U process.

Avoided cost

A couple of the underlying assumptions are that lifetime of engineered wood flooring is 25 years[2] and 50 years for ceramic tiles and the discount rate is 4%. The additional cost of engineered wood flooring from one t of FR is in the range of 46 and 100 RMB/year compared to ceramic tile, depending on the price of ceramic tile (Geng, Zhang and Yang, 2017). In this study we assume an average, 73 RMB/t FR TS.

AM

In the materials scenario AM is applied efficiently on land, with low nutrient losses, assumed to 35% N lost in water and 3% P lost in water (Hamelin, Naroznova and Wenzel, 2014). It is assumed that N and P substitutes mineral fertilizer 1:1 and data on avoided emission flows for mineral fertilizer are gathered from the Ecoinvent database, see Table S13.

Avoided cost

Treatment cost of efficiently spreading AM on land is set to 10 RMB/m3, equal to 30 RMB/t TS AM. The avoided fertilizer value is set to 5.3 RMB/kg N and 12.1 RMB/kg P. These data are from industry experts.

FW

A potential non-energy use of food waste is to use it to feed insects and harvest larvae to make animal feed. A key assumption is the yield of black soldier fly meal (BSFM) per t of FW. This is set to 111 kg BSFM per t of FW, which is a simple average from results in previous studies, see Table S10. Animal manure and sewage sludge could possibly be used for feed production as well (Čičková *et al.*, 2015). This is not included as an option in this study due to high uncertainties associated with this use.

BSFM (kg/t FW TS)	Source
104	(Guo *et al.*, 2021)
110	(Salomone *et al.*, 2017)
119	(Čičková *et al.*, 2015)

Table S10: Black soldier fly mean (BSFM) yield from FW.

[2] Following assumptions from (Geng, Zhang and Yang, 2017). This is five years longer than the estimated carbon sequestration time. This shorted lifetime is kept when assessing the avoided cost as the cost can be written off during a shorter time than the carbon is sequestrated for as building materials. Additionally the 50 year lifetime of ceramic tiles exceeds the assumed lifetime of a building. It is possible that the ceramic tiles are repurposed and given life longer than the original building in which they were installed.

Direct emissions

The direct emissions from BSFM production is assessed using data from (Mertenat, Diener and Zurbrügg, 2019) where 630 g CH_4 and 72 g N_2O is emitted per t of FW with 23% TS resulting in 2.7 kg CH_4 and 0.3 kg N_2O per t of FW TS.

Avoided emissions from BSFM

It is assumed that the avoided marginal feed is maize (avoided carbrohydrate), soybean meal (avoided protein) and palm oil (avoided fat), based on Tonini, Hamelin and Astrup (2016). To calculate the quantity of avoided marginal carbohydrate, protein, and fat by the BSFM, the methodology presented in Tonini, Hamelin and Astrup (2016) appendix S5 is used. This is based on feed equivalent called Scandinavian Feed Units (SFU):

Equation S5:

$$AF_n = SFU_{BSFM} * \left(\frac{1}{SFU_{m,n}}\right) * BSFM\%_n$$

Where AF_n is the avoided marginal feed by nutrient n (protein, fat, and carbohydrates). SFU_{BSFM} is the SFU of BSFM, and $SFU_{m,n}$ is the SFU for the marginal nutrient and $BSFM\%_n$ is the ash free dry matter content of as a share by nutrient n. Share of digestible protein and fat is taken as a simple average from BSFM studies reviewed by Gasco et al., (2020), 84% digestibility of crude protein and 94% of crude fat. Chemical properties of BSF meal is from (Čičková *et al.*, 2015).

Data from the Ecoinvent database is used to quantify avoided CO_2e from avoided feed production, see Table S11. The avoided ILUC emissions are included as 4 t CO_2e per hectare no longer demanded (European Commission, 2019). The resulting data used shown in Table S11 resulting in total avoided biogenic GHG emissions of 470 kg CO_2e per t of FW used to produce BSFM.

	BSFM crude content (%)[a]	BSFM Digestibility (%)[b]	Avoided marginal feed (kg/kg BSFM)[c]	Avoided emissions (kg CO_2e/kg BSFM feed)[c]	Ecoinvent v.3.5 process
Protein	42.1	84	0.68	3.11	Soybean meal {BR}| soybean meal and crude oil production | Conseq, U
Fat	34.8	94	0.24	1.12	Palm oil, crude {MY}| palm oil mill operation | Conseq, U
Carbohydrate	1.4		0.03	0.02	Maize grain {US}| production | Conseq, U
Fiber	7				
Ash content	14.6				
Dry matter	92.1				

Table S11: Black solider fly mean (BSFM) content, digestibility and avoided feed data used in this study. [a] (Čičková *et al.*, 2015) [b] (Gasco, Biancarosa and Liland, 2020) [c] *This study. The data is not per kg of macronutrient, but for the specific marginal feed: soybeal meal, palm oil, and maize grain.*

Avoided cost

The production cost is 5 RMB/kg larvae and the purchase price 12 RMB/kg larvae (Wang *et al.*, 2013), making the avoided cost 7 RMB/kg larvae.

SS

Direct emissions from spreading SS on fields are assumed to be the same share as spreading AM on fields, excluding storage. It is assumed that N and P substitutes mineral fertilizer 1:1 and data on avoided environmental impact of mineral fertilizer is gathered from the Ecoinvent database, see Table S13.

