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RESEARCH REPORT

Carbon-negative hydrogen production: Fundamentals for a techno-economic and environmental assessment of HyBECCS approaches

Johannes Full[1,2] | **Sonja Ziehn**[1] | **Marcel Geller**[1] | **Robert Miehe**[1] | **Alexander Sauer**[1,2]

[1]Fraunhofer Institute for Manufacturing Engineering and Automation IPA, Stuttgart, Germany

[2]Institute for Energy Efficiency in Production (EEP), University of Stuttgart, Stuttgart, Germany

Correspondence
Johannes Full, Fraunhofer Institute for Manufacturing Engineering and Automation IPA, 70569 Stuttgart, Germany.
Email: johannes.full@ipa.fraunhofer.de

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Abstract

In order to achieve greenhouse gas neutrality, hydrogen generated from renewable sources will play an important role. Additionally, as underlined in the Sixth Assessment Report of the Intergovernmental Panel on Climate Change (IPCC), new technologies to remove greenhouse gases from the atmosphere are required on a large scale. A novel concept for hydrogen production with net negative emissions referred to as HyBECCS (Hydrogen Bioenergy with Carbon Capture and Storage) combines these two purposes in one technological approach. The HyBECCS concept combines biohydrogen production from biomass with the capture and storage of biogenic carbon dioxide. Various technology combinations of HyBECCS processes are possible, whose ecological effects and economic viability need to be analyzed in order to provide a basis for comparison and decision-making. This paper presents fundamentals for the techno-economic and environmental evaluation of HyBECCS approaches. Transferable frameworks on system boundaries as well as emission, cost, and revenue streams are defined and specifics for the application of existing assessment methods are elaborated. In addition, peculiarities concerning the HyBECCS approach with respect to political regulatory measures and interrelationships between economics and ecology are outlined. Based on these considerations, two key performance indicators (KPIs) are established, referred to as levelized cost of carbon-negative hydrogen (LCCNH) and of negative emissions (LCNE). Both KPIs allow deciding whether a specific HyBECCS project is economically viable and allows its comparison with different hydrogen, energy provision, or negative emission technologies (NETs).

KEYWORDS

HyBECCS, carbon capture and storage, CCS, carbon capture and utilization, CCU, hydrogen, bioenergy, BECCS, DACCS, PCC, biohydrogen, carbon-negative hydrogen, green hydrogen, negative emission technologies, NET, carbon dioxide removal, CDR, bioenergy, waste to energy, waste to hydrogen, biogenic hydrogen, biogenic carbon dioxide, climate protection, greenhouse gas mitigation, GHG mitigation, climate change mitigation, renewable hydrogen, green technologies, carbon removal certificates, carbon removal certification, CRC

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1 | INTRODUCTION

On a global level, only with the combination of greenhouse gas (GHG) reductions and the fast deployment of negative emission technologies (NETs), humanity has a chance to limit global warming to 2°C or even 1.5°C, as strikingly alerted by the Intergovernmental Panel on Climate Change (IPCC) in its latest report (Masson-Delmotte, et al., 2021). The IPCC clearly states that a successful limitation of global warming to 1.5°C builds upon two pillars. One is the fast and deep reduction of anthropogenic GHG emissions from fossil fuel combustion and the destruction of natural carbon storages such as forests and wetlands, referred to as GHG mitigation or reduction. The second pillar is the active removal of carbon dioxide (CO_2) from the atmosphere through NETs (IPCC). Only with the combination of these two approaches, humanity can possibly stay on an emission pathway toward 1.5°C. This pathway reaches net-zero GHG emissions around 2050 and enters into a net-negative GHG emission zone afterward (Masson-Delmotte, et al., 2021; IPCC). All scenarios calculate with gross negative GHG emissions, implying the implementation of large-scale NETs (Honegger & Reiner, 2018a, p. 307; Poralla et al., 2021, p. 19; Rogelj et al., 2015; UNEP, 2017, p. 59; UNFCCC). Based on this global target, over 100 countries, together emitting over 50% of global GHG, have set themselves the goal of GHG neutrality or negativity to be achieved at different points in time before 2060 (Poralla et al., 2021, p. 26).

Most nations, as well as international associations, consider technological innovations as key factors to avoid GHG emissions in order to achieve their respective climate goals. In this context, hydrogen (H_2) production from renewable resources as well as the generation of negative emissions by means of bioenergy with carbon capture and storage (BECCS) are frequently listed as key technologies for this transition (Full, Trauner, et al., 2021; FCH JU, 2019; IPCC; Miehe et al., 2019; Wietschel et al., 2021). One innovative approach that combines hydrogen production with BECCS is the production of biohydrogen from biomass with capture and storage of the co-produced biogenic carbon dioxide, abbreviated to HyBECCS (Hydrogen Bioenergy with Carbon Capture and Storage) (Full, Merseberg, et al., 2021; Full, Trauner, et al., 2021). A selection from multiple technology combination options is the next step in the development of the HyBECCS approach. These options have to be comparable and evaluable in terms of ecological and economic aspects. Therefore, the research objective of this paper is to introduce fundamentals for a techno-economic and ecological assessment of HyBECCS approaches or individual HyBECCS projects based on standardized methods and indicators. It shall provide a basis for the optimization toward a more sustainable HyBECCS process design by maximizing the positive effects on the climate and economic returns. This might serve as a reference for private investors, as well as political decision makers, to evaluate HyBECCS approaches and enable targeted public subsidies and private investments. The assessment fundamentals are elaborated as summarized in Figure 1.

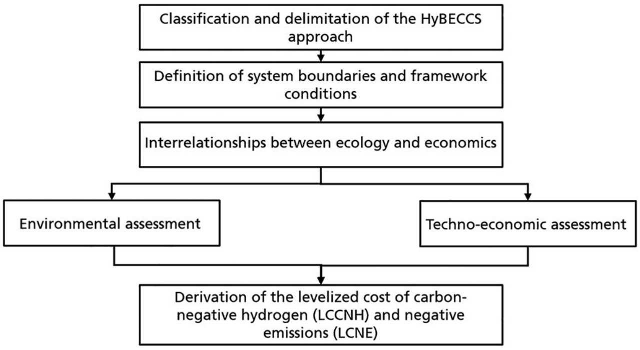

FIGURE 1 Schematic overview of the contents of the paper

First of all, a classification and delimitation of HyBECCS are essential to describe the approach in the context of negative emission technologies. Furthermore, the classification serves to ensure a consistent use of the term "HyBECCS" in further research, thus ensuring its ecological integrity. Uniform system boundaries and framework conditions are elaborated to provide a basis for standardized economic and environmental evaluation of different HyBECCS projects. Within the regulatory status quo of negative emission technologies, existing literature on BECCS and direct air carbon capture and storage (DACCS) is reviewed to identify and highlight the urgent next steps for NET implementation such as HyBECCS. Additionally, the need to develop and implement internalization mechanisms for negative emission technologies is examined. Once these steps are completed, the fundamentals for conducting an environmental and techno-economic assessment of a HyBECCS project are outlined. Based on the environmental and techno-economic assessment, two key performance indicators (KPI) are derived, namely the levelized cost of carbon-negative hydrogen (LCCNH) and the levelized cost of negative emissions (LCNE). These KPIs allow for a comparison of HyBECCS projects with different hydrogen or energy provision technologies and NETs.

2 | BASICS

2.1 | Classification and Delimitation of the HyBECCS Approach

As elaborated by Full et al. 2021, the generation of biogenic CO_2 as a by-product in most biomass to hydrogen production processes is the basis for the HyBECCS approach. This applies to both thermochemical and biotechnological technologies of biohydrogen production (Full, Merseburg, et al., 2021; Full, Trauner, et al., 2021). A simplified illustration of the approach is shown in Figure 2: On the left side, atmospheric CO_2 and water are stored via photosynthesis in biomass. In the biomass conversion plant, the biomass is converted mainly into hydrogen and biogenic CO_2. Hydrogen can be used, for example, in fuel cells to generate electricity or heat. With O_2 as educt and water as a product of the reaction, mass balance equilibrium is established for oxygen and water. Biogenic CO_2 can be stored or used in the long term, leading to negative emissions (Full, Merseburg, et al., 2021; Full, Trauner, et al., 2021). The biomass conversion plant and the carbon storage together constitute the HyBECCS project.

According to the work of Full et al. 2021, the HyBECCS approach can be split into four basic process steps: 1. substrate biomass pretreatment, 2. production of biohydrogen and biogenic CO_2, 3. separation of the product gases CO_2 and H_2, and 4. their processing for use of hydrogen and long-term storage or use of biogenic CO_2. For each of the four steps, there are different technology options to choose. The main technological advantage of the HyBECCS approach is the energy-efficient capture of biogenic CO_2 as a point source (Full, Merseburg, et al., 2021). It, furthermore, provides a double effect on climate mitigation through the provision of the emission-free energy carrier hydrogen and its potential as a CO_2 sink. The comparative advantage of HyBECCS over many other bioenergy production approaches, such as the production of hydrocarbon-based biofuels like biogas or biomethane, is that the energy carrier distributed to the end users is CO_2-free and the CO_2 emissions already occur at the plant, where they can be centrally captured (Full, Merseburg, et al., 2021). Another advantage of HyBECCS over the BECCS approach of combined heat and power (CHP) plants burning biomass is the higher flexibility and usability of hydrogen compared to electricity and heat. Hydrogen can be stored over long periods of time, transported over long distances without significant losses, and has multiple applications beyond the generation of electricity and heat (Wietschel et al., 2021) (S. 20ff). Examples are its use as auxiliary in many industrial applications and as basic material, e.g., in the urea and fertilizer production (IEA) (S. 32); (Hydrogen Council). Based on these advantages, HyBECCS is considered to be a promising and highly effective climate protection technology that is expected to play a major role in future energy systems by making a significant contribution to meeting the world's rapidly growing demand for new renewable energy sources, such as biohydrogen, and negative emissions at the same time (Coalition for Negative Emissions; FCH JU, 2019; IPCC; Wietschel et al., 2021). The approach can also be seen as part of the biological transformation process, aiming to build the economy upon sustainable, nature-based processes instead of fossil resource depletion (Full et al., 2019; Full, Baumgarten, et al., 2021; Miehe et al., 2018, 2019, 2020).

