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Reassessment of the energetic value of lignocellulosic biomass in closed carbon cycles

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ABSTRACT

Related to its energetic value, lignocellulosic biomass is typically characterized by its gross and net calorific value. However, while aiming for closed carbon cycles, this characterization does not reflect that organic matter is a carbon carrier providing “green” carbon urgently needed within a defossilized world, where material utilization of carbon for synthesizing carbon-rich materials is pursued. To address this, the assessment of biomass is expanded to include the work required to separate CO_2 from the atmosphere, which is vital for reducing carbon into biopolymers through photosynthesis. A biogenic and a technical pathway are compared to highlight the advantages of biomass utilization. The analysis reveals that relying solely on the calorific value underestimates the true energetic value of biomass in closed carbon cycles. Organic matter is predestined to be used as a carbon source to provide carbon-based materials to maximize the utilization of nature’s inherent separation and reduction capabilities. Consequently, a reassessment of the energetic value of biomass is necessary within the context of a non-fossil economy.

1. Introduction

One of the main challenges of our highly developed industrial societies is that most of the material flows within the global economy are not closed [1]. Large quantities of carbon are extracted from fossil reservoirs primarily to provide energy [2]. The resulting oxidized carbon is then released into the atmosphere as – from a human perspective – the final sink. However, nature cannot reabsorb and store this carbon dioxide (CO_2) naturally within the same time scales as humans currently release it, resulting in its accumulation within the atmosphere [3]. The consequence is that throughout the last centuries, an increasing atmospheric CO_2 level has been observed, rising from ca. 280 ppm at the beginning of the industrialization [4] to ca. 426 ppm in 2025 [5]. This accumulation has far-reaching, well-understood [2] consequences for the global climate – and thus for the whole global population – that have been widely discussed for decades [6].

To establish sustainable development pathways, closing material cycles, particularly the carbon cycle [3], is essential as our economies will continue to rely heavily on hydrocarbons in the coming decades [7]. Therefore, concepts for a (more sustainable) post-fossil society have been widely discussed for years [8], namely to capture CO_2 from the atmosphere using direct air capture (DAC) plants and subsequently reducing it to hydrocarbon molecules using hydrogen produced from water and carbon-neutral electrical energy from renewable sources. Based on such concepts, climate-neutral chemical compounds identical to those currently sourced from fossil resources can be provided [9]. Although technically feasible, such approaches are highly energy-intensive and thus relatively expensive.

Primary biomass is organic material that plants produce via photosynthesis, from sunlight, water, and CO_2 from ambient air. This biogenic matter essentially consists of organic compounds/biopolymers (i.e., molecules with carbon, hydrogen, and often oxygen) embedded within the biomass as macromolecules/molecule chains (primarily as cellulose, hemicellulose, and lignin [10]). To date, lignocellulosic biomass has been valued by its energy content, measured as the gross and the net calorific value (*GCV* and *NCV* respectively). Under the conditions given in the current economic system, this is reasonable and purposeful insofar as – if the material streams (in this case, the carbon) are not recirculated/not closed – ultimately, only the actual energy content produced during combustion/oxidation counts. The resulting emissions are released into the atmosphere and are therefore outside the scope of consideration.

In an economic system primarily based on the energetic use of fossil fuels – like in our current global economy – such fuels are also valued

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according to their gross and net calorific value. Fossil resources are extracted from the underground, used for energy provision, and the resulting combustion/oxidation products are released into the atmosphere, being – again – the final sink (i.e., no closed cycles, open system). Although this procedure is common today on a global scale and ultimately increases the carbon inventory in the atmosphere [3], this energetic evaluation based on the calorific value is reasonable and purposeful; after all, only the gross or net calorific value is the target value of this process, and the resulting energy-free waste (here: CO_2) does not count. These frame conditions also make it possible to compare it with the aforementioned lignocellulosic biomass on a fair and equal basis.

However, if a defossilized world aims to keep the carbon inventory in the atmosphere constant, the valuation of biomass/lignocellulose via the gross or net calorific value is incomplete. Such a rating only insufficiently reflects the energetic value of biomass/lignocellulose as a carbon carrier. If the overarching long-term development goal in our global economies is to close the respective material cycles, the carbon cycle must ultimately also be closed – especially to keep the carbon content within the atmosphere constant (and thus to stabilize the global climate). The consequence of this is that – if this goal is to be achieved through technical measures – CO_2 must be separated from ambient air by DAC and chemically converted into hydrocarbons or other organic chemical compounds. These organic molecules can then be converted back into CO_2 during a subsequent energetic utilization to close the carbon cycle.

