

Life cycle assessment and techno-economic comparison of methane production routes from sewage sludge: incineration vs. hydrothermal gasification and anaerobic digestion

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Aim of this document

This document compiles all detailed calculations, methodologies, and results related to the analysis of various treatment and valorization pathways for sewage sludge. The first section provides an overview of the methods used, including the main equations of the model. The second section presents the detailed results, with focus on the Life Cycle Assessment (LCA) and the five endpoint indicators from the IMPACT World+ method.

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S1. Methods

S1.1 Complete flowsheet of the routes studied

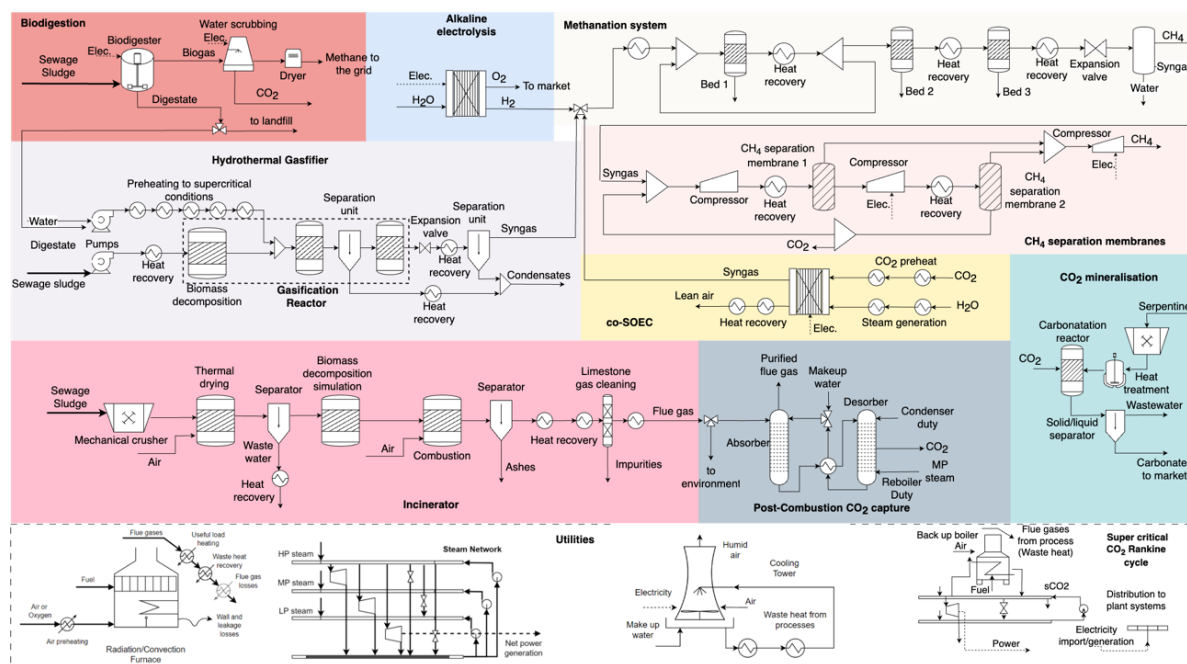


Figure 1: Integrated flowsheet of sewage sludge treatment technologies with upgrading syngas units, and CO₂ management processes, and auxiliary utility systems.

S1.2 Sewage sludge composition

The sewage sludge (Table 1) considered has a composition determined from the mean value of those reported for the proximate and ultimate analysis in the open literature for this specific type of biomass, on a wet basis [10], [13], [14], [15], [16], [17], [18], [19].

Table 1: Proximate and ultimate analysis of sewage sludge.

Proximate Analysis	Value (%)	Ultimate Analysis	Value (%)
Moisture content	79.27	C	34.84
Fixed Carbon	9.51	H	6.07
Volatile Matters	61.95	O	24.07
Ash	28.54	N	4.76
		S	1.72

S1.3 Set of equations used to model HTG reported in literature.

Table 2: Set of equations used to model HTG reported in literature.