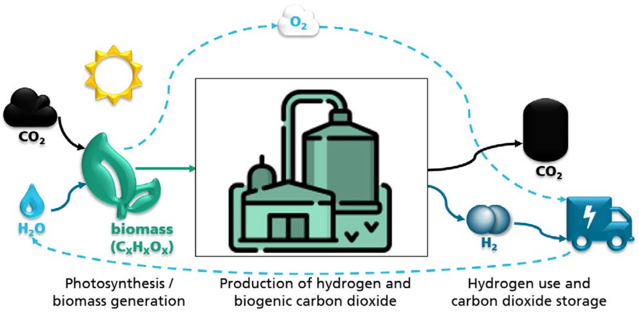

FIGURE 2 Simplified illustration of the HyBECCS approach (arrow = mass flow, dashed arrow = mass balance equilibrium)

HyBECCS can be placed in the context of existing technology clusters and definitions some of which are not yet clearly distinguished. Experts criticize the continued lack of clarity, for example, on the exact definition of NETs, carbon dioxide removal (CDR), and carbon capture and storage (CCS) (Poralla et al., 2021; Tanzer & Ramírez, 2019). To establish a consistent use of terms in the interest of the ecological integrity of HyBECCS, the following clarifications are stated. Carbon capture and storage (CCS) embraces all anthropogenic activities to capture and store carbon dioxide in the—yet to be defined—long term (IPCC). CO_2 to be stored in CCS approaches can be of any type: fossil, atmospheric or biogenic. It is, however, of utmost importance to keep in mind that CCS of fossil carbon dioxide emissions is not a NET technology and can never generate net-negative emissions. Fossil CO_2 and other GHG are emitted when burning fossil fuels or when their derivatives decompose after use. Even in the yet utopic case of a 100% carbon dioxide capture rate, the process always remains GHG positive, or carbon-neutral when not considering process emissions and other GHG than CO_2. Fossil CCS can, in the best case, only reduce the total GHG footprint of the overall process, qualifying thus merely as a so-called GHG mitigation activity or GHG reduction activity (Poralla et al., 2021). In contrast, carbon dioxide removal (CDR) and NET refer to anthropogenic activities that remove CO_2 from the atmosphere and thus lower its overall atmospheric concentration. Hence, only the CCS of atmospheric or biogenic CO_2 can qualify as CDR or NET. NETs and CDR can be grouped into nature-based approaches such as afforestation or reforestation, wetland restoration, enhanced weathering, soil carbon sequestration and accelerated mineralization, on the one hand, and technological or hybrid approaches such as DACCS and BECCS, on the other hand (Poralla et al., 2021, p. 18). Biohydrogen production technologies that enable the storage of biogenic carbon in solid form, such as biomethane pyrolysis, can also be considered as HyBECCS concepts. However, the focus of consideration in this paper is on the capture and storage of gaseous CO_2 from biohydrogen processes. According to the definitions above, all considered concepts (CCS, NET, CDR) can apply to the HyBECCS concept. It is able to remove carbon dioxide from the atmosphere and can, therefore, be considered as CDR via CCS of biogenic CO_2. This implicit condition is specified in more detail in 3.2. In addition to storage options, the biogenic carbon dioxide can also be combined with carbon utilization (CU). Carbon utilization comprises all approaches where carbon dioxide is used as feedstock or auxiliary (IPCC). In case the utilized carbon dioxide is stored over a very long period for such use, the respective CU approach can be considered as carbon storage (CS). However, the definition of how long CO_2 has to be stored in order to count as "stored" with a positive effect on global climate is still pending for CS, in general, and for long-term CU, in special. The term "CS" within "HyBECCS" comprises the long-term carbon storage as well as the long-term extraction of CO_2 from the atmosphere via carbon utilization. The following Table 1 summarizes the characteristics of the technologies and technology clusters under consideration.

Also for hydrogen, clarification is needed due to inconsistencies and imprecisions in literature. Hydrogen is often categorized in colors. In the "theory of colors" of hydrogen, grey hydrogen is extracted from fossil resources, thus releasing fossil GHG emissions and accelerating global warming. Blue hydrogen is grey hydrogen combined with CCS. Fossil CO_2 emissions from hydrogen production by steam reforming of natural gas are captured and stored in this process. Even though blue hydrogen is partly considered as low-carbon or even carbon-neutral (Bundesministerium für Bildung und Forschung - BMBF; Minli et al., 2021; Noussan et al., 2021; Yan et al., 2020), recent lifecycle assessments show that it causes as little as 9%–12% less GHG than grey hydrogen, especially due to high fugitive methane emissions (Howarth & Jacobson, 2021). Turquoise hydrogen, derived from the pyrolysis of methane and producing solid carbon, can theoretically be GHG neutral when the used electricity is entirely renewable (Newborough & Cooley, 2020). Green hydrogen is either only defined as hydrogen from water electrolysis using electricity generated with renewable energy or additionally includes biomass-based hydrogen production methods, the product being called biogenic hydrogen (Newborough & Cooley, 2020) or biohydrogen (Full, Merseburg, et al., 2021). Hydrogen from electrolysis and biohydrogen is mostly not GHG-neutral due to process GHG emissions, but can mostly be considered as low-carbon hydrogen. Despite on-going initiatives, there is no established uniform threshold of GHG intensity for hydrogen to qualify as "green" or "low-carbon" (certifhy; Hinicio; Newborough & Cooley, 2020). Therefore, hydrogen is categorized in this paper as GHG-neutral, -positive, or -negative according to its GHG balance. The prefix "GHG-" can also be replaced by "carbon-" in this context, resulting in the terms carbon-neutral, -positive, or -negative, which are, respectively, used as synonymous alternatives.

2.2 | System Boundaries and Framework Conditions

To evaluate the economic efficiency and the environmental performance of HyBECCS approaches, a uniform framework is required. Figure 3 represents the system boundaries for techno-economic and environmental assessment of HyBECCS approaches. The system boundary of HyBECCS projects (B3) is divided into two system elements, each of which can be considered separately with its own system boundary: The generation of hydrogen and biogenic CO_2 from biomass is referred to as the system element HyBECC and as system boundary B1. The storage of carbon dioxide or its long-term utilization is referred to as system element CS/CU and as system boundary B2.

In addition to the actual step of hydrogen and carbon dioxide derivation from biomass substrates, the HyBECC

TABLE 1 Summarized classification of the considered technologies and technology clusters and their respective characteristics. (Own elaboration based on AACE International (2020), Couper (2003), Kunysz (2020), Matthes et al. (2020), Towler and Sinnott (2013), Weber (2016), Zimmermann et al. (2020))

Type of CO_2	CCS	CDR/NET	GHG balance	Technology options
Fossil	✓	×	Positive	
Biogenic from non-renewable biomass (e.g. slow-growing biomass)	✓	×	Positive	
Biogenic from renewable biomass (e.g. fast-growing biomass)	✓	✓	Potentially negative	BECCS, HyBECCS
Atmospheric	✓	✓	Potentially negative	DACCS

system boundary B1 also includes the pretreatment steps of the biomass input (I) as well as gas processing of the resulting hydrogen and the captured CO_2. The CS/CU system boundary B2 includes the transport of captured CO_2 to the storage or utilization site, the storage itself and its maintenance (CS) as well as the processing of the CO_2 for utilization (CU). Both subsystem boundaries B1 and B2 can be considered individually or combined to evaluate the HyBECCS system (B3). Related costs (C), revenues (R), and emissions (E) are assigned to the two subsystem boundaries B1 and B2 and summed up in the HyBECCS system boundary B3. In general, the emission flows E1, E2, E2b, and E3 can be of different types (e.g., noise, pollutants, and greenhouse gases) and the system abstraction above can be used for the analysis of emission flows of any kind. For the present analysis, however, all emission streams only represent the respective greenhouse gas emissions. Their characteristics and interrelationships are described in more detail in the following.

The system element HyBECC (B1) causes GHG emissions (E1), for example, indirectly through the biomass generation, procurement, pretreatment, and process energy demand. Various types of costs (C1) are incurred, such as capital and operating expenditures. Revenues of the HyBECC system element are generated by the sales of hydrogen (R1a) and of biogenic carbon dioxide (R1b), summed up in R1. In addition to the production of hydrogen and biogenic CO_2, fermentation digestates or residues (D) are produced as by-products. Depending on the composition of these residues, either further revenues can be generated by selling them, e.g., as fertilizer, or costs that can incur for their disposal. Therefore, they can either be included in the costs C1 or the revenues R1. The same applies for the purchase of the biomass input (I), which can either generate costs or an income, the latter in case of waste or residues for which disposal fees incur (Thrän & Pfeiffer, 2013). It should be noted that using residual and waste biomass for biohydrogen production, the long-term storage of the carbon bound in the digestates can lead to further negative emissions. This is the case if, for example, the residual is used as agricultural fertilizer and a substantial amount of the carbon in the digestate remains in the soil (Antonini et al., 2020). This effect would be taken into account within B1, where it would be included negatively in the total of E1.

System boundary B2 covers the CS/CU system element. The emissions in subsystem B2 contain the process emissions of the CS/CU process (E2b) and the amount of biogenic CO_2 permanently stored or used, being the gross negative GHG emissions (E2a). Since the amount of biogenic CO_2 permanently stored or used has been removed from the atmosphere during the biomass growth via photosynthesis, negative emissions can be generated (Kemper, 2015). E2a enters the emissions balance as a negative value and is fundamental for HyBECCS approaches to achieve an overall negative GHG balance. It must be noted that the physical amount of negative GHG emissions (E2a) actually stored is not necessarily equal to the amount of biogenic CO_2, which is transferred from balance boundary B1 to B2. This difference is due to potential leakages (L) in the system B2 which can occur during the transport to the storage site or the storage itself. Revenues (R2) accrue when being recompensated through incentives for generating negative emissions. It is important to keep in mind that, in the case of CS, the subsystem B2 does not generate any other income than the compensation for negative emissions. The costs (E2) are composed of the capital and the operational expenditures including the purchase price for biogenic CO_2 produced within B1 (C2b) as well as all other costs for the carbon storage or utilization process (C2a). The material flow of biogenic CO_2 leaving the HyBECC system boundary B1 corresponds to the material flow of biogenic CO_2 entering the CS/CU system boundary B2 as feedstock for negative emission generation. From the perspective of system boundary B1, the biogenic CO_2 generates a revenue flow (R1b) from its sale, whereas, for B2, the same biogenic CO_2 material flow generates costs (C2b) for its purchase. For CU approaches, revenues depend on the respective product. Summarized, the total costs of the HyBECCS approach (C3) incurred within the system boundary B3 can then be calculated according to Equation 1.