Comparing this type of cycle with that of biomass, it is evident that an evaluation of biomass/lignocellulose only via the gross or net calorific value is inadequate. This is due to the following aspects:

- To build up organic materials, the plant has to separate CO_2 from the atmosphere. To do this, nature has to perform the same separation work as DAC plants. This separation work realized by each plant is ultimately included in the photosynthetic efficiency, respectively, the plant's energy efficiency. However, it is not reflected in the calorific value of the biomass, although this would be necessary if the biomass is compared fairly with a corresponding technical system to close the carbon cycle.
- The CO_2 absorbed by the plant is then subsequently chemically reduced using various biochemical processes to be converted into organic molecules/biopolymers. This chemical reduction work, which can be recovered again during oxidation of the molecules, is ultimately described by the gross and net calorific value. It characterizes the energy that the plant stores within the solid biogenic material through a partial reduction of CO_2 and H_2O and the subsequent chemical synthesis of organic molecules. A comparable technical system has to perform basically the same chemical reduction work – but most likely via a different and clearly less complex synthesis pathway.

Consequently, in a defossilized world characterized by closed carbon cycles, biomass needs to be assessed fairly compared under the discussed premises being different from today; i.e., the above-mentioned differences from a comparable technical system need to be considered. Consequently, in addition to the gross or net calorific value, taking only the chemical reduction work of the plant recoverable by a complete combustion/oxidation into account, the separation work of CO_2 from the atmosphere must be considered. A fair comparison of a biomass-based and a technically based carbon cycle is only possible under these preconditions.

2. Methodological approach

Against this background, an approach to improve the assessment of the potential role of biomass as an energy and carbon carrier in a post-fossil economy is presented below. To this end, the synthesis of organic matter by nature via the photosynthesis pathway to form lignocellulose (wood) is compared to a theoretical technological pathway to form the same chemical molecular formula (Fig. 1). The lignocellulose is approximated by an average chemical composition of $CH_{1.4}O_{0.7}$ [11] and was chosen because it represents the most widely available biogenic material.

Both pathways start with solar energy, water, and air as feedstock. In these processes, water and CO_2, separated from ambient air, are used for the production of the model biomass represented by the formula ($CH_{1.4}O_{0.7}$) with oxygen generated as a by-product. For the natural photosynthesis process, the simplified overall chemical equation (with net water balance, additional details available in the Supplementary material A) is shown in Eq. (1). In the technical pathway, the process begins by using electrolysis to separate water into hydrogen (H_2) and oxygen (O_2) (Eq. (2)). These products are subsequently used to synthesize the model molecule, as outlined in Eq. (3).

$$CO_2 + 0.7\ H_2O \rightarrow CH_{1.4}O_{0.7} + O_2 \tag{1}$$

$$2\ H_2O \rightarrow 2\ H_2 + O_2 \tag{2}$$

$$CO_2 + 2\ H_2 \rightarrow CH_{1.4}O_{0.7} + 1.3\ H_2O \tag{3}$$

First, the separation work of CO_2 from ambient air is quantified. Then, the chemical reduction work for the biological pathway is calculated and compared with a respective technical system allowing for a post-fossil hydrocarbon supply.

2.1. Separation work

The minimum theoretical energy requirement of separating CO_2 from air can be determined when the temperature and the amount of CO_2 in the air are known [12]. Generally, the process of separating a gas mixture is considered the reverse of their mixing (Eq. (4), [13]), as described by the Gibbs free energy of mixing (ΔG_{mix}). This energy can be calculated with the enthalpy of mixing (ΔH_{mix}), the temperature (T) and the entropy of mixing (ΔS_{mix}). The minimum theoretical separation energy (w_{min}) is calculated, assuming the gas components behave as ideal gases and are at uniform temperature and pressure with the environment, resulting in zero enthalpy of mixing.

Eq. (4) can be reformulated to Eq. (5) to represent the energy of mixing different gas components i, their mole number n, mole fraction in the mixture y, the mole fraction in the separated gas x and the universal gas constant R. For a pure product gas, x in Eq. (5) has to be set to $x = 1$.

$$w_{min} = -\Delta G_{mix} = -(\Delta H_{mix} - T\ \Delta S_{mix}) \tag{4}$$

$$\Delta G_{mix,ideal} = n\ R\ T \sum_{i}^{N} y_i \ln\left(\frac{y_i}{x_i}\right) \tag{5}$$

To achieve complete separation of pure CO_2 ($x_{CO_2} = 1$) from air, CO_2 must be isolated from other gases present, primarily nitrogen, oxygen, and argon. Eq. (5) is therefore reformulated into Eq. (6) [12], with y_{CO_2} as the CO_2 mole fraction within the air (or gas mixture).

$$w_{min}\left(T, y_{CO_2}\right) = -\frac{R\ T}{y_{CO_2}}\left[y_{CO_2} \ln\left(y_{CO_2}\right) + \left(1 - y_{CO_2}\right)\ln\left(1 - y_{CO_2}\right)\right] \tag{6}$$

For air with $y_{CO_2} = 426$ ppm (compare [5] 2025) the minimum work of separation $w_{min} = 21.72\ \text{kJ mol}_{CO_2}^{-1}$ ($T = 298.15$ K, $x_{CO_2} = 1$), equivalent to 493 $\text{kJ kg}_{CO_2}^{-1}$. The dependence of the minimum work of separation on the initial gas fraction is illustrated in Fig. 2.