Avoided cost

Avoided cost of fertilizer is assumed to be the same as for AM, 5.3 RMB/kg N and 12.1 RMB/kg P. Treatment cost of efficiently spreading SS on land is assumed to be the same as for AM; 10 RMB/m3, equal to 50 RMB/t TS SS.

Section 2c. Reference Scenario

Management assessments of unutilized CR, AM, FW, and SS are gathered from literature and simplified to two pathways per resource, see Table S12. Forestry residues (FR) are assumed to be burnt in forest or abandoned with a 50/50 ratio.

	CR [a]	FR	AM [b]	FW [c]	SS [d]
Open burning	85%	50%			
Applied on field			89%		
Abandoned	15%	50%	11%	5%	59%
Landfilled				95%	41%

[a]Calculated using data from (Fang, Wu and Xie, 2019). *Quantities currently retained in fields, used for feed, paper industry, and other uses are excluded.* [b]Calculated using data from (Sommer *et al.*, 2016). Tables 3.4 & 3.5. [c]Calculated using data from (MoHURD, 2019). [d]Calculated using data from (Qu *et al.*, 2019).

Table S12: Overview of treatment of unutilized resources.

CR – Open burning

When CR are burnt in fields CH_4 and N_2O emissions are emitted (IPCC, 2006). Adding to this $PM_{2.5}$ emissions are defined crop type (Zhang *et al.*, 2017) and weighted by crop residue composition in this study, 33% maize, 29% rice, 13% wheat (the remainder as other) with a resulting $PM_{2.5}$ emissions of 10.6 g $PM_{2.5}$/kg CR burnt.

CR – Abandoned

When CR is abandoned in fields some carbon is sequestrated. Calculated using data from (Tonini, Hamelin and Astrup, 2016) appendix S9. Resulting in 4.3 % carbon sequestration over 100 years.

FR – Open burning

Emissions from open burning of FR are calculated using IPCC methodology and data on CH_4 and N_2O emissions (IPCC, 2006), Table 2.5 in IPCC (2006). Oxidation factor assumed to be 90%. $PM_{2.5}$ emission factor 9.7 kg/t burnt dry matter (Wu *et al.*, 2018), Table 5 in IPCC (2006).

FR – Abandoned

When FR is abandoned approximately 5% of carbon is sequestered, using a simple average from studies: (Mäkinen *et al.*, 2006; Melin, Petersson and Nordfjell, 2009; Müller-Using and Bartsch, 2009; Repo, Tuomi and Liski, 2011). Of the remaining carbon 90% is assumed to be lost as CO_2 and 10% lost as CH_4 (Mann and Spath, 2001).

AM – Applied on field

When AM is applied on land the nutrients supplied are typically not accounted for, resulting in extensive over application of nutrients (Bai *et al.*, 2016). Bai et al., (2016) assessed nutrient losses from AM in China. The losses after storage are 55% N and 11% P, these occur during treatment and application of AM. For N and P losses from AM applied on field, we considered that 55% N and 11% P is lost (Bai *et al.*, 2016).

Unit: Tg	After storage	Applied to crops	Treatment losses	Application losses	Losses	Ecoinvent v.3.5 process
N	5.6	4	1.6	1.5	55%	Nitrogen fertiliser, as N {GLO}| market for | Conseq, U
P	1.9	1.7	0.1	0.1	11%	Phosphate fertiliser, as P_2O5 {GLO}| market for | Conseq, U

Table S13: N and P losses from treatment and application.

Some carbon is sequestered when AM is applied on fields (Hamelin, Naroznova and Wenzel, 2014). Adding to this, we considered CH_4 emissions from outdoor storage and digestate storage, N_2O emissions made up by losses from storage and spreading AM on field, based on Hamelin, Naroznova and Wenzel (2014).

AM - Abandoned

Abandoned AM is dumped in waterways or in piles on land for no subsequent use. It is assumed that half of manure is dumped in waterways and half is dumped in piles, i.e. half anaerobic and haft aerobic conditions[3]. Equation S6 is used to calculate CO_2e emissions from abandoned manure.

Equation S6:

$$CO2e_{Ab_{AM}} = (VS_{AM} * B_0 * 0.67 * MCF * GWP_{CH4}) + (N_{AM} * NEF * \frac{44}{28} * GWP_{N2O})$$

Where VS_{AM} is the volatile solids content of AM, B_0 is the maximum potential methane yield[4] per unit of VS, 0.67 is the conversion factor for kg CH_4 per m3 CH_4, MCF is the methane conversion factor, and GWP denotes the global warming potential. N_{AM} is the nitrogen content in AM in kg per tonne, NEF is the N_2O emission factor. For N and P losses, the N and P dumped in waterways is assumed to be lost, whereas the N and P dumped in piles is assumed to have the same lost rate as AM applied on field.

FW– Abandoned/landfilled

Abandoned food waste is assumed to be dumped in aerobic conditions such as simple landfills without membranes protecting from leachate. Abandoned FW is modelled as simple landfill using equation 1 from IPCC default method 2.1.1 and the same equation, Equation S7, is used for landfilled FW, which is modelled as sanitary landfill (IPCC, 2003).