$$C3 = C1 + C2 = C1 + C2a + C2b \tag{1}$$

The total profit P3 achieved through HyBECCS can be calculated according to Equation 2. It is summed up from the revenues generated by the sales of hydrogen R1a, of the biogenic carbon dioxide R1b, and of the negative emissions or long-term carbon dioxide utilization R2, which together give the overall revenues for biohydrogen production and negative emissions R3, minus the total costs C3. In the case of separate operation of the system elements HyBECC and CS/CU, the respective profit can also be calculated within the subordinate system boundary B1 and B2. The profit for the production of hydrogen and biogenic CO_2 (P1) is then considered independently of the profit from the storage or long-term use of the biogenic CO_2 (P2).

$$\begin{aligned} \text{P3} &= \text{P1} + \text{P2} = \text{R1} - \text{C1} + \text{R2} - \text{C2} \\ &= \text{R1a} + \text{R1b} - \text{C1} + \text{R2} - \text{C2a} - \text{C2b} = \text{R3} - \text{C3} \end{aligned} \tag{2}$$

To assess the environmental impact of HyBECCS, all emissions of the system boundary B3 have to be considered. As explained above, this paper focuses on the

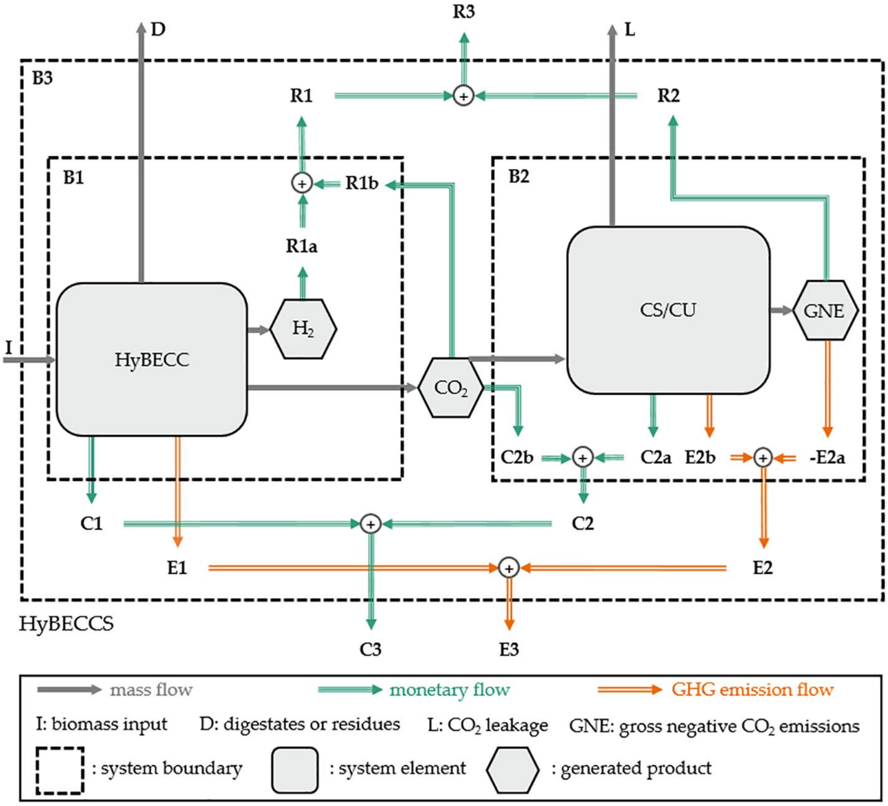

FIGURE 3 System boundaries (B) for HyBECCS approaches with mass flows for biomass input (I), hydrogen (H2), carbon dioxide (CO2), stored carbon dioxide referred to as gross negative emissions (GNE), residues or digestate from biohydrogen production (D) and carbon dioxide leakages (L), monetary flows divided into costs (C), revenues (R), and emission flows (E)

TABLE 2 Framework conditions (FC) for HyBECCS approaches and projects

N°	Framework condition (FC)	Consequence
FC1	$E3 < 0$	HyBECCS project = Negative Emission Technology (NET) project and Biohydrogen = Carbon-Negative Hydrogen (CNH) and permission to issue carbon removal certificates (CRC)
FC2	$P3 > 0$	HyBECCS project is economically viable

impact on the global climate of HyBECCS approaches. For this purpose, only positive and negative (stored) GHG emissions are to be balanced. The sum of all GHG emissions within B3 can be considered as its greenhouse gas footprint, which can be calculated according to Equation 3.

$$E3 = E1 + E2 = E1 - E2a + E2b \tag{3}$$

In case, the greenhouse gas footprint of a specific HyBECCS project (E3) is negative, it actually generates net negative GHG emissions and thus qualifies as a NET project. The co-generated hydrogen can then be considered carbon-negative hydrogen (CNH).

The definitions and framework conditions (FC) summarized in Table 2 are established as described above and apply to all HyBECCS projects:

This means that only HyBECCS projects that fulfill the first framework condition (FC1) above ($E3 < 0$) are NET and CDR and its produced biohydrogen is allowed to be qualified as CNH. Furthermore, only in case the total profit is positive ($P3 > 0$), the HyBECCS project is economically viable as the second framework condition (FC2) states.

2.3 | Regulatory Status Quo of NETs

All emission pathways to limit global warming to 2°C or even 1.5°C calculate with gross-negative GHG emissions, and thus CDR, from 2030 on (Honegger & Reiner, 2018a; Poralla et al., 2021; Rogelj et al., 2015; UNEP, 2017). The CDR amount needed to reach global climate goals is estimated to be 5–20 $GtCO_2$ per year, summing up to 444–1000 $GtCO_2$ until 2100 (Boysen; Honegger & Reiner, 2018b; Poralla et al., 2021). With each lost year that CDR is not implemented on a large scale, the challenge of sufficient adoption of these technologies increases (Poralla et al., 2021, p. 19). However, the scientific evidence and urgency of NET implementation are not reflected in reality: Globally, government policies and private sector initiatives supporting NETs are very sparse to date (Jeffery et al., 2020, p. 9f). The few governmental or private ambitions focus on biological CDR approaches such as afforestation and reforestation. NETs like DACCS and BECCS are supported by single countries such as Sweden, some public funds, and very few private entities. Poralla et al. (2021) provide a good overview on the supportive instruments existing worldwide. Emerging voluntary markets for CDR credits also primarily focus on biological storages (Jeffery et al., 2020, p. 9f; Poralla et al., 2021, p. 31). Incentives to mobilize technological approaches linked with permanent underground storage, such as BECCS and DACCS, are widely missing. As the contribution to GHG mitigation, an external benefit of NETs, does not generate revenues by itself and thus does not translate into an economic advantage for the operator, the externalities of GHG mitigation and emission must be internalized (Mankiw, 2001, p. 172). One option is the internalization of the external costs caused by GHG emissions by carbon pricing mechanisms. However, the internalization approach with result-based crediting of the actual negative emissions achieved is only one option of financial NET support and primarily adequate for mature NETs (Poralla et al., 2021, p. 23). Even though the technology readiness level of BECCS is relatively high with 6–9 for bioenergy processes and 4–7 for CCS, there are only single large-scale BECCS plants in operation (Poralla et al., 2021, p. 17). At the current stage of BECCS implementation, technology selection, learning curves, scale-up, and cost reduction promise significant efficiency gains. For the current development stage of NETs, subsidies for research, design, development, and demonstration (RDD&D) are thus more appropriate and urgently needed (Honegger, 2020). Besides direct subsidies, further instruments to speed up the NET implementation range from tax credits, concessional loans, grants to feed-in tariffs, all instruments successfully applied for the deployment of renewable energies around the world (Poralla et al., 2021, p. 23). Furthermore, existing barriers that hinder the implementation of CDR, such as the regulatory uncertainty on the export of CO_2 for geological storage, or on the geological storage itself, have to be abolished (Poralla et al., 2021, p. 31). There will be no NET activities without external incentives due to the special economics of these approaches. This is especially true—and unfortunate from a climate protection perspective—for HyBECCS as it has multiple benefits for the global climate, not only actively removing CO_2 from the atmosphere, but at the same time mitigating fossil GHG emissions by generating biohydrogen, potentially pushing fossil alternatives from the market. The special economics of HyBECCS and how to solve the dependency between the political framework, its economics, and climatic impact, will be discussed in the following subsection.

2.4 | Interrelationships between Ecology and Economics

The economic and ecological, especially climatic benefits of HyBECCS approaches can be best explained by looking at the two main products of HyBECCS: biohydrogen and negative emissions. On the one hand, the generation of hydrogen from biomass provides the valuable energy carrier hydrogen at a low GHG footprint and is carbon neutral when only considering the biomass conversion. The reason for this is that the CO_2 emitted during the biomass conversion equals the amount of CO_2 removed from the atmosphere during the growth of the biomass (Singh & Rathore, 2017). GHG emissions of HyBECCS processes are thus limited to process emissions from the hydrogen production process (incl. biomass generation) (E1) and CCS (E2b). Compared to fossil energy carriers, the use of biohydrogen avoids fossil GHG emissions from fossil fuel generation and its combustion or the decomposition of its derivatives after utilization. This contribution to GHG mitigation is the first external benefit of HyBECCS, as depicted as white box in Figure 4. It does not generate revenues by itself and thus does not translate into an economic advantage for the operator. Without external intervention, the GHG reduction would not entail any financial added value. Ideally following the so-called “polluter pays principle,” the external costs caused by GHG emissions are internalized. Common approaches are cap-and-trade systems such as the EU-ETS, where GHG-emitting installations have to purchase emission allowances, or carbon taxes, potentially complemented by baseline-and-credit mechanisms such as the Clean Development Mechanism (CDM) (European Commission). If applied sufficiently, this translates into a comparative price advantage for biohydrogen in case it causes less GHG emissions and thus has lower GHG internalization costs to bear than fossil alternatives, as depicted as grey boxes in Figure 4. It is important to mention that the GHG emissions of all technologies, even if considered as low- or zero-emission technologies, should be included in such GHG internalization mechanisms to allow the comparison of the social costs of HyBECCS products with alternatives for energy or hydrogen provision. The negative CO_2 emissions depicted as green box in Figure 4 constitute the second external benefit of HyBECCS. The generation of negative emissions is linked with costs for CO_2 capture, transportation, and storage (cf. Equation 1). CCS cost estimations in the