2.2. Reduction work

The feedstock for the synthesis of organic matter by nature via the photosynthesis pathway is basically H_2O and CO_2. The plant converts

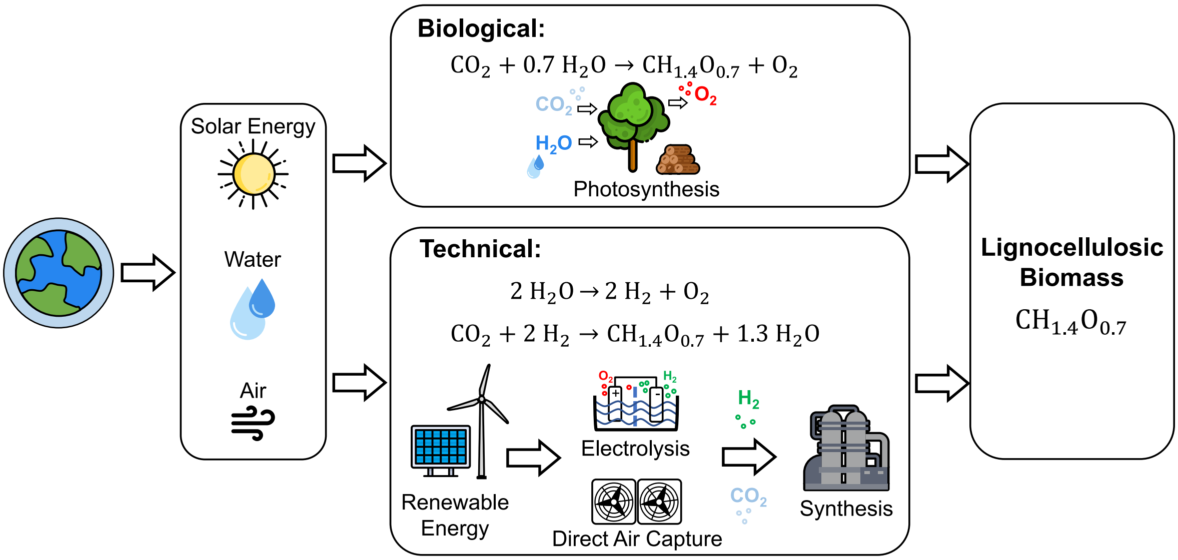

Fig. 1. Flow chart with biological and technical pathways. Solar energy, water, and air (CO_2 has to be separated from the air) are used as feedstock for the model biomass production, approximated by the average composition of lignocellulosic biomass.

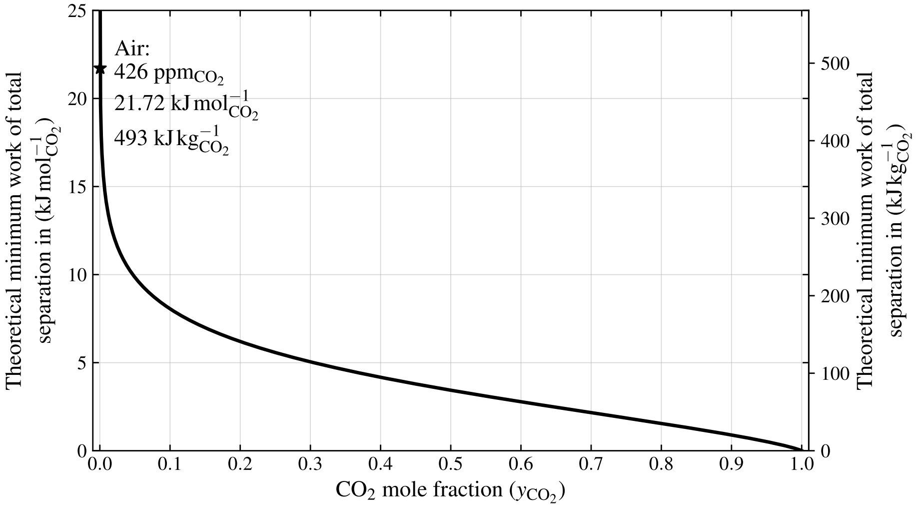

Fig. 2. Theoretical minimum energy requirement of total separation of CO_2 from a gas mixture as a function of the mole fraction y_{CO_2} in the initial gas mixture.

these educts into long-chain organic macromolecules/biopolymers (primarily cellulose, hemicellulose, and lignin in most terrestrial plants) via various intermediate stages. If lignocellulose, as the most widely available biogenic material, is approximated by an average chemical composition of $CH_{1.4}O_{0.7}$ (this roughly corresponds to the composition of wood [11]), the energy required for the necessary chemical reduction work of the educts can be derived relative to the reactants.