Process	Reaction	References
WGS	$\text{CO} + \text{H}_2\text{O} \rightarrow \text{CO}_2 + \text{H}_2$ (R3)	[1], [2], [3], [4], [5], [6], [7], [8], [9], [10], [11]

SMR	$\text{CH}_4 + \text{H}_2\text{O} \rightarrow \text{CO} + 3\text{H}_2$ (R4)	[1], [2], [12], [10], [5], [7], [3], [8], [11]
Hydrogenation	$\text{CO} + 2\text{H}_2 \rightarrow \text{CH}_4 + \frac{1}{2} \text{O}_2$	[2], [6]
Boudouard	$2\text{CO} \rightarrow \text{CO}_2 + \text{C}$	[2], [10], [4], [6], [7]
Biomass decomposition	$\text{CH}_x\text{O}_y + (1-a)\text{H}_2\text{O} \rightarrow \text{CO} + (1-a + y/2) \text{H}_2$	[9], [10], [5], [8], [7]
Methanation	$2\text{H}_2 + \text{CO}_2 \rightarrow \text{CH}_4 + 2\text{H}_2\text{O}$	[6], [9], [7], [4]
Methane formation	$\text{C} + 2\text{H}_2 \rightarrow \text{CH}_4$	[7], [4]
Carbon oxidation	$\text{C} + \text{O}_2 \rightarrow \text{CO}_2$	[10], [4], [7]
Steam reforming	$\text{C}_n\text{H}_m + 2n\text{H}_2\text{O} \rightarrow (2n + m/2)\text{H}_2 + n\text{CO}_2$	[10]
Carbon monoxide combustion	$\text{C} + \text{O} \rightarrow \text{CO}$	[4]

S1.4 Calculation of Methane Yield and Carbon Conversion

The performance of the model can be established by the calculation of the total syngas yield and carbon conversion yield.

S1.4.1. Methane Yield

The total methane yield ($Yield_{\text{CH}_4}$) refers to the amount of methane produced per unit of sewage sludge processed in a specific conversion process. It is expressed in percentage, according to Equation (1), where $m_{\text{total,CH}_4}$ and $m_{\text{sewagesludge}}$ are the total methane flow rate and the mass flow rate of the sewage sludge, respectively.

$$Yield_{\text{CH}_4} = \frac{m_{\text{total, CH}_4}}{m_{\text{sewagesludge}}} \quad (1)$$

S1.4.2. Carbon Conversion Efficiency

The carbon conversion efficiency, expressed in percentage, corresponds to the total carbon (TC) in the methane produced divided by the total carbon in the sewage sludge, according to Equation (2).

$$\text{Carbon Conversion} = \frac{TC_{\text{CH}_4}}{TC_{\text{sewagesludge}}} \quad (2)$$

S1.5 Methodology for calculating the exergy and LHV of the components

The determination of exergy values for material flows is based on Szargut's reference environment for standard chemical exergy [20]. This environment defines stable and abundant reference substances, along with their concentrations, at a temperature of $T = 298.15 \text{ K}$ and a pressure $P = 101.325 \text{ kPa}$.

The chemical exergy E_{ch} of the material flows is calculated using Equation (3) [21]:

$$E_{ch} = \Delta_f G + \sum_{el} n_{el} E_{ch,el} \quad (3)$$

where E_{ch} and $E_{ch,el}$ are the standard chemical exergies, in kJ/mol, of the compound and constitutive element, respectively. n_{el} represents the molar quantity of each element in the compound, and $\Delta_f G$ is the Gibbs standard free energy of formation of the compound at ambient temperature, in kJ/mol.

Industrial solid and liquid fuels, as well as materials like biomass, are typically composed of multiple chemical compounds. The ratio of chemical exergy to the lower heating value $\phi = \frac{E_{ch}}{LHV}$ remains constant for pure substances with identical mass ratios of chemical constituents (H/C, O/C, N/C). Szargut [21] developed correlations to describe the dependence of ϕ on these atomic ratios. For methane, ϕ is equal to 1.04, whereas for biomass with C/O between 0.5 and 2, ϕ can be calculated at standard conditions (P_0, T_0) using Equation (4):

$$\phi_{dry} = \frac{1.044 + 0.0160 \left(\frac{H}{C}\right) - 0.3493 \left(\frac{O}{C}\right) \left[1 + 0.0531 \left(\frac{H}{C}\right)\right] + 0.0493 \left(\frac{N}{C}\right)}{1 - 0.4124 \left(\frac{O}{C}\right)} \quad (4)$$

The lower heating value (LHV) and specific chemical exergy (E_{ch}), both in MJ/kg, of the materials considered in this work can be found in Table 3.