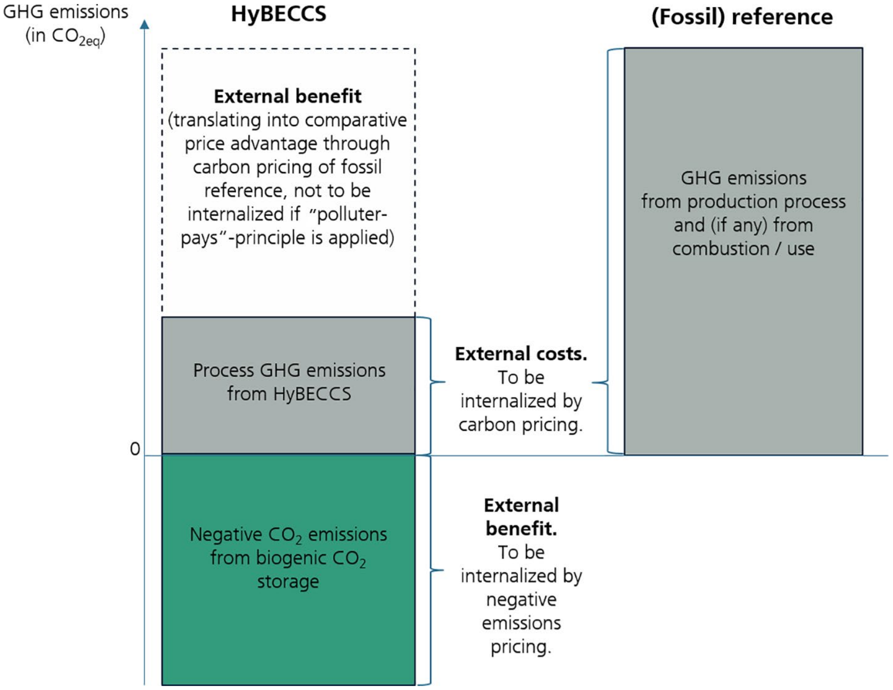

FIGURE 4 External benefits of HyBECCS compared to a (fossil) reference. green bar = negative emissions; grey bar = process emissions; dashed white bar = difference of process emissions resulting in external benefit (Not to scale)

literature vary broadly and depend, beyond others, on the CO_2 concentration at source, plant scale, transportation mode, the distance to the storage site, and the type of storage (Agora Energiewende und Wuppertal Institut, 2019; Poralla et al., 2021; Trippe, 2013). These costs are—from the operator's perspective—not (over)compensated by any income. The external benefit of the negative emissions for global climate must thus be internalized to make them happen.

High concentration and purity of the CO_2 to be captured using HyBECCS approaches compared to direct air capture (DAC) or post-combustion capture (PCC) as well as the emission-free use of hydrogen resulting in a higher possible CO_2 capture rate compared to hydrocarbon-based biofuels generated with other BECCS technologies are further advantages of the HyBECCS approach. They reduce the total energy demand and increase the CO_2 yield (Full, Merseburg, et al., 2021, p. 15; Singh & Rathore, 2017). However, these advantages translate into lower production costs—and comparative advantages of HyBECCS over other NETs. They thus do not have to be internalized. The production of hydrogen as a marketable product likewise constitutes a direct economic advantage of HyBECCS over other NETs, who often lack any revenue other than from negative emissions. This reduces the external financial need of HyBECCS approaches or increases the possible profit margin, making it a highly valuable model for both efficient GHG mitigation and removal in the pursuit of the 1.5°C goal. The example of HyBECCS and its externalities—a typical case of market failure in political economics (Mankiw, 2001, p. 172)—proves the urgency of developing and implementing internalization mechanisms for negative emissions and of sharpening existing instruments for GHG reduction.

3 | FUNDAMENTALS AND GUIDELINES FOR ENVIRONMENTAL ASSESSMENT

Over the last decades, the increasing awareness of the negative impact of human activities on the environment and the regulatory adoption of environmental awareness gave birth to many ecological guidelines and standards. They range from macro-level approaches such as national GHG inventories over meso-level analysis like environmental assessments to micro-level assessments addressing products or services (DIN e.V. DIN EN ISO 14040, 2021, p. 8; Frischknecht, p. 17; Hauschild et al., 2018; Kaltschmitt & Schebek, 2015; Klöpffer & Grahl, 2009). HyBECCS projects can have multiple impacts on the environment, such as acidification and eutrophication or the depletion of the ozone layer and abiotic resources. They depend on the feedstock used, the distances and mode of transportation of biomass and products as well as the chosen conversion technology (Fajardy et al., 2019). All those impacts have to be evaluated in an environmental assessment (EA). The EA has to follow the local legislation or, if not existent or insufficient, best international practice, always aiming to minimize negative impacts. However, the key of HyBECCS in climate protection lies in its ability to deliver biohydrogen and negative emissions. Any HyBECCS approach or project can only contribute as NET in case it actually has a negative GHG balance, which means that it actually removes more CO_2 from the atmosphere than it emits GHG. In such a case, the co-generated hydrogen can be considered as CNH as per framework condition FC1 above. The focus herein is to develop a guideline to assess the ability of a HyBECCS project to deliver negative emissions and to produce CNH. Even though all environmental impacts are equally important, they are not included in the further assessment, as established evaluation methods already exist. The following fundamentals for environmental assessment of HyBECCS are limited to considerations on climate change mitigation. A distinction is made between technology level (3.1.) assessing the technology choice as a first step and project level (3.2.) evaluating the actual GHG balance of the specific HyBECCS project.

3.1 | Eligibility on a Technology Level

There are two conditions that need to be fulfilled on a technology level for a HyBECCS project in order to be able to deliver net negative emissions: The theoretical ability for CO_2 removal and the theoretical permanence of the CO_2 storage. The theoretical ability for CO_2 removal is given for all types of BECCS approaches, as the CO_2 in the product gas is removed from the atmosphere during biomass growth. Accordingly, this has also to be verified for HyBECCS technology options. Controversy exists over biomass substrates that are not clearly assigned. For example, very slow-growing biomass, such as peat, does not qualify as renewable (Kaltschmitt & Schebek, 2015, p. 246). Consequently, for HyBECCS or BECCS approaches in general, a positive list of eligible technologies and raw material has to be elaborated and adapted to the state of the art and technology over time. Only in case technology and raw material from that list are applied, the HyBECCS project has the theoretical ability to generate negative emissions. The second condition for a HyBECCS approach in order to deliver negative emissions is that the captured CO_2 is permanently removed from the atmosphere. Different storage options are characterized by different time horizons of storage as well as different risk profiles concerning reversibility and leakage. Considering the current state of the art, HyBECCS approaches can be combined with three different storage options: (1) mineral carbonation, also known as mineralization or enhanced weathering, (2) geological underground storage, for instance in depleted oil/gas reservoirs or saline aquifers, and (3) in long-term CCU application, such as in the built environment in low-carbon concrete (Azapagic et al., 2018, p. 21; IPCC, p. 39). Mineralized carbon is safely stored in the long term, whereas geological underground storage is estimated to be safe for over 1000 years when best practice is applied (IPCC, 2005b; Möllersten et al., 2020; Poralla et al., 2021, p. 21). The third storage option for biogenic CO_2 from HyBECCS, long-term CCU applications, has a higher risk of reversals, insecurity concerning the time horizon of storage, and further challenges such as monitoring the permanence due to the dispersed places of use (Otto et al., 2017). Moreover, there is no clear definition of how long CO_2 has to be safely stored in order to count as negative emission with an effective impact on global climate. For the CO_2 storage technologies, a positive list of eligible approaches has to be elaborated and updated over time to reflect the state of the art. Only in case technology from that list is applied, the HyBECCS project has the theoretical ability to generate negative emissions. In case a HyBECCS approach or project fulfills both conditions on the technology eligibility, it has the theoretical ability to generate negative emissions and CNH, which means that it has the theoretical ability to fulfill the framework condition FC1 above.

3.2 | Eligibility and Assessment on a Project Level

Even though a HyBECCS approach has the theoretical ability on the technological level to deliver net negative emissions according to 3.1., this does not mean that every HyBECCS project applying such a technological approach is able to do so, which means that not every HyBECCS project is able to fulfill framework condition FC1 above. The actual GHG footprint highly depends, for instance, on the raw material production, the efficiency of the bioenergy conversion, and the distance to the CO_2 storage site. For each project, the expected climatic performance thus has to be assessed ex-ante before its implementation and monitored ex-post during its operation. The relevant category to evaluate the contribution of HyBECCS to a global negative emission budget are the GHG emissions, internationally convened to be quantified in CO_2 equivalents (CO_2eq) and with regard to the global warming potential over 100 years (GWP_{100}) (DIN e.V. DIN EN ISO 14044), p. 31; IPCC, 2015c; p. 87; Lozanovski, 2013, p. 60). A proven practice to quantify the GHG emissions of projects and services is a life cycle assessment (LCA) in line with the regulations of the international standards ISO 14040 and 14044 (DIN e.V. DIN EN ISO 14040: 2021; Klöpffer & Grahl, 2009; Kaltschmitt & Schebek, 2015; DIN e.V. DIN EN ISO 14044: Lozanovski, 2013). The application of these LCA standards guarantees the scientific veracity of the assessment and is the basis for the comparability of the results with competing approaches. Furthermore, the holistic perspective of an LCA is especially suitable for new approaches like HyBECCS. In addition to GHG emissions, potential sustainability issues other than the contribution to global warming can be revealed during the inventory phase of the LCA. Specifics for the determination of the GHG footprint of a HyBECCS project are elaborated in the following.