The reduction work following Eq. (1) can be quantified as the respective enthalpy change ΔH_r. In this case this is the gross calorific value of the approximated biomass ($CH_{1.4}O_{0.7}$).

Using the proximate estimation of Boie, the net calorific value (*NCV*) of $CH_{1.4}O_{0.7}$ is calculated (Eq. (7)) with x_C, x_H and x_O as mass fractions of carbon, hydrogen, and oxygen [11]. Subsequently, the gross calorific value (*GCV*) of the dry model biomass can be derived from the *NCV* and the hydrogen mass fraction (Eq. (8), [11]), taking into account that 2443 $kJ\,kg^{-1}$ is the latent heat of water vaporization at 25 °C and that all hydrogen is condensed in the form of water.

$$NCV = 34.8x_C + 93.9x_H - 10.8x_O \tag{7}$$

$$GCV = NCV + 24.43x_H \tag{8}$$

Thus, the reduction work of the biomass formation (model biomass $CH_{1.4}O_{0.7}$) is 18.96 $MJ\,kg^{-1}_{CH_{1.4}O_{0.7}}$ resp. 466.47 $kJ\,mol^{-1}_{CH_{1.4}O_{0.7}}$.

2.3. Technical pathway

Comparably to biomass formation through photosynthesis, the model biomass ($CH_{1.4}O_{0.7}$) or similar products can theoretically also be synthesized through modern process technologies from similar educts. This is CO_2 and H_2 provided from water splitting. Based on these educts, an exothermal reaction (Eq. (3)) can be realized. Theoretically, an endothermal reaction is also possible; however, this reaction is unlikely due to the large Gibbs free energy change and is thus not discussed here (see Supplementary material A).

For the calculation of the required energy input, the educts H_2 and CO_2 have to be provided.

- In the closed carbon cycle, CO_2 has to be separated (as in nature) from the environment, summing up to 21.72 $kJ\,mol^{-1}_{CO_2}$ resp.

$493\ \mathrm{kJ\ kg}^{-1}_{CO_2}$ for the separation from ambient air with 426 ppm (Section 2.1).
- Hydrogen can be provided by splitting water (Eq. (2)) based on electrical energy. To calculate the energetic effort, the enthalpy change of the reaction ΔH_r is calculated with standard enthalpy of formation ΔH_f (Table 1 and Eq. (9)).

$$\Delta H^0_r = \sum_{products,p} n_p \Delta H^0_{f,p} - \sum_{reactants,r} n_r \Delta H^0_{f,r} \tag{9}$$

The energy requirement is $285.8\ \mathrm{kJ\ mol}^{-1}_{H_2}$. Furthermore, ΔH_r is calculated for Eq. (3) with Eq. (9). In the exothermal reaction (Eq. (3)) $105.16\ \mathrm{kJ\ mol}^{-1}_{CH_{1.4}O_{0.7}}$ is released as heat.

3. Comparison and discussion

In this section the results of the two pathways are compared and subsequently discussed inside the system boundaries. Finally, the discussion is widened to a broader context.

3.1. Comparison

Assuming closed carbon cycles, the biogenic and the technical pathways can be compared on a fair basis because both concepts start with CO_2 removal from ambient air and provide the same organic compound ($CH_{1.4}O_{0.7}$).

- Biogenic pathway: The energetic value of lignocellulosic biomass (approximated as $CH_{1.4}O_{0.7}$) is the sum of the work of CO_2 separation ($21.72\ \mathrm{kJ\ mol}^{-1}_{CO_2}$) and the chemical reduction work ($462.80\ \mathrm{kJ\ mol}^{-1}_{CH_{1.4}O_{0.7}}$) (Eq. (1)). Both components sum up to $484.52\ \mathrm{kJ\ mol}^{-1}_{CH_{1.4}O_{0.7}}$.
- Technical pathway: The energetic efforts needed to synthesize the same organic molecule ($CH_{1.4}O_{0.7}$) technically from CO_2 (removed from ambient air) and H_2 (derived from water splitting) is the sum of CO_2 separation work ($21.72\ \mathrm{kJ\ mol}^{-1}_{CO_2}$) and the work for water splitting to provide $2\,H_2$ through water splitting ($571.60\ \mathrm{kJ\ mol}^{-1}_{CH_{1.4}O_{0.7}}$). Additionally, $108.80\ \mathrm{kJ\ mol}^{-1}_{CH_{1.4}O_{0.7}}$ is released as heat from the reaction. This sums up to $484.52\ \mathrm{kJ\ mol}^{-1}_{CH_{1.4}O_{0.7}}$ and $593.32\ \mathrm{kJ\ mol}^{-1}_{CH_{1.4}O_{0.7}}$ if the heat release is not considered.