Table 3: Calculated lower heating value (LHV) and specific chemical exergy (E_{ch}) for sewage sludge, digestate from sewage sludge digestion, and methane.

Materials	LHV [MJ/kg]	E_{ch} [MJ/kg]
Sewage sludge	14.62	16.52
Digestate	11.12	13.68
CH ₄	50.00	52.00

The LHV, in MJ/kg, is estimated based on Channiwala and Parikh correlations (Equation 5) for digestate and sewage sludge, based on the mass fractions of the constitutive elements [22].

$$LHV = 349.1 \cdot C + 1178.3 \cdot H + 100.5 \cdot S - 103.4 \cdot O - 15.1 \cdot N - 21.1 \cdot ASH - 0.0894 \cdot Hh_{lv} \quad (5)$$

where carbon (C), hydrogen (H), sulfur (S), oxygen (O), nitrogen (N), and ASH are the respective mass fractions of the components in the dry biomass, and h_{lv} is the enthalpy of evaporation of water at standard conditions (2,442.3 kJ/kg).

S1.6 Methodology used for carbon footprint assessment in the OSMOSE platform

The calculation of the carbon footprint is done in the OSMOSE platform, in which each energetic and material flow and each technology have associated a corresponding impact factor ($\zeta_{CO_2^+}$). The total equivalent CO_2 emissions, (CO_2^{ei}) (ei is environmental impact), including emissions from technologies construction ($\xi_{Cu}^{CO_2}$), dismantling ($\xi_{du}^{CO_2}$), and operational emissions ($CO_2^{ei,op}$), in Equation (5), are coming from the Ecoinvent database version 3.10 and

each emission factor is sized to the technologies, assuming linear equivalence. In Equation (6), (f_u^{mult}) represents the sizing factor of a unit as determined by the optimization process.

CO_2 -equivalent emissions calculated considering the direct emissions from all material flows, or resources (re) in the set (RE) ($\epsilon_{re}^{\text{CO}_2}$). Additionally, the export of resources, such as the methane produced, is represented as ($\epsilon_{se}^{\text{CO}_2}$).

$$\text{CO}_2^{ei} = \text{CO}_2^{ei,op} + \sum_{u=1}^U (\xi_{Cu}^{\text{CO}_2} + \xi_{du}^{\text{CO}_2}) f_u^{\text{mult}} \quad (5)$$

$$\text{CO}_2^{ei,op} = \sum_{t=1}^T \left(\sum_{re=1}^{RE} m_{re,t}^+ \epsilon_{re}^{\text{CO}_2} + \sum_{se=1}^{SE} m_{se,t}^- \epsilon_{se}^{\text{CO}_2} \right) \quad (6)$$

S1.7. Market costs details

Table 4: Market costs and selling prices for feedstock and products.

Material/Energy	Price	Unit	References
Electricity	0.200	€/kWh	[23]
Methane	0.070	€/kWh	[24]
Water	0.002	€/kg	[25]
Water disposal	0.002	€/kg	[25]
Limestone	0.040	€/kg	[26]
Serpentine	0.024	€/kg	[27]
Magnetite	0.030	€/kg	[27]
MgCO ₃	0.200	€/kg	[28]
SiO ₂	0.050	€/kg	[29]
NaCl	0.120	€/kg	[27]
NaHCO ₃	0.375	€/kg	[27]

S1.8. Technological costs details

Table 5: Technologies and associated costs.

Technology	Cost	Unit	References
Co-electrolysis	1200	€/kW _(elec)	[30]
Methanator	300	€/kW _(CH₄)	[31]
CH ₄ membrane	6.95	€/(kg _(CH₄) /h)	[32]
Alkaline electrolyser	1200	€/kW	[30]
Incineration gas cleaning	1300	€/(Nm ³ /h)	[33]
Water scrubbing cost	15	€/(Nm ³ /h)	[34]
Anaerobic digester	220	€/(t/h)	[35], [36]
HTG	1060	€/(t/h)	[37]
Serpentine-based CO ₂ mineralisation reactor	1355	€/(t/h)	[38]