First, as the LCA allows climatic assessments relative to a specific product or service, a so-called functional unit has to be defined. To answer the question whether a HyBECCS project generates negative emissions, the functional unit shall be one ton of CO_2 permanently stored. For the climatic appraisal of the HyBECCS approach, negative emissions are thus considered to be the main product of the process. Hydrogen is considered as co-product. For different valuation approaches like the economic and the holistic assessment, however, other perspectives can be chosen. Equation 3 above can thus be converted as follows, now expressing the GHG emission factor (EF) of the negative emissions, in tCO_2eq per tCO_2 stored.

$$EF = \frac{E1 + E2b}{|E2a|} \tag{4}$$

In case the emission factor is smaller than one ($EF < 1$), the HyBECCS project generates net negative emissions and the eligibility to qualify as NET is proven; the framework condition FC1 above is fulfilled. The hydrogen produced can thus be referred to as CNH. In case of an emission factor bigger than one ($EF > 1$), more process GHG emissions are generated than CO_2 is permanently stored, the project generates net positive emissions and contributes to global warming. The comparison of the emission factors of different HyBECCS approaches or NETs, in general, allows conclusions on the efficiency of the different approaches. The GHG emissions of HyBECCS to be considered are the following, according to Figure 3 above: The process GHG emissions emitted during the HyBECC process of producing hydrogen and biogenic CO_2 (E1), the process GHG emissions emitted for the storage (CS) or long-term use (CU) of the biogenic CO_2 (E2b) and the amount of CO_2 stored in the long term, being the negative CO_2 emissions (E2a). The GHG footprint of the HyBECCS project can be calculated according to Equation 3 and allows the determination of the emission factor EF. It shows whether—in the case of ex-ante estimations—the project is expected to generate net negative emissions and—in case of measurements during operation—whether it actually generates net negative emissions. In case the total emissions (E3) are negative, which means that EF is smaller than one, the HyBECCS project actually generates net negative emissions and the generated hydrogen can thus be considered as CNH, as defined in the framework condition FC1 above. The specifics to determine E1, E2a, and E2b are discussed in detail in the following. The calculation of the process GHG emissions E1 and E2b shall, in general, follow the rules of the ISO 14040 and 14044 standards. However, the following specifications and choices given by the ISO framework should be followed in order to safeguard the ecological integrity of HyBECCS approaches. For the sake of comparability and fairness, the same rules must be applied to competing approaches. The process GHG emissions of HyBECC (E1) are generated during all steps necessary to provide hydrogen and biogenic carbon dioxide. The provision of the biomass used, which can have an important share in the total GHG emissions, must be considered (IE, p. 26). This is especially important for international traded biomass in order to avoid GHG accounting leakages in global supply chains. All direct emissions for machines, transportation, etc., and indirect emissions generated, for example, during the production of fuels or fertilizers, the generation of purchased electricity, or due to land-use changes shall be included (Hauschild et al., 2018, p. 494). However, double accounting of GHG has to be avoided. No direct and indirect GHG emissions are allocated on waste and residues. They “leave” the upstream product system without being burdened with any GHG footprint (DIN e.V. DIN EN ISO 14044, p. 26; Thrän & Pfeiffer, 2013, p. 87). This means that for bioenergy approaches using waste or residues as raw material for the energy conversion, no GHG emissions must be taken into account for the provision of such biomass except for its transportation to the plant and its processing. This rule honors the ecological advantages of approaches growing or obtaining raw material in an efficient and ecological way, whereas dedicated, land- or resource-intensive cultivation of biomass is disadvantaged. A recent study shows that optimization of the hydrogen production process can lead to negative emissions even without CCS: In case the digestates from the hydrogen production are used as fertilizer and a major part of its carbon content is stored in the soil, the GHG balance of the hydrogen production over its entire life cycle can be negative (Antonini et al., 2020). Consequently, when CCS is additionally applied, the GHG negativity of this optimized HyBECCS approach and its contribution to climate change mitigation can increase.

The process emissions E1 should furthermore ideally include the making, construction, and deconstruction of the infrastructure needed for the biohydrogen generation process in order to realistically calculate the total GHG emissions. For the main process, the biomass conversion to hydrogen, all relevant material and energy streams have to be taken into account. For the present impact category, the global warming potential, minor inputs, and outputs can be cut-off to a maximum of 5%, the impact of such cut-off however being scrutinized in a sensitivity analysis (Lozanovski, 2013, p. 56). For hydrogen, all steps of further processing and transportation until its intended end use should be included in the LCA. Long transportation routes to the site of usage might spoil the ecological advantages of hydrogen. The inclusion of all transportation emissions thus favors decentralized projects using local biomass over large-scale projects located far from any site of consumption. This might alleviate the disadvantages of missing economies of scale of decentralized plants. The required conditions (e.g., pureness and pressure) of the produced hydrogen depend on the envisaged use. It also affects the energy need, thus the GHG footprint and needs to be defined beforehand. The same applies for the required characteristics of the biogenic CO_2, to be defined as so-called reference flow in the LCA (Klöpffer & Grahl, 2009, p. 37). One major advantage of hydrogen is that it oxidizes to water; its use is thus CO_2-emission-free. Fossil fuels, on the contrary, emit GHG when burned. A "cradle-to-grave" approach of the LCA is thus advisable for a realistic comparison of fossil and hydrogen-based applications in order to reward this benefit. The HyBECC system element simultaneously delivers hydrogen and biogenic CO_2. Potentially, further co-products like digestates usable as fertilizer or other usable components in the product gas can be generated. An allocation of the total GHG emission over the different products would be possible (DIN e.V. DIN EN ISO 14044, p. 26; Lozanovski, 2013, p. 43). However, the complete accounting of all GHG is essential for the present assessment and thus no allocation is undertaken in order to avoid an accounting leakage through co-products not covered by GHG internalization mechanisms. Concerning the biogenic carbon dioxide, only its generation, capture, compression and, if needed, conditioning for transportation (IPCC, p. 5) are to be included in the LCA of the HyBECC system boundary B1. Assumptions for the project lifetime can be taken from proven comparable technologies. Dividing the total GHG emissions (E1) resulting from the HyBECC system element by the product quantity, results in the GHG intensity of such product, for example, in $tCO_2eq/kWh\ H_2$. The comparison of the results from several HyBECC approaches allows a prioritization according to the climatic efficiency of biomass conversion.

The further lifecycle of the biogenic CO_2 is covered by the system boundary B2. For process, GHG emissions of CS/CU (E2b), multiple factors like the CO_2 transportation mode, distance and storage or long-term utilization technology (Honegger & Reiner, 2018b, p. 308; Poralla et al., 2021, p. 21) influence the GHG footprint of CS/CU and have thus to be considered. The calculation of the GHG emissions emitted for the storage of the biogenic carbon dioxide shall, in general, follow the same rules elaborated above for the HyBECC process within the framework of the ISO 14040 and 14044. The system boundary encompasses all processes needed for the transportation of the CO_2 from its site of generation to the storage site, the storage itself, for example, the injection into the underground, as well as all provisions necessary to assure the permanence of the storage. Further compression might be needed at the storage site in case the pressure of the arriving CO_2 is not sufficient for the storage (IPCC, p. 11). All direct and indirect process GHG emissions are to be included in the LCA. In the case of biogenic CO_2, losses of this product through equipment leaks or accidental releases are GHG-neutral and only result in a loss of negative emissions. Contrary to fugitive emissions of fossil CO_2 (IPCC, p. 7), they do not have to be included in the LCA. They should, however, be avoided. The first result of the LCA of boundary B2 is the total GHG emission accruing for the transportation and storage of the biogenic carbon dioxide. The second result is, when dividing the total GHG by the product amount, the GHG intensity of the product, in $tCO_2eq/\ tCO_2stored$. The comparison of different CS/CU approaches allows selecting efficient technologies to minimize their impact on global warming.

Negative emissions (E2a) are the total amount of biogenic CO_2 stored in the long term. The stored CO_2 amount has to be measured continuously by proven measurement equipment at the injection or storage site (IPCC, p. 11). CO_2 leakage from transportation and compression is already taken into account at this point, as they occur before measurement. Other types of leakages, such as CO_2 migration and blowouts, have to be avoided by a diligent selection of technology and site as well as the use of adequate equipment, materials, and techniques (IPCC). However, as they cannot be excluded to happen, risk deductions depending on the technology applied are likely to be necessary for a realistic estimation of negative emissions over the long term. Such deductions may be applied as default values depending on the specifics of the CS plant and need to be elaborated and introduced on a global level. Pre-operational estimations of the negative emissions are possible by stoichiometric approaches and experimental results on the product gas composition, giving the amount of biogenic CO_2. After the deduction of transportation and storage losses, as well as risk deductions for leakages at the storage site, the amount of CO_2 actually stored in the long term can be estimated.

After the determination of E1, E2a, and E2b, the emission factor EF of the specific HyBECCS project under evaluation can be calculated according to Equation 4 above. In case the emission factor is smaller than one, the HyBECCS project generates net-negative GHG emissions and, consequently, carbon-negative hydrogen. This means that the framework condition FC1 above is fulfilled. Such HyBECCS project thus contributes to the deceleration of global warming.

It is important that E1, E2a, and E2b are stated separately in order to allow evaluations on the absolute impact of the HyBECCS approach or project on the environment.

Two projects with the same amount of net-negative emissions could show significant differences in the absolute amount of positive (E1 + E2b) and negative (E2a) emissions. The separate statement is thus especially important to save potentially scarce CO_2 storage capacities (Azapagic et al., 2018) and to safeguard resources. Furthermore, a separate statement is required in case different incentive schemes (or prices) apply to the different types of emissions. Another reason for the separate statement is that the climate goals for emission reduction, on the one hand, and negative emissions, on the other, might change over time, reflecting the progressing defossilization and the increasing need of global net negative emissions. Moreover, different emission caps for each process type (BECC, CCS) might be introduced to enforce the technological progress and would only be verifiable in case of separate statements.

The following Table 3 shows an overview of the most relevant aspects for the calculation of the GHG balance of a HyBECCS project.

4 | FUNDAMENTALS AND GUIDELINES FOR TECHNO-ECONOMIC ASSESSMENT

HyBECCS approaches have to be economically viable in order to bring its products—hydrogen and negative emissions—to the market. Techno-economic assessments of production processes are of great importance in order to examine their profitability, to identify potential barriers for a successful market integration like cost drivers, and give an important basis for technical development. Furthermore, they help to identify business cases and are valuable tools for decision making and monitoring (Zimmermann et al., 2020). Generally, to estimate profitability, the capital and operational expenditures must be determined. At the example of the HyBECCS processes, these must be derived for the biohydrogen production as well as for the capture, transport, and storage or the use of biogenic carbon dioxide, according to Equation 1. Fundamentals for the cost estimation of HyBECCS processes and proposals for the selection of suitable estimation methods are outlined in 4.1. Once both the capital and operating costs of the HyBECC and the CS/CU plant are determined, the total profit P3 of the HyBECCS plant can be calculated by summing up the costs (C3) and revenues (R3), according to Equation 2. In case of higher revenues than costs (R3 > C3), the HyBECCS project is profitable (P3 > 0), which represents the second framework condition (FC2). If the costs outweigh the revenues (C3 > R3), the project should not be implemented from an economic point of view.