3.2. Discussion inside system boundaries

The energy requirements for all these discussed reactions are shown in Fig. 3. Based on this graphic, the following conclusions can be drawn, considering the frame conditions and assessment boundaries defined above.

- Compared to the separation work to provide CO_2 from ambient air, the chemical reduction work to reduce CO_2 and H_2O to $CH_{1.4}O_{0.7}$ is much higher, i.e., the energy requirement for providing $CH_{1.4}O_{0.7}$ is dominated by the latter. Thus, the characterization of solid biomass (here: lignocellulose) with the gross or net calorific value describes the majority of the energy contained within the biomass, even within the system boundaries employed here.
- Related to the theoretical energy requirement, there is a small difference between the natural and the technical pathway according to Eq. (3). For the technical pathway, more energy is needed because hardly recoverable waste heat is produced.
- The comparison of both pathways shows that from a theoretical point of view related to the energetic efforts for the provision of $CH_{1.4}O_{0.7}$ keeping the discussed system boundaries in mind, there is no significant difference.

Table 1
Standard enthalpy of formation.

Compound	$\Delta H_f\ \left(\mathrm{kJ\ mol}^{-1}\right)$
$CO_2(g)$	– 393.5
$H_2O(l)$	– 285.8
$O_2(g)$	0
$H_2(g)$	0

Overall, the assessment shows that within a closed carbon cycle consideration, the value of biomass should be considered higher than its current value described solely by the gross and net calorific value. It should be regarded at least as much higher as the theoretical minimum work of CO_2 separation from ambient air. Nevertheless, this theoretical assessment also needs to be discussed within the context of the given technical constraints and the predefined borderlines of this analysis. Keeping this in mind, the following points should be mentioned:

- The influence of the CO_2 separation work, accounting for about 4 % of the total energy requirement, seems relatively small and even neglectable. However, when considering the actual effort required for DAC units and the electrolyzer technology available today instead of the theoretical values, the effect of CO_2 separation relative to the overall balance becomes apparent. So far, the energy needed for CO_2 separation is more than one order of magnitude larger (Fasihi et al. ([14]): $1535\ \mathrm{kWh\ t}^{-1}_{CO_2}$ for high-temperature aqueous solution DAC and $2000\ \mathrm{kWh\ t}^{-1}_{CO_2}$ for low-temperature solid sorbent DAC) compared to the theoretical value of $21.72\ \mathrm{kJ\ mol}^{-1}_{CO_2}$ which is $137\ \mathrm{kWh\ t}^{-1}_{CO_2}$, and currently, electrolysis efficiencies for hydrogen provision from water are at ca. $65\ \%_{GCV}$ [15]. Thus, keeping the given technical constraints in mind, the technical pathway is clearly more energy-intensive than the biomass pathway when biomass is assessed by the calorific value and the CO_2 separation work (Fig. 4).
- The "classical" assessment of biogenic material with the gross or net calorific value does not reflect the overall energy (sunlight) used by nature; of course, the build-up of organic matter by plants needs more energy as is reflected within the calorific value simply due to the fact that plants are organisms requiring energy for living [16]. But (a) solar energy is naturally abundant and available, and (b) this energy is outside the assessment boundaries defined here (and also not reflected within the gross or net calorific value typically used so far for describing the energetic value of the biomass).

3.3. Contextualization

Besides the theoretical assessment several additional critical factors influence the choice between biomass utilization and the utilization of technical alternatives in a post-fossil, circular carbon economy. These considerations extend beyond system boundaries defined strictly by energy and carbon content and address land use, resource competition, ecological impacts, socio-economic contexts, and the practical implications of deploying biomass versus technical pathways.