Flue gas CO ₂ capture unit	48.7	€/ (t _(CO₂) /h)	[39]
Incineration	38	€/ (t _(waste) /h)	[40]

S2. Results

S2.1. Syngas composition and carbon conversion yield

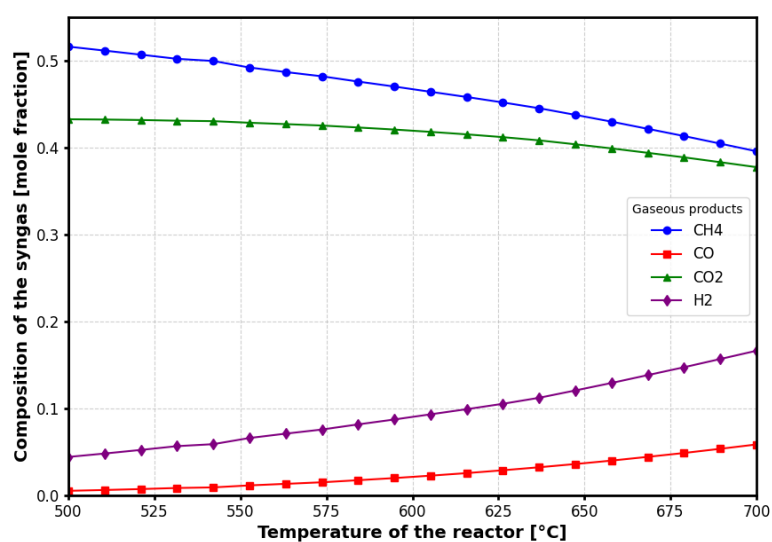


Figure 2: Syngas composition variation as a function of temperature, with a water-to-biomass ratio of 40% and at a pressure of 220 bar.

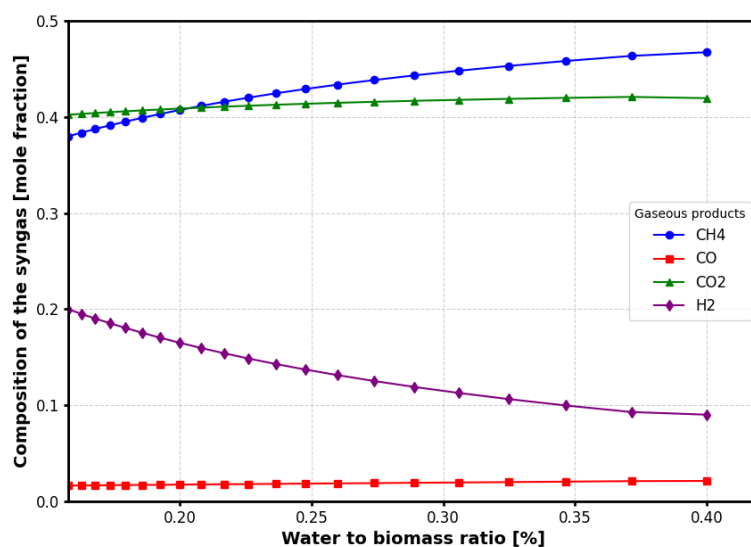


Figure 3: Syngas composition variation according to water-biomass concentration, at a temperature of 550°C and at a pressure of 220 bar.

S2.2 Control volume and exergy efficiency of the sewage sludge treatment considering the HTG