In system boundary B1, the main product is biohydrogen, which generates revenues (R1a) as shown in 2.2. The additional revenues from the sale of co-products, here coming from the sales of biogenic CO_2 (R1b), are deducted from the total production costs. Dividing the annualized production costs by the annual product quantity results in the unit production costs, in the case of hydrogen the levelized cost of energy (LCOE) (IE). The LCOE can be related either to mass (e.g., in EUR/kg H_2) or to net calorific value (e.g., in EUR/kWh H_2) (Lozanovski, 2013; Matthes et al., 2020). In case biohydrogen from HyBECCS is only compared to other hydrogen generation systems, mass-based production costs can be chosen. A more general comparison with other types of energy conversion technologies can be envisaged by choosing the energy-based LCOE. In case only the carbon storage system (B2) is considered, where negative emissions are the main product, the unit production costs are expressed in EUR/tCO_2stored. In case the HyBECCS system boundary (B3) is considered, the main product may either be biohydrogen or negative emissions. In such a case, the revenues from the sales of the co-product must be deducted from the total costs when determining the unit production costs of the main product. In case the negative emissions are chosen as the main product, the comparison of the HyBECCS approach with other NETs is possible. The outcome is the unit production costs of the main product in EUR per unit of the main product, for example, the LCOE of biohydrogen. In the following, the unit production costs *before* the internalization of external costs and benefits are defined as "internal LCOE" of the product. The GHG internalization costs are stated separately from the internal LCOE. This differentiation applies independently from whether the external costs and benefits are partly or entirely internalized, which is partly the case in some countries and/or sectors with established carbon pricing mechanisms. The separate statement of the GHG internalization costs shall raise the transparency and comparability of different alternatives in terms of their climatic impact. The internal LCOE for hydrogen with biogenic CO_2 as co-product (system boundary B1) is defined, for example, in EUR/kWh H_2, according to Equation 5.

$$internal\ LCOE\,(B1) = \frac{C1 - R1b}{annual\ H2\ production} \tag{5}$$

The internal levelized costs of stored carbon (LCSC) for the system boundary B2 can be defined as follows, in EUR/tCO_2stored.

$$internal\ \ LCSC\,(B2) = \frac{C2}{E2a} \tag{6}$$

TABLE 3 Overview of relevant aspects for the calculation of GHG balance of HyBECCS projects

E1: GHG emissions from HyBECC (Hydrogen Bioenergy & Carbon Capture)
Life Cycle Assessment according to ISO 14040/14044
Impact category: Global warming potential over 100 years (GWP_{100})
Functional unit: one ton of CO_2 permanently stored
"Cradle-to-grave"-approach, including GHG emissions from: • Biomass cultivation/provision • All direct emissions (transportation, etc.) • All indirect emissions (incl. land use changes, infrastructure, deconstruction)
No allocation (side effect: co-product biohydrogen is "zero-emission")
No GHG allocation on waste and residues → "zero-emission" biomass input
Double accounting of GHG has to be avoided
Cut-off of material & energy flows at maximum of 5% → effect to be checked in sensitivity analysis
+ Potential sustainability issues of new HyBECCS approaches can be revealed during LCA inventory phase
E2b: GHG emissions from CS (Carbon Transport & Storage)
Life Cycle Assessment according to ISO 14040/14044
Impact category: Global warming potential over 100 years (GWP_{100})
Functional unit: one ton of CO_2 permanently stored
"Cradle-to-grave"-approach, including GHG emissions from: • CO_2 transportation from HyBECC plant to the storage site • Storage (for example, injection into the underground) • O&M (Operation and Maintenance) (all provisions necessary to assure the permanence of the storage)
E2a: Negative Emissions
Unit: tons of CO_2 permanently stored
Ex-ante estimations through stoichiometric approaches & experimental results on the product gas composition
Measurements during operation must be: • continuously • with proven measurement equipment • at the injection or storage site – Lack of uniform standards for measurement, reporting and verification (MRV)
Risk deductions (for leakage, accidental release) to be applied – Lack of uniform definition of default values for risks
– Scientific & regulatory uncertainty on necessary duration of storage, responsibilities, liabilities, etc.
! Separate statement of absolute amount of E1, E2a and E2b necessary.
! Uniform LCA system boundaries for comparative assessments

The internal levelized costs of negative emissions (LCNE) for the HyBECCS system boundary B3 can be defined according to the following equation, in EUR/tCO_2stored.

$$internal\ LCNE\,(B3) = \frac{C3 - R1}{E2a} \tag{7}$$

The internal LCOE for carbon-negative hydrogen (system boundary B3) is defined as follows, where no revenues from the co-product, the negative emissions, are included. This is because they come from the internalization of the external benefit from negative emissions, not considered in the internal cost calculation (expressed, for example, in EUR/kWh H_2).

$$internal\ LCOE = \frac{C3}{annual\ H2\ production} \tag{8}$$

However, an important aspect for the economic viability of HyBECCS concepts is monetary incentives for GHG reduction as well as for storing biogenic CO_2. After presenting the most relevant aspects for the capital and operational cost estimation in 4.1., the internalization of those external benefits will be discussed in 4.2, resulting in the derivation of two key performance indicators (KPIs) for the evaluation of HyBECCS projects: The levelized cost of carbon-negative hydrogen (LCCNH) and negative emissions (LCNE). The chapter closes by presenting an exemplary basic model for HyBECCS regulatory systems in net-zero or net-negative emission economies.

4.1 | Capital and Operational Cost Estimation

Suitable estimating approaches for capital costs of HyBECCS projects like capacity, factor, module, and detail methods are to be chosen in terms of estimation accuracy and effort and must be selected depending on the project planning degree of the HyBECCS project, the data availability, and the objective of the estimation (Weber, 2016). In order to select an adequate method for estimating capital cost for HyBECCS approaches, the current degree of the project definition and some key indicators or information about the cost of the equipment must be known (Kunysz, 2020). The degree of the project definition depends solely on the available information about the project. Certain project states are associated with a certain degree of the project definition. In preliminary, approval and detailed planning it ranges from 10% to 15%, 25% to 35%, and 85% to 95%, respectively (Weber, 2016). Figure 5 illustrates a schematic guide to select one of the mentioned methods described below.

Capacity methods usually are applied for projects with planning degrees below 2% (Kunysz, 2020) for giving order-of-magnitude estimates or to carry out process comparisons. The capital expenditures can be estimated using key indicators such as investment costs and capacity of similar existing plants or through gross annual sales and capital turnover ratio. If the technical sizing has not yet been carried out, but key indicators are known, the capacity methods are suitable (Kunysz, 2020; Towler & Sinnott, 2013). Factorial methods are based on rough technical sizing of the plant and an estimate of the major equipment´s purchase cost. They usually are applied at project definition degrees up to about 30% (Weber, 2016). Depending on the applied factorial method, purchase equipment costs are estimated by multiplication with specific factors, for instance, location or material peculiarities (Towler & Sinnott, 2013). Due to its higher project planning degree, factorial methods often deliver higher estimation accuracies than capacity methods, which is why they commonly are used for more detailed estimations like feasibility studies, concept assessments, or preliminary budget approvals (AACE International, 2020). Cost estimations according to the module methods require a functional classification of the plant into modules and are typically deployed for budget approvals. Each module is designed based on a P&I diagram by cost-relevant equipment data, such as material, process temperatures, or pressures. Therefore, higher project planning degrees than 2%, as well as information about module costs are required (Weber, 2016). Due to the modularity of HyBECCS technologies, the module method is especially suitable. If the project definition lies in between 2 and 30%, either factorial or module methods are applicable (AACE International, 2020). Module methods are more commonly used at higher project definition degrees. Otherwise, in the case of known equipment cost factors, such as Lang- or Hand-factors, the factorial methods can be applied (Couper, 2003; Kunysz, 2020). The detailed estimation methods are based on binding offers or offers from completed similar projects and are applied for cost control or budget compilation. They require the highest project planning degrees and provide the most accurate estimation of these four methods (Kunysz, 2020). If the project definition is above 30% (AACE International, 2020) and binding offers or offers of already completed, similar projects are available, detailed methods are commonly used (Kunysz, 2020; Towler & Sinnott, 2013). If there are no offers, but it is possible to form functional units and information about modular costs is available, the module method can be applied. If equipment cost factors are known, the factorial methods are suitable. Access to reliable data for completely new developed technologies is often not available. As recent data on actual prices for similar process equipment is a highly reliable source, economic data from existing plants can be used as a basis for the techno-economic assessment (Towler & Sinnott, 2013). Therefore, as HyBECCS is a combination of biohydrogen production and CCS/CCU, data from existing BECCS- or CCS-plants and biohydrogen processes can be used for HyBECCS plant cost estimations.

Operational expenditures can be divided into variable and fixed production costs. Variable costs are proportional to plant output, meaning for HyBECCS, increased hydrogen and carbon dioxide production or a greater amount of carbon dioxide stored is generally associated with increasing variable costs. Typical variable costs for HyBECCS plants comprise costs for raw materials like biomass, auxiliaries such as process water or electricity, consumables, waste disposal for biomass residues as well as the costs for hydrogen and carbon dioxide processing and its transport to the CS/CU plant site. Variable costs can usually be decreased by operating the plant more efficiently, for instance by increasing the biomass to hydrogen conversion rate or energy efficiency. Estimating the raw material or consumable costs of a new plant requires an estimate of the amounts of raw materials or consumables needed as well as corresponding prices. The prices can either be forecasted using existing pricing methods or determined from current market prices. Estimating the utility costs of the HyBECCS system requires mass and energy balances as well as a preliminary design of the heat recovery system. Costs for waste