Equation S7:

$$CO2e_{WC_{FW}} = TS_{FW} * MCF_s * DOC * F * \frac{16}{12} * CH4_{GWP}$$

Where TS_{FW} is the share total solids in food waste, FW. MCF_s is the methane correction factor by site type s, for abandoned FW this is 0.4 and F is the fraction of CH_4 in landfill gas, the IPCC default value 0.5 is used (table 5.1(IPCC, 2003)). Collected landfill could potentially be utilized, but is assumed to be flared where the CH_4 is converted to CO_2 in the flaring process. DOC is the share of degradable organic carbon in wet food waste. It is assumed that 50% or carbon content is degradable following assumptions from Zhang et al. (2020). 16/12 is the conversion of C to CH_4 and $CH4_{GWP}$ is the global warming potential for CH_4. For sanitary landfill the MCF is 1. N_2O gas emissions from landfill are insignificant (IPCC, 2006). The conservative assumption is used that all lignin in the FW, 8.1% (Li *et al.*, 2013), will not degrade, meaning that this carbon is sequestered.

N leachate and P losses from landfill of municipal solid waste (MSW) has been modelled in a 100 year perspective (Manfredi and Christensen, 2009) and found that 29% of initial N was lost through leachate in simple landfills and 14% in sanitary landfills. These shares are used for N leachate from abandoned and landfilled FW in this study. For P losses Equation S8 is used, parameters and values listed in Table S14.

Equation S8:

$$FWP_{losses} = MSW_{PL} * MSW_L * \frac{FW_{P\%}}{MSW_{FW\%}} * FW_{TS\%}$$

[3] The climate conditions in China vary by geographic location and is assessed using the IPCC map of climate zones. An average of primarily cool dry temperate and warm moist temperate conditions, but also including cool moist temperate, warm dry temperate, and tropical moist conditions resulting in an MCF of 53% for liquid slurry to illustrate anaerobic conditions and 3% for solid storage to illustrate aerobic conditions, as half is assumed to be abandoned in aerobic and half in anaerobic conditions this results in an average MCF of 28% which is used to calculate emissions from abandoned AM. Values are found in IPCC, 2019 updated GHG emission inventory, Chapter 10, volume 4, table 10.17 (IPCC, 2019a). Similarly, the N_2O emission factor (NEF) is an average of emission per kg of nitrogen in manure for liquid slurry management and solids storage, 0.005 kg N_2O-N/kg N found in IPCC, 2019 updated GHG emission inventory, Volume 4, Chapter 10, table 10.21 (IPCC, 2019a).

[4] Calculated using coefficients from (Fen *et al.*, 2017), applied to Chinese AM mix (36% cattle, 19% sheep, 19% pigs, 25% chicken volatile solids) resulting in an average of 0.28 m3 CH4 / kg VS.

Description	Parameter	Value	Source
Leachate from municipal solid waste (MSW) in liter/t of wet waste	MSW_L	4300 L (simple landfill) 2000 L (sanitary landfill, of which 800 L to wastewater treatment plant with 22% P removal)	(Manfredi and Christensen, 2009)
Phosphate converted to P in leachate using ratio 3:1	MSW_PL	4.7 mg P/L (direct emitted) 3.6 mg P/L (for leachate treated in wastewater treatment plant)	(Manfredi and Christensen, 2009)
Phosphate share in food waste (of MSW total phosphate)	FW_P%	91%	(Sokka, Antikainen and Kauppi, 2004)
Share of FW in MSW	MSW_FW%	41%	(Yang et al., 2018)
Share of total solids in FW	FW_TS%	28%	(Yang et al., 2018)

Table S14: Parameter and values for calculating P losses from landfill of food waste.

SS - Abandoned

Abandoned SS is assumed to be discharged in waterways. Associated GHG emissions are calculated using Equation S9 with emission factor 0.068 kg CH_4/kg BOD assuming 0.51 kg BOD/kg VS and 0.005 N-N_2O per kg N (IPCC, 2019b)(Tables 6.3 and 6.8A). The crude fiber content of SS, 7.1% (Liu *et al.*, 2012) is assumed to be sequestered.

Equation S9:

$$CO2e_{WC_{SS}} = (EF_{CH4} * 0.51 * VS_{SS} * GWP_{CH4}) + (NEF_{SS} * \frac{44}{28} * N_{SS} * GWP_{N2O})$$

Where $CO2e_{WCSS}$ is the CO_2e emissions for worst case treatment of sewage sludge in kg CO_2e/t of total solids. EF_{CH4} is the emission factor for discharge of wastewater into aquatic environments in kg CH_4/kg BOD. 0.51 is the BOD content per kg VS. NEF is the emission factor for discharging wastewater into water environments, 44/28 is the conversion factor of N_2O -N to N_2O. N_{SS} is the N content in SS and GWP_{N2O} is the global warming potential for N_2O. The crude fiber content in SS is assumed to be sequestrated, the rest is degraded resulting in 835 kg CO_2e per t TS for abandoned SS. All N and P content is counted as lost as SS is assumed to be dumped in waterways.

SS – Landfilled

Landfilled SS is modelled as a sanitary landfill where the crude fiber content in SS is assumed to be sequestrated, the remaining carbon content is degraded as CO_2 and 60.6 kg CH_4 is emitted per t dry matter sludge (Wei *et al.*, 2020). Share of N and P ending up in water from conventional wastewater treatment systems from Chinese case study (Xu *et al.*, 2020). The crude fiber content of SS, 7.1% (Liu *et al.*, 2012)is assumed to be sequestered.