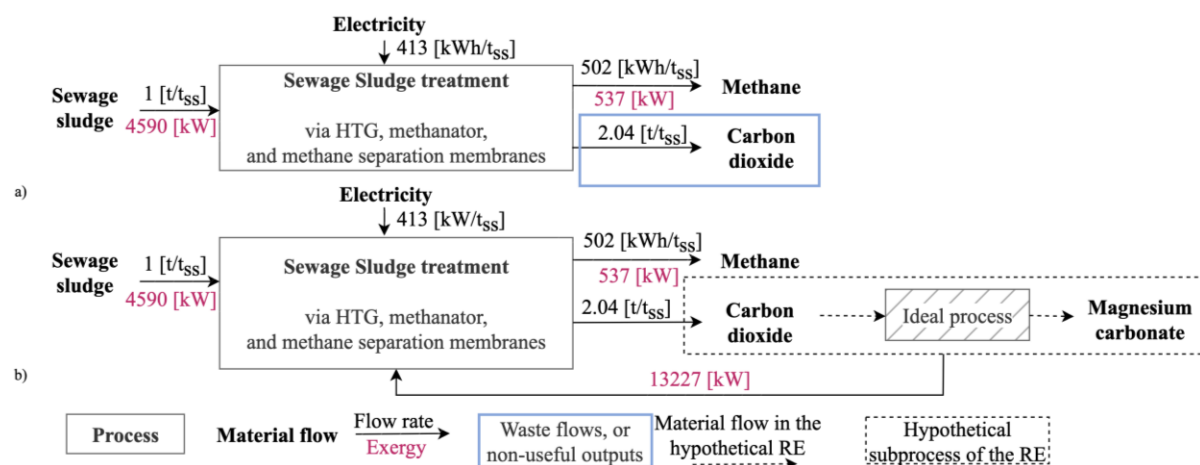


Figure 4: (a): Control volume of the sewage sludge treatment considering route (a) (HTG+methanation+membranes), and Morris and Szargut [20] reference environment (RE). (b): Control volume and exergy flows of the similar route, studied with the proposed reference environment.

S2.3. Impact scores across the five endpoint categories for the 19 routes studied

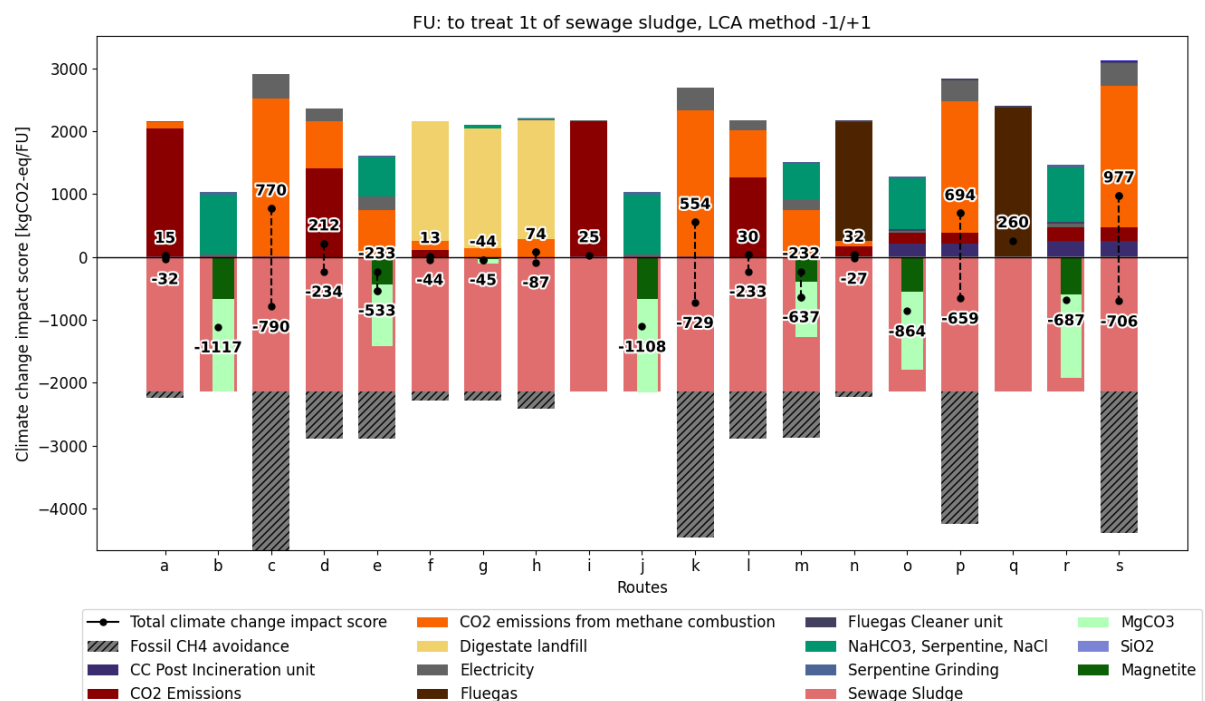


Figure 5: Carbon footprint impact score of the 19 routes studied, considering 0% and 100% methane avoidance. Routes can be found in Table 1.