When biogenic material (here: lignocellulosic biomass) is available (e.g., as waste stream) its energetic value, as provided by nature, is adequately described by the gross and net calorific value because the biochemical processes underpinning biomass formation occur largely beyond human control. However, the same does not hold true for technical processes that provide chemical compounds similar to biomass. For these technical pathways, the system boundaries must be extended to include the considerable effort required to harness solar energy – such as through photovoltaic cells or wind turbines – to generate electricity for driving both water electrolysis and carbon dioxide separation from the atmosphere. Nature's work in separating and

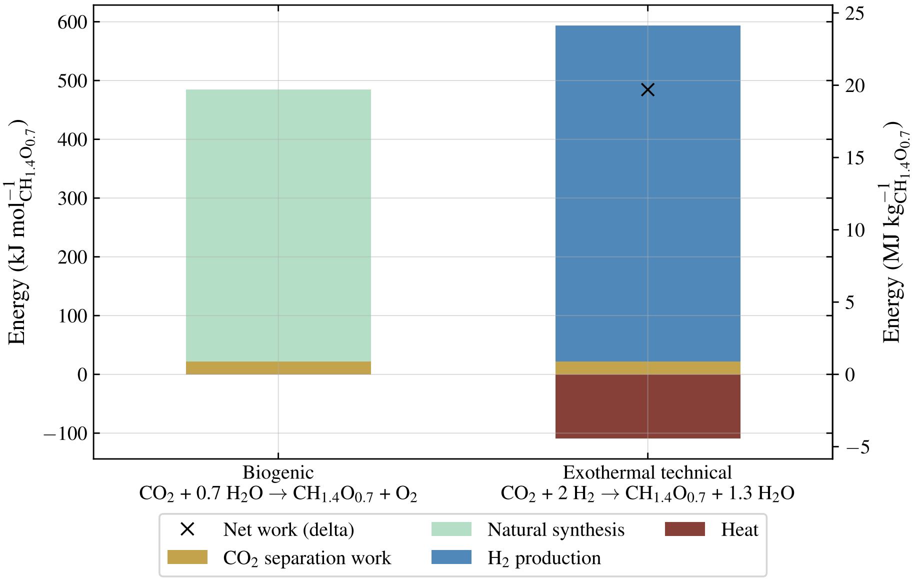

Fig. 3. Theoretical energy requirements for the generation of a molecule with the average chemical composition of lignocellulose ($CH_{1.4}O_{0.7}$) following a) the photosynthetic and b) an exothermal technical pathway.

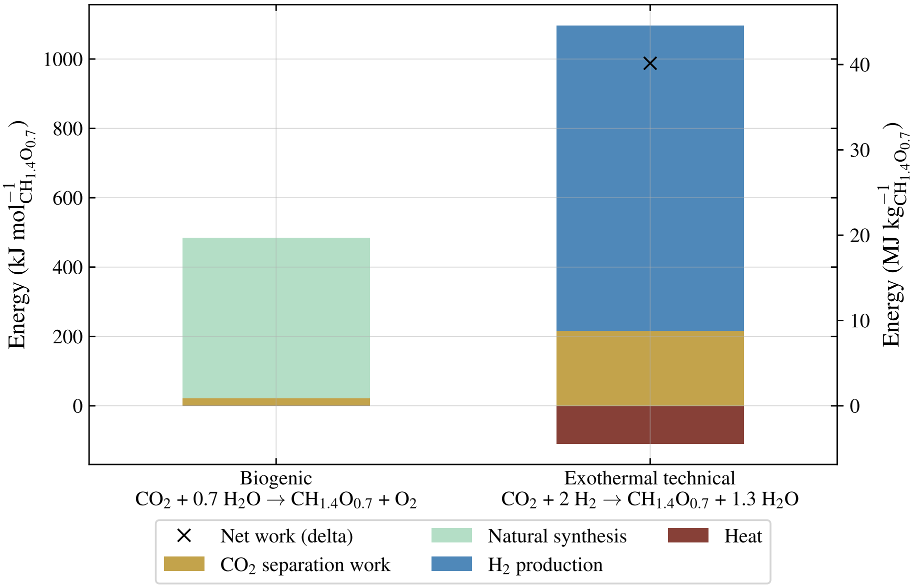

Fig. 4. Energy requirements for the generation of a molecule with the average chemical composition of lignocellulose ($CH_{1.4}O_{0.7}$) following a) the photosynthetic and b) the exothermal technical pathway. For the non-photosynthetic process, the energy requirement for the CO_2 separation and the H_2 generation via electrolytic water splitting is adjusted to represent current technological systems. (10 times the energy requirement for DAC and electrolysis efficiency of 65 % related to the gross calorific value).

reducing carbon dioxide is effectively a “gift” embedded within biomass, whereas technical systems must explicitly supply the entire energy input.