Section 2d. Overview of sequestered carbon

The resulting carbon sequestration from the different processes detailed above is summarized in Table S15.

Scenario	Resource	Application	Share of resource-C sequestered
Reference	CR	Abandoned	4.3%
Reference	FR	Abandoned	5%
Reference	FW	Abandoned (5%); Landfilled (95%)	8.1%
Reference	SS	Abandoned (59%); Landfilled (41%)	7%
Reference/Materials	AM/SS	Applied on field; Efficient land application	1.7%
Green Fuels/Combustion	AM/FW/SS	Biogas digestate	6%
Green Fuels	CR	Pyrolysis	35%
Green Fuels	FR	Pyrolysis	32%
Materials	CR/FR	Building materials	100%

Table S15: Overview of the considerations made regarding carbon sequestration by scenario resource category and application.

Section 3. Results

Section 3a. Costs and flows

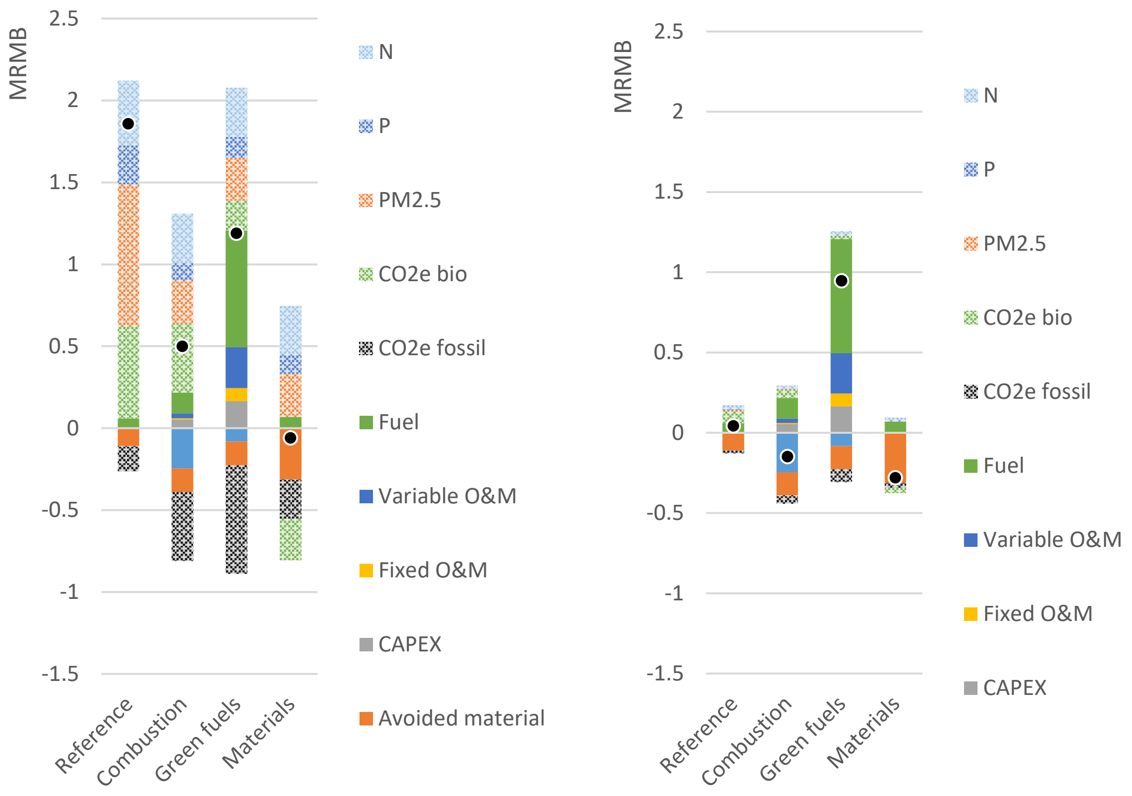

Figure S3: System costs with externalities priced using alternative societal costs (left) and forecasted CO_2 cost and current taxes for N, P, and $PM_{2.5}$ cost (right).