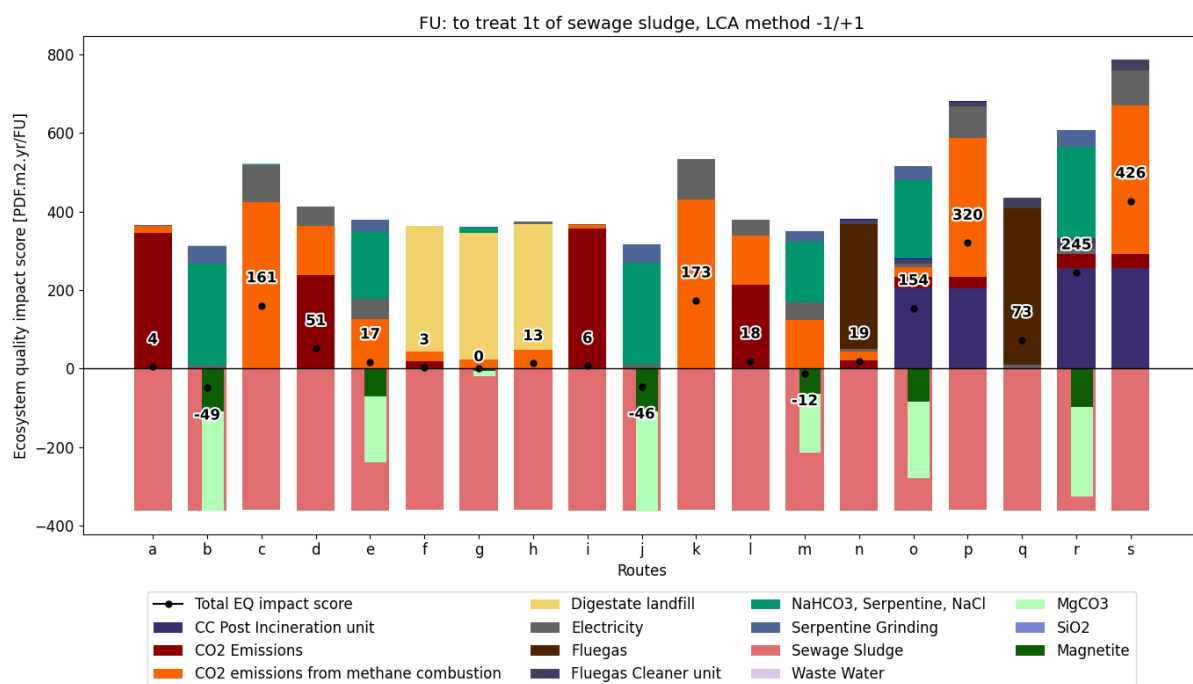


Figure 6: Ecosystem quality (EQ) impact score of the 19 routes studied. Routes can be found in Table 1.