However, if the biogenic material is not readily available, land use becomes a critical factor influencing the feasibility of biomass cultivation versus constructing technical infrastructure. A rough estimation of the area required to produce the same amount of energy can be made based on empirical data for photovoltaic (PV) systems and biomass production. For instance, median energy outputs of fixed-tilt PV plants in the United States reached approximately 1.1 GWh $ha^{-1}a^{-1}$ in 2019 [17]. In contrast, high-yield biomass crops such as maize (a fast-growing C4 plant) yield net energy outputs of about 0.14 GWh $ha^{-1}a^{-1}$, with significant variability depending on species and local conditions [18]. This disparity indicates that, from an energy provision perspective, technical pathways can be multiple times more land-efficient than biomass cultivation. However, it should be noted that converting existing agricultural land to PV installations may involve land use changes with associated trade-offs.

Considering the production of the model biomass – accounting for both stored chemical energy and molecular carbon – the biological pathway still requires significantly more land due to the inherently low energetic efficiency of photosynthesis (approximately 1 to 2 % for C3 and 3 to 4 % for C4 crops under normal field conditions and only during the active phase of the vegetation period [19]). By contrast, commercial silicon photovoltaic modules reach 22 % [20] efficiency and more, while current water electrolysis (efficiency of 65% (relative to the gross calorific value) [15]) and direct air capture technologies (the fraction of the energy required for the carbon separation is significantly lower than the energy requirements for hydrogen provision (compare Fig. 4)) – although energy-intensive – are sufficiently efficient in energy utilization to match photosynthesis. The spatial footprint of synthesis and electrolysis plants is generally minor compared to photovoltaic arrays or agricultural land and can be neglected in this comparison. Besides PV, wind is expected to grow the strongest of all renewable energy technologies. It has lower land use requirements than PV if only the infrastructure area is considered, however, if the spacing is included its land-use intensity increases significantly [21].

Biomass is a limited resource (however, strictly speaking, not the biomass is limited but the available fertile land). This finite available resource is demanded from the food and fodder markets, the markets for raw materials, and the energy markets within the heat, mobility, and electricity sectors [22]. Within a defossilized world with closed carbon cycles, the demand for biomass will most likely increase considerably [23]. Thus, with a high probability, sustainably available biomass will not be able to cover the overall carbon demand even within a decarbonized world (i.e., a more electric world), considering the aforementioned competitive situation. Given the critical need to safeguard global food security and preserve biodiversity, the cultivation of dedicated energy crops on arable land is widely regarded as unsustainable and conflicts directly with food production priorities. Consequently, this study strongly advises that biomass utilization strategies prioritize organic by-products, residues, and wastes that are currently unused and occur throughout the overall provision chains from the cultivated area to the final use [24] rather than expanding land use for energy crops. Such organic side streams are a carbon source useable without major competition, minimal associated land use, avoiding the critical trade-offs of dedicated biomass cultivation for energy. And – because these materials are often declared as waste – they provide the separation and the reduction work “for free”.

In addition to land use and availability constraints, the ecological and environmental impacts of biomass cultivation warrant careful consideration. Biomass production can influence biodiversity positively or negatively depending on management practices, crop choices, and landscape context [25,26]. Unlike technical infrastructures such as photovoltaic or wind installations that additionally require material extraction and processing, biomass-growing areas inherently support living ecosystems and associated biodiversity. Nonetheless, precisely quantifying these effects necessitates detailed, site-specific life cycle assessments beyond the scope of this analysis.

Biomass also plays a key role in terrestrial carbon cycling. Woody biomass acts as a temporal carbon storage, potentially sequestering carbon for decades to centuries. In contrast, many synthetic fuels release carbon dioxide rapidly upon consumption, while some carbon-based products like plastics, may retain carbon for longer periods, adding complexity to carbon retention times. Additionally, biomass continuously exchanges carbon with the atmosphere through respiration and decomposition processes [27]. For instance, the decay of biomass components, such as fallen leaves, releases CO_2; this biological activity contributes to the characteristic seasonal fluctuations in atmospheric CO_2 concentrations, which are more pronounced in the Northern Hemisphere due to its larger landmass and higher biomass density. Consequently, biomass serves as a dynamic carbon buffer rather than a permanent sink, with true long-term carbon sinks primarily located in oceanic carbonate reservoirs [27].

These intertwined ecological and biogeochemical dynamics underscore that biomass utilization affects more than just carbon storage or energy production – it also influences ecosystems, biodiversity, and carbon cycle feedbacks. A comprehensive evaluation of these factors should be addressed in dedicated, multidisciplinary studies to guide sustainable biomass deployment within future circular carbon economies.

Large-scale technical solutions, such as integrated biomass refineries and advanced utilization chains prioritizing cascade use (from food to materials to energy), are generally feasible in more developed regions where sufficient biomass residues and robust logistics infrastructure enable biomass aggregation and processing. These approaches support efficient and sustainable biomass utilization at scale.