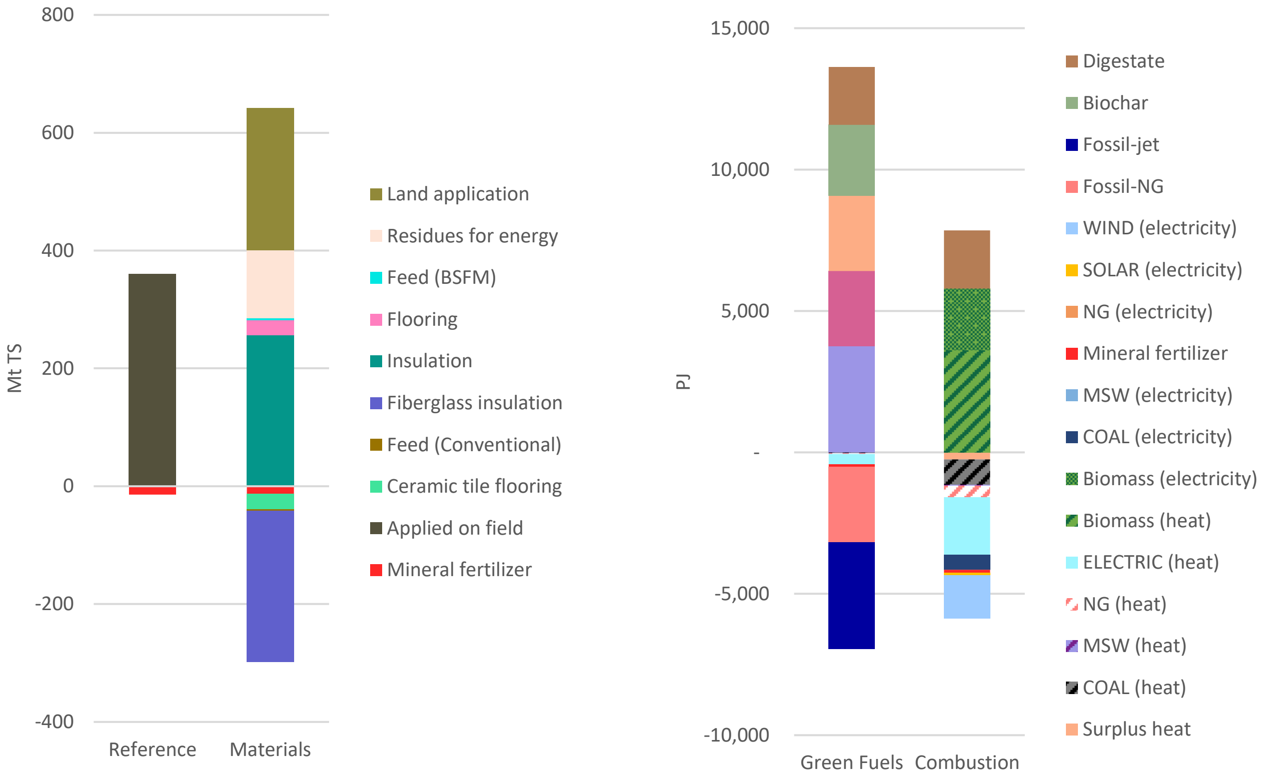

Figure S4: Produced and avoided products in the Reference and Materials scenarios (left), Green Fuels and Combustion scenarios (right).

Section 3b. Sensitivity analysis

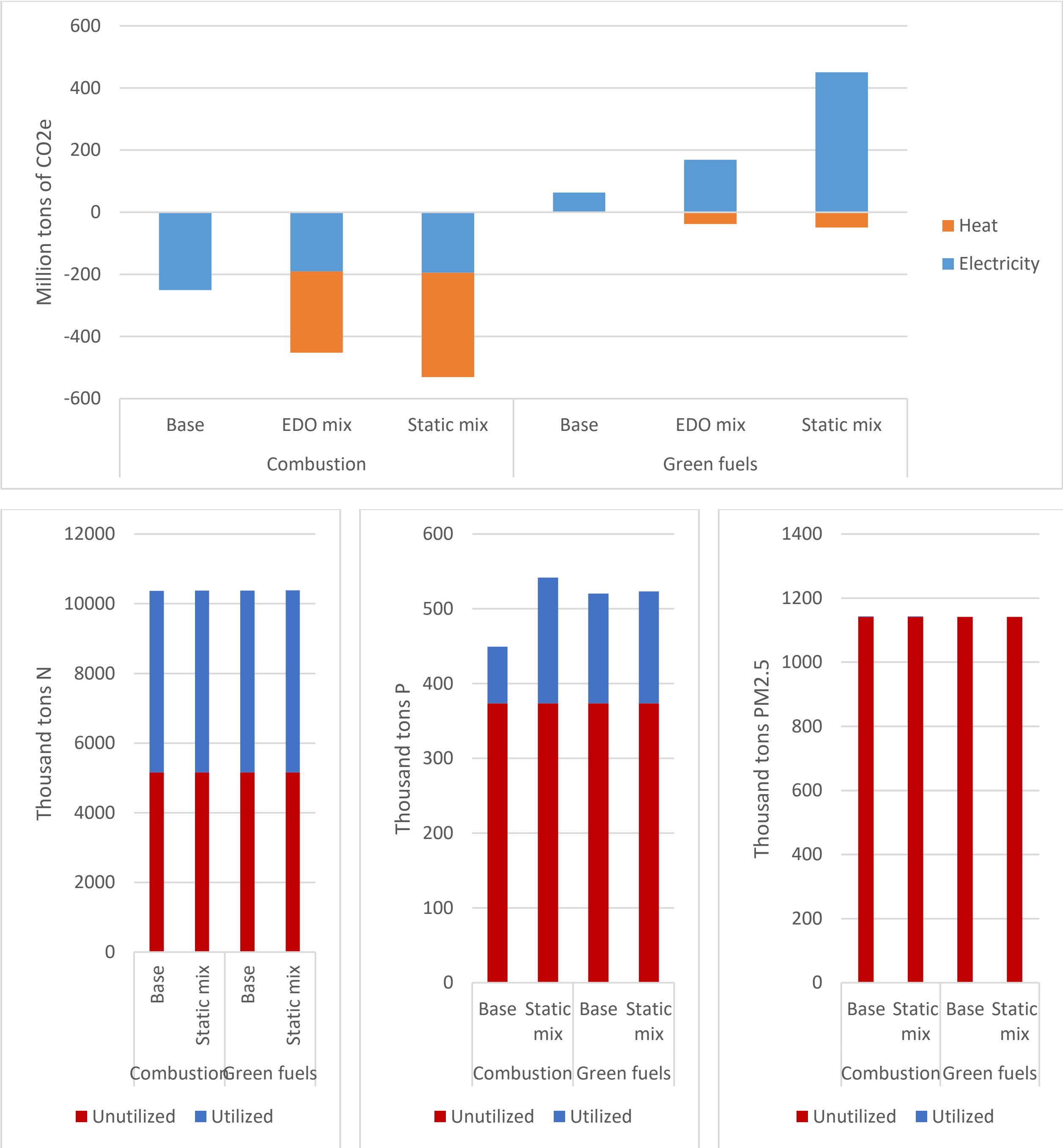

Figure S5: Environmental impacts on fossil CO_2e from avoided fuel (top) N, P, and $PM_{2.5}$ in sensitivity analysis on marginal emissions.