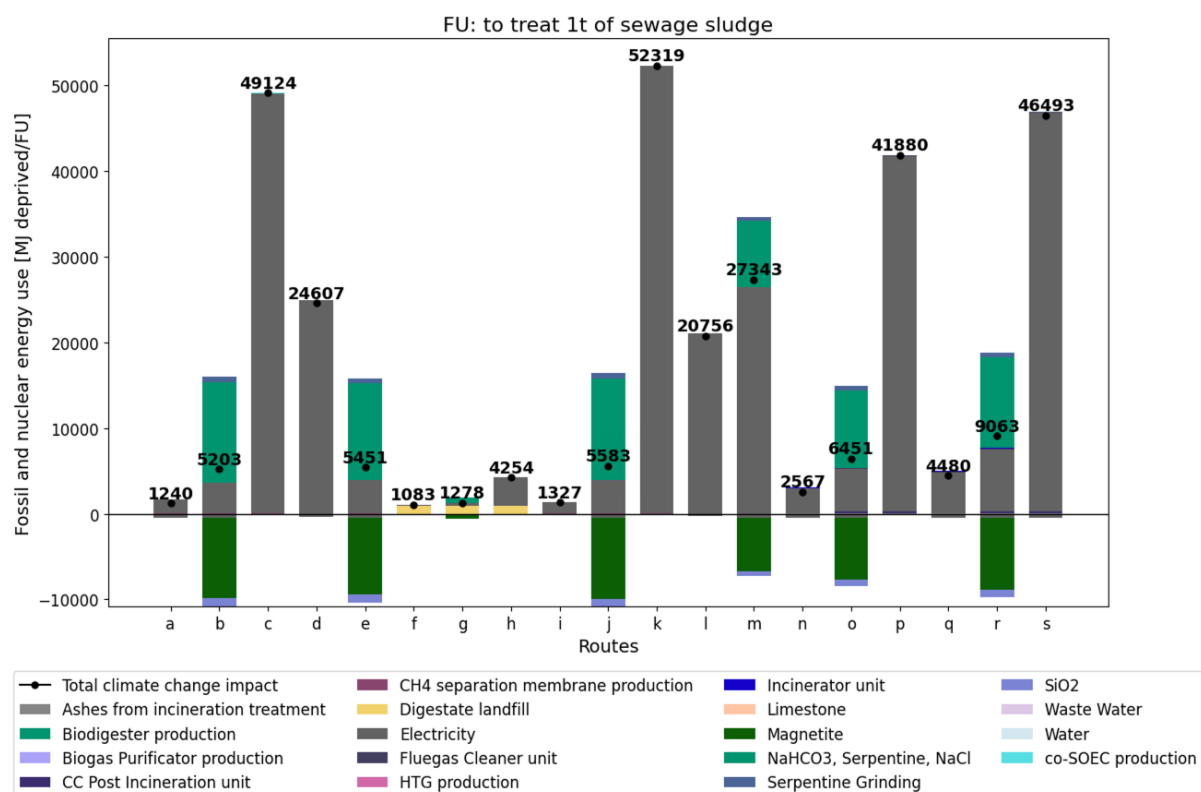


Figure 7: Fossil and nuclear energy use impact score of the 19 routes studied. Routes can be found in Table 1.