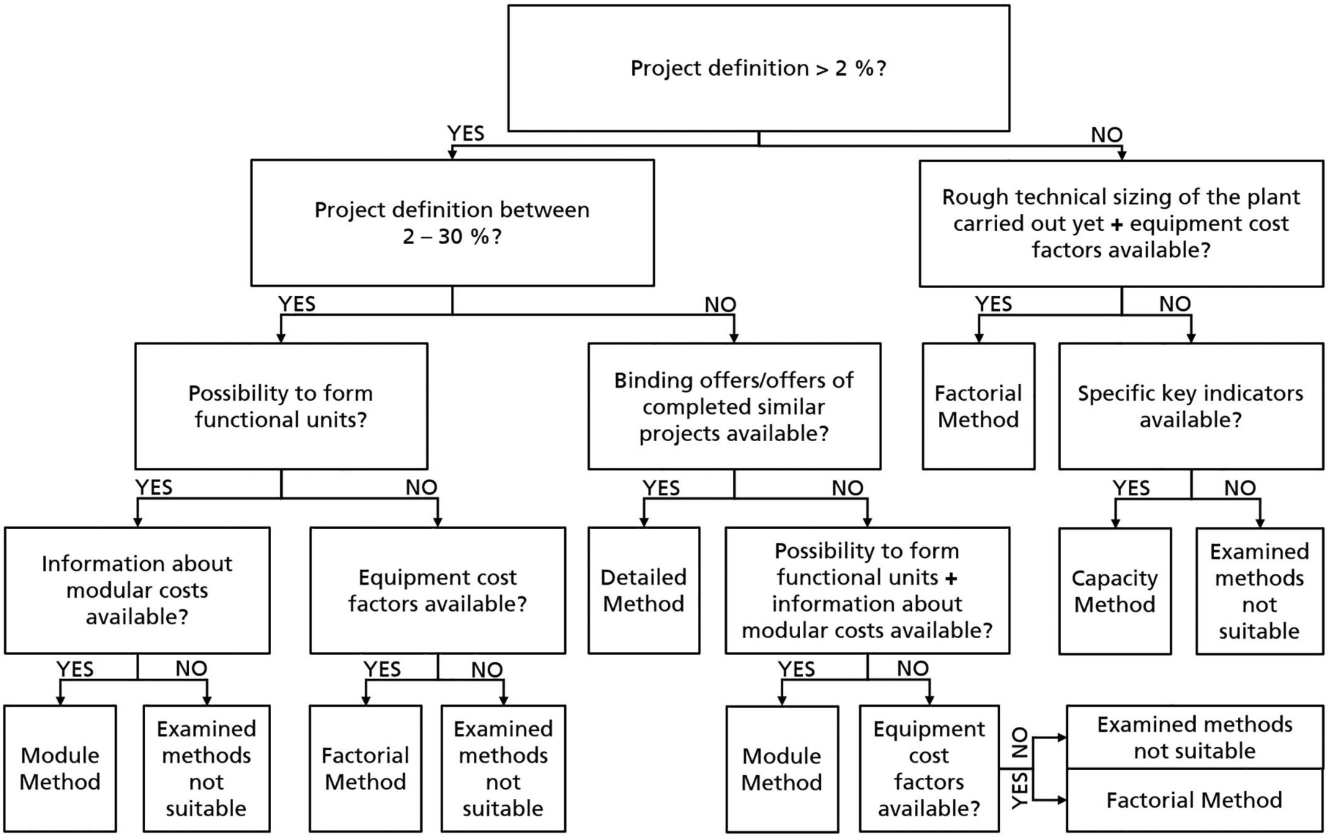

FIGURE 5 Guideline for the selection of a capital cost estimation method (Own elaboration based on AACE International (2020), Couper (2003), Kunysz (2020), Peters et al. (2003), Towler and Sinnott (2013), Weber (2016), Zimmermann et al. (2020))

disposal in HyBECC (B1) may occur, for instance, from biomass residues or wastewater that cannot be recycled or sold as a by-product. As HyBECCS plants can be configurated on a variety due to their modularity regarding the biomass pretreatment, hydrogen production pathway, product gas separation, and its processing as well as in terms of the carbon storage option or carbon utilization case, specific raw materials, consumables, auxiliaries, and additional waste treatments can be required. Fixed costs incur irrespective of the plant output, meaning that a decrease in production does not lead to a reduction in fixed costs. Fixed costs for HyBECCS generally include operating labor, supervision, maintenance, property taxes and insurance, general plant overhead, sales and marketing costs as well as license fees and capital charges. Labor costs, property taxes, and insurance or capital charges depend on the location of a plant (Towler & Sinnott, 2013). Due to the high variety of possible HyBECCS configurations and the dependence of some fixed costs on the plant location, operational expenditures need to be estimated for each HyBECCS plant individually. Guidelines and general reference values for estimating variable and fixed costs are outlined, for example, in Towler and Sinnott, (2013) (p. 373ff) or Peters et al. (2003) (pp. 259ff).

4.2 | Internalization of External Costs

The economics of HyBECCS approaches are characterized by a very high dependency on the regulatory framework it is embedded in and, in the ideal case, its ecological benefits. In order to evaluate HyBECCS concepts with regard to their economic viability, these aspects must be considered. In 4.2.1., two single-value KPI are developed taking into account monetary incentive schemes for environmental benefits. These KPIs allow the comparison of different HyBECCS approaches or projects, but also the comparison with other NETs like BECCS approaches or even conventional, potentially fossil-based alternatives. The target KPIs presented merge the outcome of the economic analysis with the outcome of the climatic assessment (cf. 3.). It represents the production costs of a product, including the internalization costs and benefits of the external effects on the global climate. For CNH, it can be considered as the levelized cost of carbon-negative hydrogen (LCCNH), and, for negative emissions, as the levelized cost of negative emissions (LCNE). Uniform incentive schemes for external cost savings through greenhouse gas reduction as well as the creation of negative emission have to be established in order to reach and maintain greenhouse gas neutrality. A basic model for such a regulatory, result-based system building on carbon removal certificates (CRCs), also known as negative emission certificates (NECs), is shown in 4.2.2.

4.2.1 | Determination of the Levelized Cost of Carbon-Negative Hydrogen (LCCNH) and Negative Emissions (LCNE)

One result of the techno-economic assessment, to be carried out in accordance with the provisions elaborated in 4.1., are the total internal production costs of the main product. To understand the economic interrelationships of the HyBECCS approach in a more holistic view, the internalization of the external costs and benefits of the HyBECCS project must be considered. As elaborated in 2.4., external costs are caused by the process GHG emissions of the HyBECC system element (E1) and the CS/CU system element (E2b). The total amount of E1 and E2b is an outcome of the LCA (cf. 3.2.). For the internalization, the external costs of the GHG emissions have to be monetarized. An option is the offsetting of process GHG emissions with emission reduction certificates from renewable energy projects. Such offsetting renders all HyBECCS products GHG neutral. An alternative to be discussed is the offset of unavoidable process GHG emission against CO_2 permanently stored. After this first internalization step, the biohydrogen can thus be considered carbon-neutral hydrogen. The offsetting means that only the net-negative emissions, meaning those negative emissions that exceed the process emissions of the HyBECCS process, are fully rewarded on the market. The internalization costs have to be added to the total production costs. When the annualized internalization costs are divided by the annual product quantity, they can be added to the internal LCOE. In case the internal LCOE and internalization costs per unit are stated separately, different approaches can be compared in terms of their relative GHG footprint. For such a comparison, the same carbon price has to be applied to all alternatives.

Additionally, the external, GHG-related benefit of the HyBECCS project, which is according to 3.4., the negative emissions, need to be internalized. The determination of the total amount of biogenic carbon dioxide that is permanently stored, referred to as gross negative emissions (E2a), is an outcome of the LCA (cf. 4.2.). In case the project generates net-negative emissions ($EF < 1$) as per framework condition FC1, the project qualifies to receive a revenue stream (R2) based on a uniform negative emission unit price for each ton of gross negative emissions. The price to be received per unit of gross negative emissions has to be the same for all alternative NETs in order to render the different approaches comparable. In reality, however, different prices may be negotiated in direct carbon removal certificates (CRCs) purchase contracts. A possible approach for incentives based on CRCs is described in 4.2.2. As the process GHG emissions have been internalized, only the net-negativity is fully rewarded through additional income. In case the hydrogen to be sold can prove that the co-produced biogenic CO_2 is actually used for long-term storage or use and the project generates net-negative emissions ($EF < 1$), the biohydrogen, already carbon-neutral after the first internalization step, can be considered as CNH. For the internalization of the external profit of the negative emissions, the revenue from the sales of the co-product, the negative emissions, is to be deducted from the total production costs. As a quality feature for mere marketing purposes, either the “net negative intensity” (in tCO_2stored/kWh H_2) could be indicated. Alternatively, only the share of hydrogen equal to the total amount of net negative emissions can be declared as CNH, whereas the remainder is to be declared carbon-neutral hydrogen. The production costs of one unit of carbon-negative hydrogen produced, including (i) the internalization costs for all process GHG emissions as well as (ii) the revenue for the negative emissions, for example in EUR/kWh H_2, is referred to as levelized cost of carbon-negative hydrogen (LCCNH). It has to be underlined that only in case the biogenic CO_2 is actually used for long-term storage or use and the project generates net-negative emissions ($EF < 1$), the product is CNH and the KPI can be called LCCNH, as defined in the framework condition FC1 above. This means that the designation as LCCNH already includes the validation of the hydrogen being carbon-negative. In all other cases, the resulting KPI would merely represent and be called the external, GHG-related LCOE of hydrogen. The target KPI for NET comparison is the levelized cost of negative emissions (LCNE), expressed in EUR/tCO_2stored. Also, LCNE can only be used in case the biogenic CO_2 is actually used for long-term storage or use and the project generates net-negative emissions ($EF < 1$). For a better understanding, the stepwise internalization procedure is exemplarily shown for the HyBECCS system (B3) in the following and expressed as Equation 9.

First, the internal LCOE of produced biohydrogen, in EUR/kWh H_2, is determined from the total production costs. If the project generates net-negative emissions, as per framework condition FC1, all process GHG emissions (E1 and E2b) are monetized via carbon pricing, leading to an increase in the LCOE. Afterward, the revenues from the sales of gross negative emissions (R2) are deducted, leading to a decrease in the LCOE. The sum of the internalization costs is divided by the annual H_2 production amount (in kWh H_2). The result is the LCCNH (in EUR/kWh H_2), which can be easily compared to the LCCNH of other specific HyBECCS projects or the LCOE of any other energy carrier such as fossil fuels.

$$LCCNH = Internal\ \ LCOE + \frac{E1\ \ internalization\ \ costs + E2\ \ binternalization\ \ costs - R2}{annual\ \ H2\ \ production} \tag{9}$$

Figure 6 illustrates the functionality of one of the developed KPI. The LCCNH from an exemplary HyBECCS process is compared to the LCOEs of several other energy carriers. Due to missing data from real HyBECCS plants, the LCCNH is only an assumption for illustration purposes and not based on real values. The values of the alternatives are based on actual data from Howarth and Jacobson, (2021), IPCC and Couper, (2003). The blue bars represent the respective internal LCOE (before GHG internalization). The red bars represent the internalized costs for the specific GHG emissions depending on the assumed carbon price. The GHG internalization costs are shown separately in this example (in red), independently from whether the GHG emissions are partly already internalized through carbon pricing mechanisms for some alternatives and in some countries (World Bank, 2021) and would thus be part of the internal costs. For HyBECCS, the green bars represent the LCOE reduction due to the application of CCS. This means that, in this example, the capture and storage of the biogenic CO_2 generate more income from sales of carbon removal certificates than costs (including GHG internalization costs for CCS process emissions). In this example, the costs can be reduced from a total of 0,20 EURO/kWh to a final LCCNH of 0,13 EURO/kWh (dotted line) at an assumed carbon price of 300 EUR/tCO_2eq. The LCCNH as the final KPI shows the competitiveness of biohydrogen from HyBECCS in comparison to alternatives. Here, the LCCNH of biohydrogen from an exemplary HyBECCS plant is compared to the LCOE of hydrogen from other sources as well as to the wholesale prices of fossil energy carriers (IRENA, 2019; Matthes et al., 2020, p. 29).