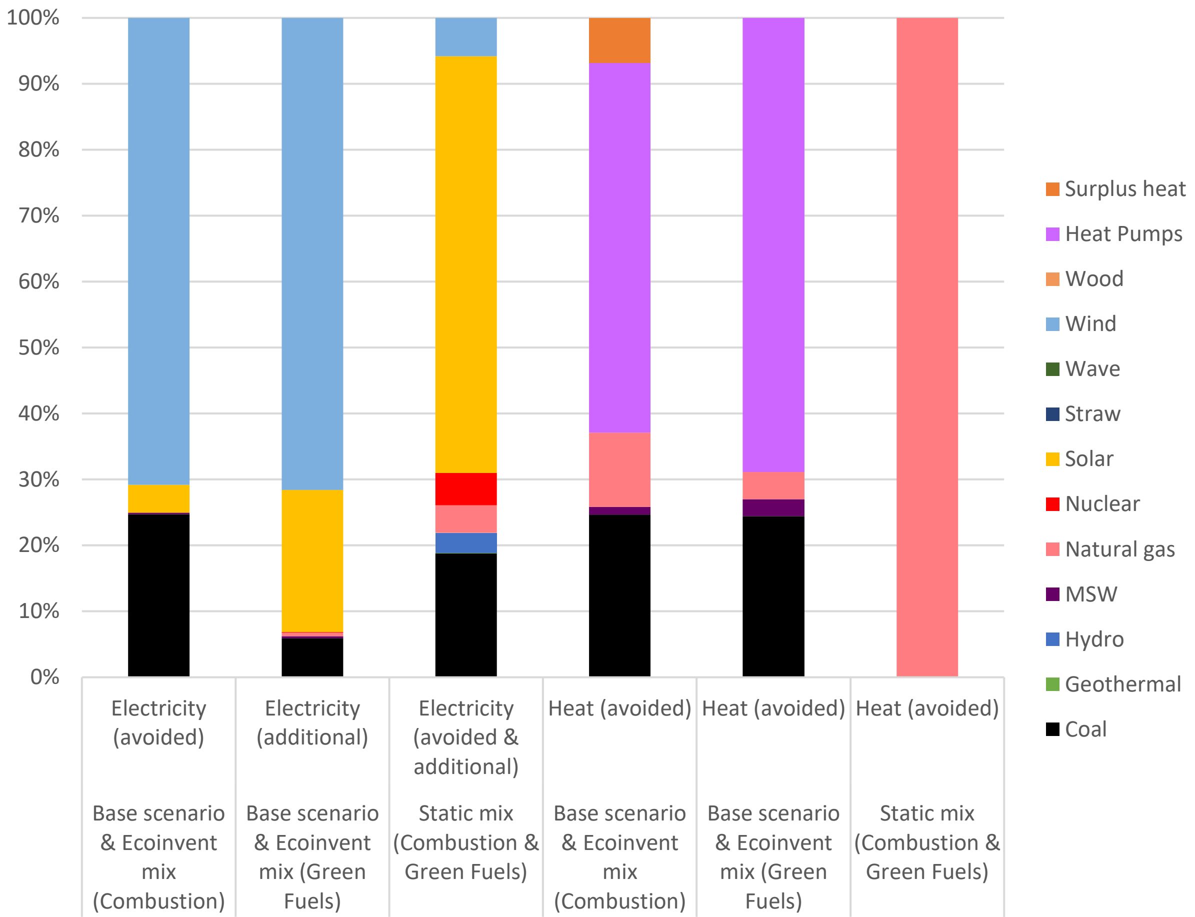

Figure S 6: Electricity and heat mixes used in sensitivity analysis by scenario and sensitivity analysis. The data for the static electricity mix is from Vandepaer et al. (Vandepaer *et al.*, 2019).

Section 3c. Specified GHG emissions by scenario

The following figures show the processes which contribute to GHG emissions. Note the difference in x-asis and legends across the scenarios.