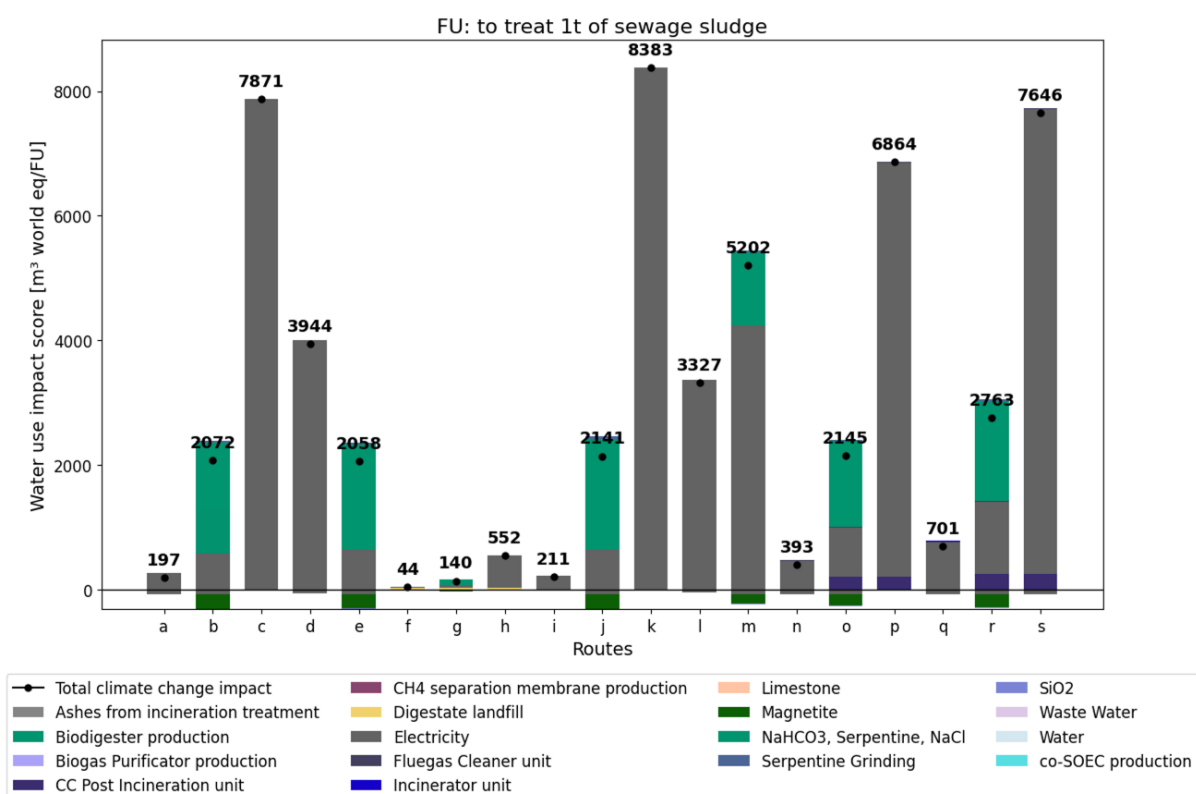


Figure 8: Water use impact score of the 19 routes studied. Routes can be found in Table 1.

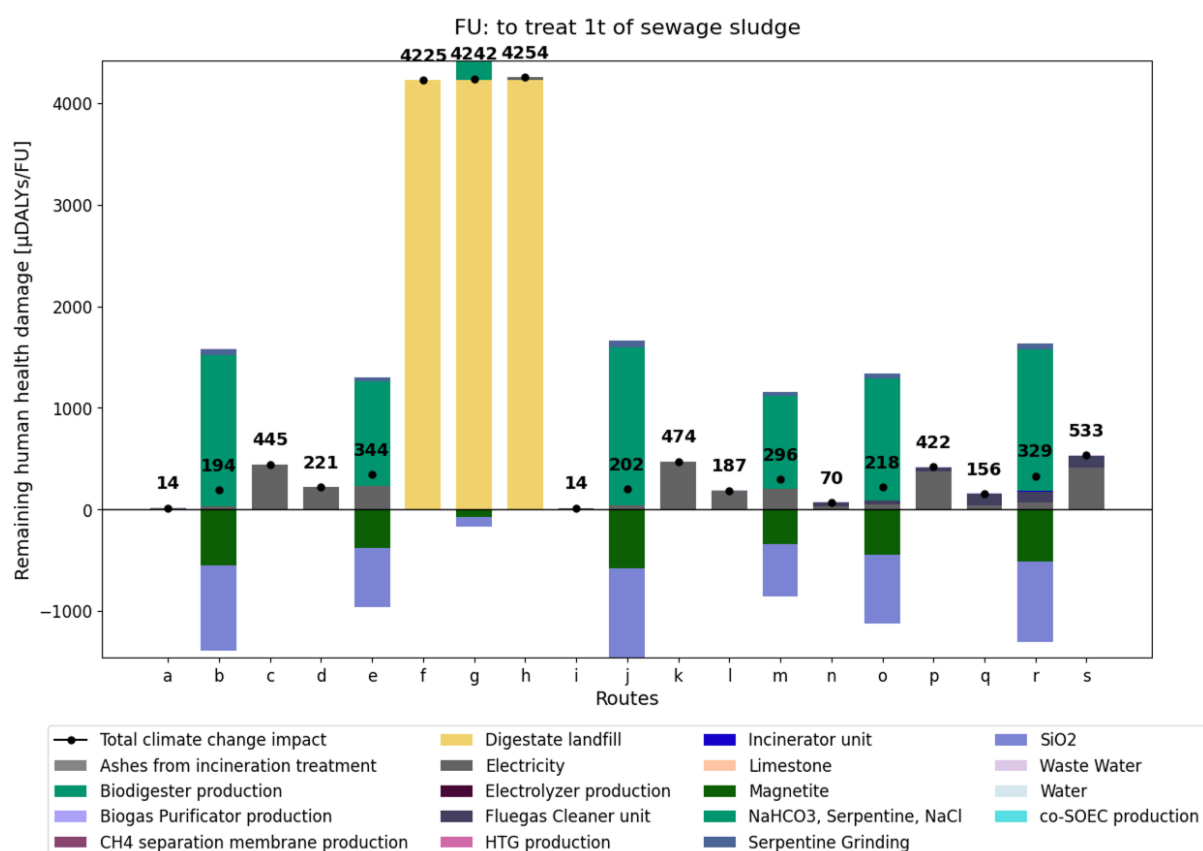


Figure 9: Human health impact score of the 19 routes studied. Routes can be found in Table 1.

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