In contrast, communities with limited access to modern energy infrastructure often rely on low-cost, locally sourced biomass for basic energy needs like cooking and heating due to economic constraints and the lack of collection, transportation, and centralized processing infrastructure. Biomass combustion at the point of use thus remains the main, and often only, readily available energy option. Thus, biomass utilization as a carbon source rather than an energy source is less feasible for these communities. However, decentralized renewable alternatives – such as solar thermal or photovoltaic systems – may offer promising options to gradually complement or replace traditional biomass use in these contexts.

While sustainable biomass production combined with infrastructure construction could eventually support more structured biomass value chains in such areas, realizing this potential requires coordinated development efforts. Thus, although the general conclusion to value biomass as material before utilization as an energy source holds true, its practical implementation depends strongly on the socio-economic context and scale. Tailored strategies that reflect these realities are essential to advancing sustainable and efficient energy transitions in both large-scale and small-scale settings.

Generally, the commercial viability of the processing concepts benefits from economies of scale, making large-scale implementations more cost-effective if the impact of increasing average feedstock delivery costs can be offset. However, for carbon capture, containerized or modular solutions enable decentralized processing at smaller scales [28]. While larger systems tend to lower costs per unit of output, these modular approaches could help overcome logistical challenges associated with feedstock transport and localized supply [29].

Due to nature’s separation and reduction work, biogenic material has to be seen as a valuable carbon carrier able to provide carbon within a defossilized world. Therefore, using biomass as a hydrogen source while emitting CO_2 is a less promising approach. It is much more promising to provide hydrogen from water splitting and to use organic matter as a carbon source. If CO_2 is emitted the pre-concentrated stream should be utilized to have reduced separation work in comparison to DAC (compare Fig. 2). Processes that favor higher pre-concentration can be favorable (e.g., oxy-fuel combustion).

Based on these considerations and keeping the goal of closed carbon cycles in mind, the sole focus on energy efficiency, being one of the main optimization criteria today, needs to be broadened towards carbon use efficiency (i.e., carbon bound in the product compared to carbon in the input (Eq. (10)). Under these premises the already partly reduced carbon compounds contained in waste streams of biomass/organic materials should be used and further processed to contribute to an overall economy with increasingly closed carbon cycles. Such an approach is much more energy efficient compared to the reduction of the same amount of CO_2 technically requiring, first, the separation from ambient air and, second, the reduction of it.

$$\eta_C = \frac{C_{product}}{C_{feed}} \tag{10}$$

Thus, within economic systems with closed carbon cycles, biomass should be seen less as an energy source and more as a carbon source for carbon-based products. In organic matter, nature provides a solid, easily transportable, and storable carbon source containing already partly reduced carbon.

4. Conclusion

This analysis of the value of biomass advocates for a paradigm shift in valuing biomass within future post-fossil economies based on closed carbon cycles. Supposed that carbon gains economic value in the years to come, the characterization of organic matter solely via the gross and net calorific value is insufficient because it does not reflect the work nature performs to separate carbon (CO_2) from the atmosphere. Therefore, this study highlights the necessity of accounting for both the CO_2 separation and chemical reduction work (already reflected in the gross and net calorific value) that are intrinsic to biomass formation through photosynthesis, rather than solely considering its calorific value. By acknowledging the energy-intensive processes involved in replicating nature's carbon cycle through technical methods, it becomes evident that biomass holds a higher intrinsic value than is currently recognized. This re-evaluation highlights the importance of prioritizing biomass as a versatile carbon carrier over its use as an energy source, especially given the extensive energy demands associated with current-day technical pathways. Thus, economic systems striving for a closed carbon cycle should encourage biomass utilization towards synthesizing carbon-based products.

In this context, it is crucial to emphasize the hierarchy of biomass use: food production should have the highest priority, followed by the use of biomass for materials and chemicals, with energy generation as the last resort. Adhering to this priority ensures sustainable management of the limited biomass resource while minimizing competition between critical sectors.

CRediT authorship contribution statement

Wolfram G. Tuschewitzki: Writing – original draft, Visualization, Methodology, Conceptualization. **Marvin Scherzinger:** Writing – review & editing, Methodology, Conceptualization. **Martin Kaltschmitt:** Writing – review & editing, Supervision, Methodology, Conceptualization.

Declaration of generative AI and AI-assisted technologies in the writing process

During the preparation of this work the authors used ChatGPT and Grammarly in order to improve readability and language. After using this tool/service, the authors reviewed and edited the content as needed and take full responsibility for the content of the publication.

Appendix A. Supplementary data

Supplementary data to this article can be found online at https://doi.org/10.1016/j.biombioe.2025.108581.

Data availability

No data was used for the research described in the article.

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