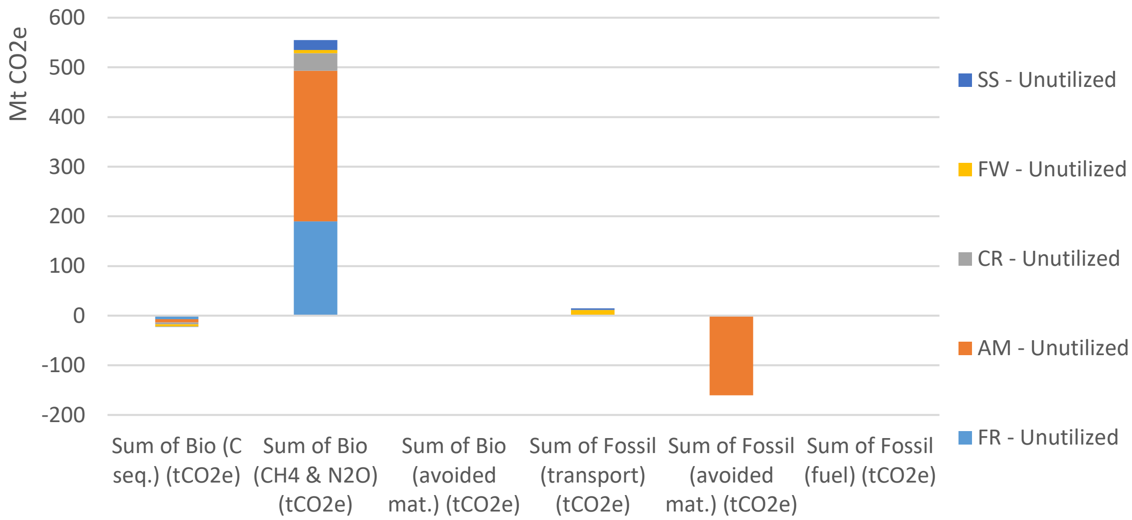

Figure S 7: GHG emissions by type and process in the Reference scenario.

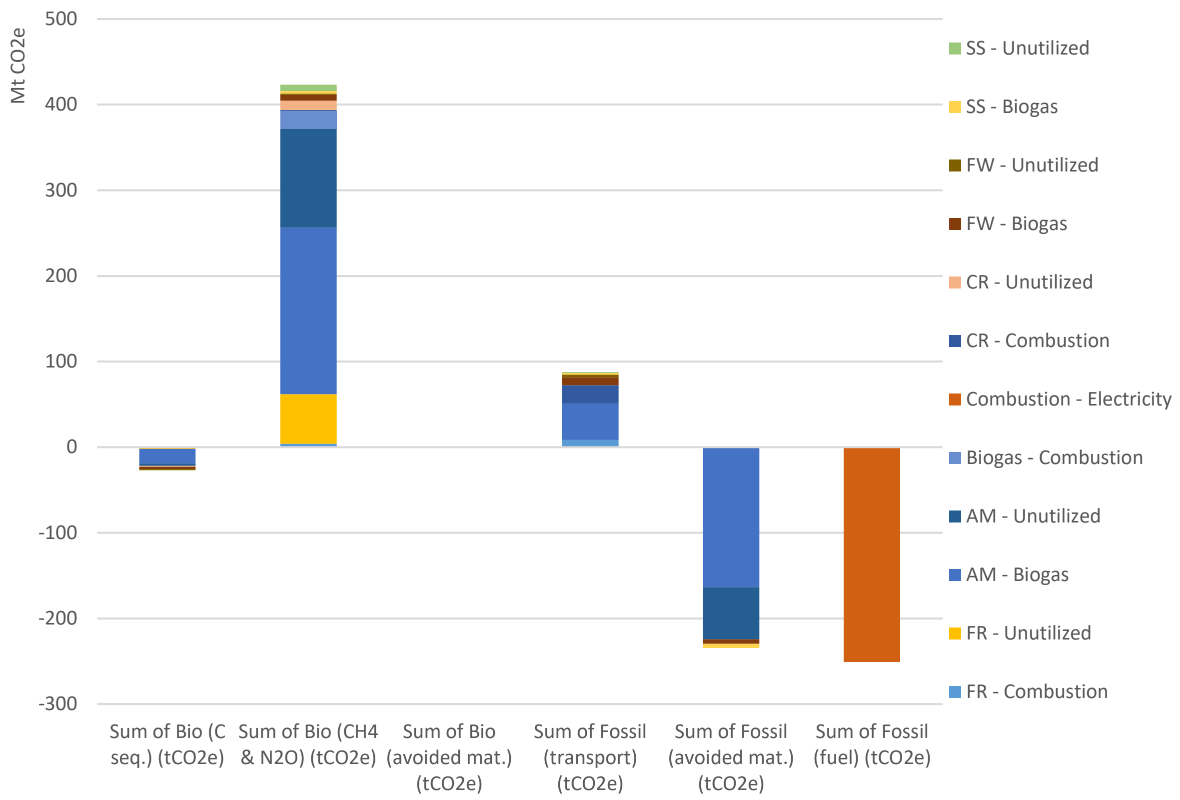

Figure S 8: GHG emissions by type and process in the Combustion scenario.

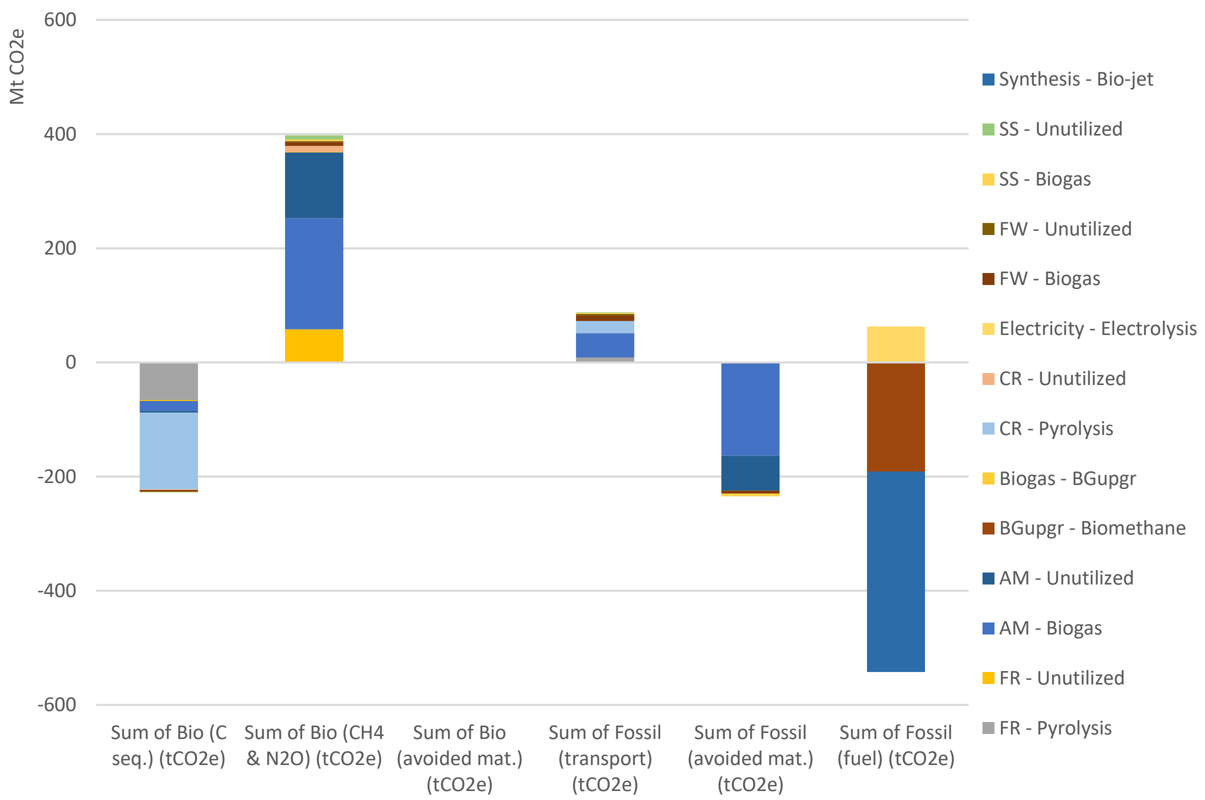

Figure S 9: GHG emissions by type and process in the Green Fuels scenario.

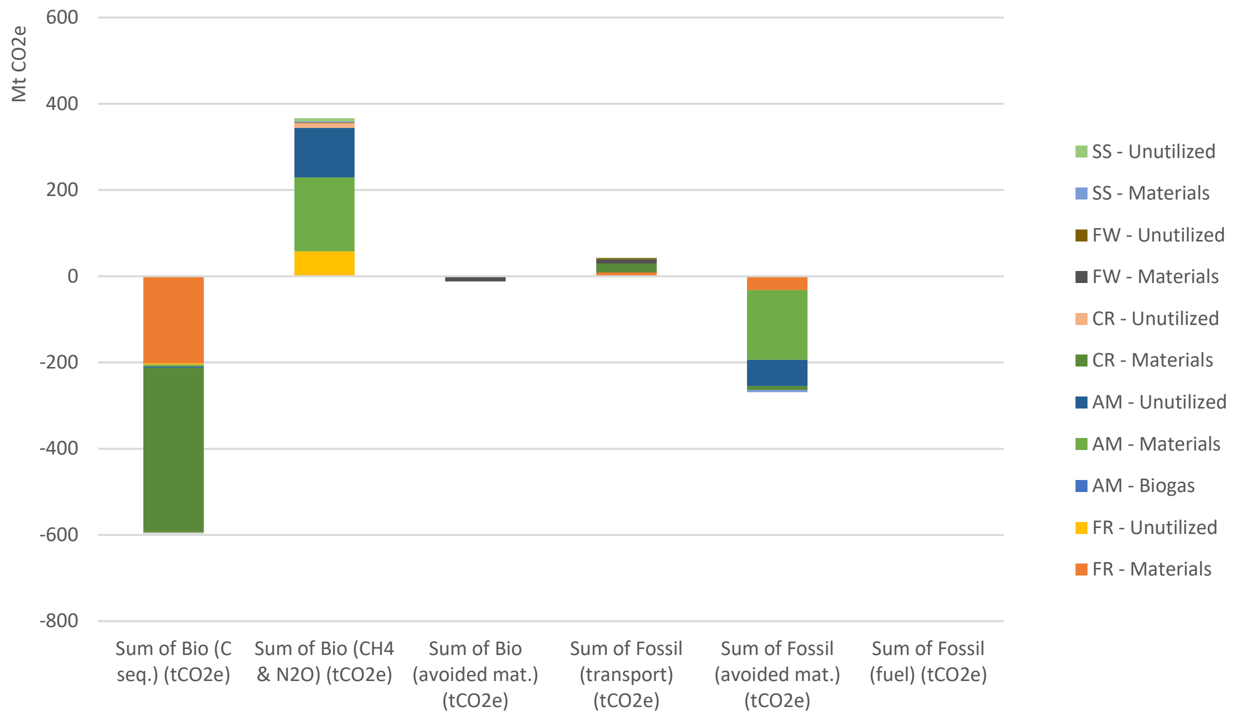

Figure S 10: GHG emissions by type and process in the Materials scenario.

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