Figure 7 compares the levelized costs of negative emissions (LCNE) from HyBECCS with the LCNE of other negative emission technologies. Due to missing data from real HyBECCS plants, the LCNE for HyBECCS is only an assumption for illustration purposes and not based on real values. The values of the alternatives are based on actual data from Poralla et al. (2021) and Möllersten et al. (2020). For HyBECCS, the purple bar represents the internal LCNE before GHG internalization. The red bars represent the internalization costs for the specific GHG emissions depending on the assumed carbon price. For HyBECCS, the green bar represents the cost reduction due to the generation and sale of hydrogen. This means that, in this example, the total unit costs can be reduced from a total of 360 EUR/tCO2stored to a final LCNE of 110 EUR/tCO2stored (dotted line) at a carbon price of 300 EUR/tCO_2eq. The LCNE as the final KPI shows the competitiveness of negative emissions from HyBECCS in comparison to alternative NETs. Here, the LCNE of negative emissions from an exemplary HyBECCS plant is compared to the costs of BECCS and DACCS. For both alternatives, the striped bars represent cost ranges gathered from studies (Möllersten et al., 2020; Poralla et al., 2021). As long as no GHG internalization for process emissions is undertaken for DACCS and BECCS, those cost ranges represent the internal LCNE.

4.2.2 | Exemplary Basic Model for HyBECCS Regulatory Systems in Net-zero or Net-negative Emission Economies

As the CS/CU subsystem of HyBECCS, in most cases, does not generate any other marketable product than the

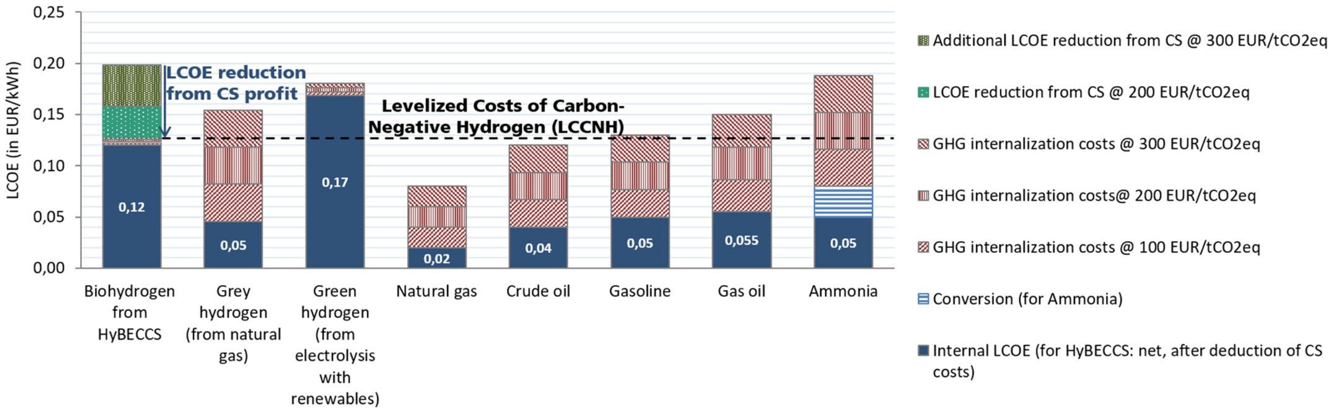

FIGURE 6 Exemplary comparison of the Levelized Costs of Carbon-Negative Hydrogen (LCCNH) of biohydrogen from HyBECCS with hydrogen from other sources and wholesale prices of fossil energy carriers. Assumptions: Net calorific value for hydrogen. Specific GHG emission for ammonia corresponds to those of grey hydrogen. Ammonia is calculated as H2 equivalents. (Own elaboration based on Fischedick and Adolf (2017), Hinicio, Matthes et al. (2020))

negative emissions, but generate costs for the carbon storage, the CS/CU subsystem would not be implemented without external incentives to (over)compensate such CO_2 capture and storage costs. In order to achieve a global economy with first net-zero and then net-negative GHG emissions, according to the emission pathways of the IPCC (Masson-Delmotte, et al., 2021), uniform incentive schemes have to be established. Various approaches have been developed and rules for such certification systems have been set forth (Honegger & Reiner, 2018a; Tanzer & Ramírez, 2019). The variety of incentives schemes can be divided into result-based and non-result-based approaches. In the early implementation phase of HyBECCS, non-result-based incentives schemes are appropriate and urgently needed. Examples are subsidies for research, design, development, and demonstration (RDD&D), tax credits, concessional loans, and grants (Poralla et al., 2021, p. 23). At a later stage with HyBECCS and other NETs being broadly operational, a result-based approach, based on carbon removal certificates (CRCs), can be established to strive for cost efficiency (Rickels et al.). The European Commission aims to develop such a regulatory framework for the certification of carbon removals in 2022 (European Commission). A basic model for such a regulatory, result-based system building on CRCs from HyBECCS could work as described in the following. It shall give an example of how negative emissions from HyBECCS plants can be economically rewarded in order to convert HyBECCS into a working business case. This basic model respects the general rules elaborated and broadly accepted in scientific discussion on carbon removal certification (Honegger, 2020; Tanzer & Ramírez, 2019).

In HyBECCS plants, CRCs can be generated when verified negative emissions are produced, for example, through measurement at CS sites that store certified and GHG-neutral (after internalization) biogenic CO_2. The precondition for the issuance of CRCs is that net-negative emissions are generated as per framework condition FC1 ($E3 < 0$). CRCs can be issued on a quantity basis per ton of biogenic CO_2 permanently stored. These certificates can be sold on a free market to offset emissions of certain, predefined types. Figure 8 below depicts the mechanism at the example of HyBECCS. As shown in the figure, the process emissions of the HyBECCS process chain (E1 and E2b) could be compensated through CRC purchase and offsetting. For an operator with internal access to negative emissions, e.g. when considering the whole HyBECCS process (B3) or only the CS boundary (B2), the offset could be done with the cancellation of CRCs in the amount of process emissions. At the same time, a revenue stream is generated by the sale of CRCs issued for the negative emissions (E2a) and sold on the CRC market. This would create a self-regulating market mechanism ensuring, in a first step, net-zero emissions, in case all process emissions are obliged to be offset against negative emissions. Risk deductions for uncertainties on the permanence of CO_2 storage would have to be considered within such an offsetting mechanism.

Regulatory intervention is also possible and enables the targeted pursuit of predefined emission paths: By removing

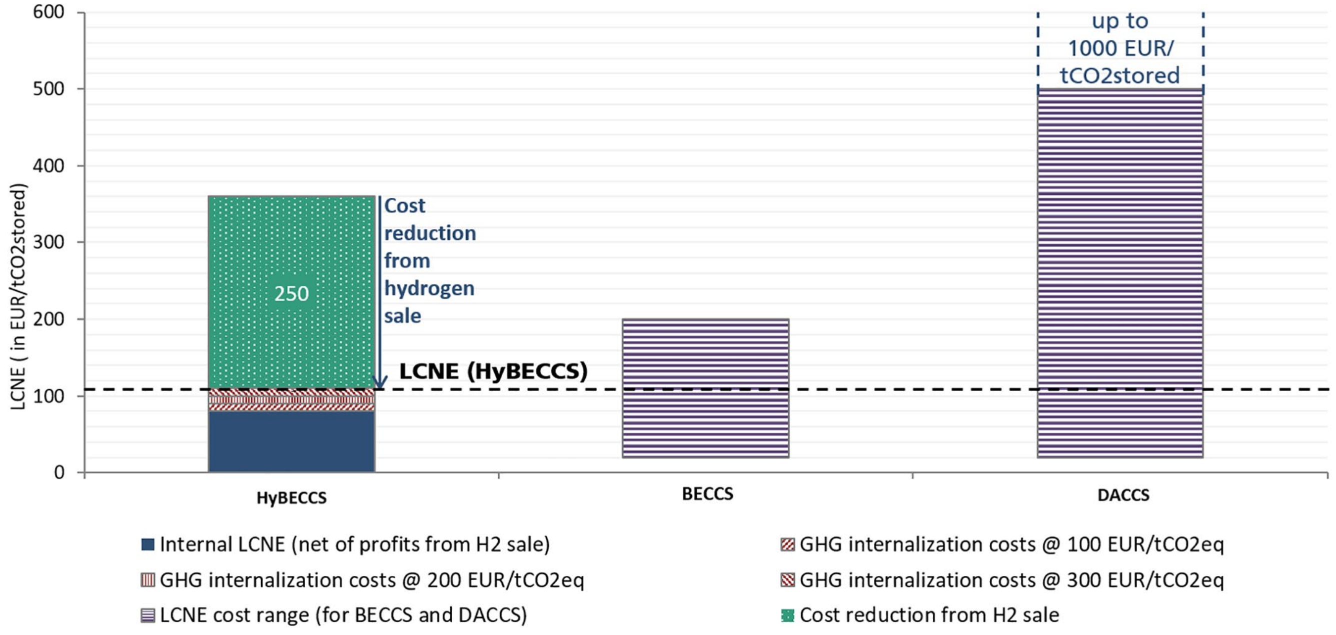

FIGURE 7 Exemplary comparison of the Levelized Costs of Negative Emissions (LCNE) of negative emissions from HyBECCS with other NETs. (Own elaboration based on Möllersten et al. (2020), Poralla et al. (2021))

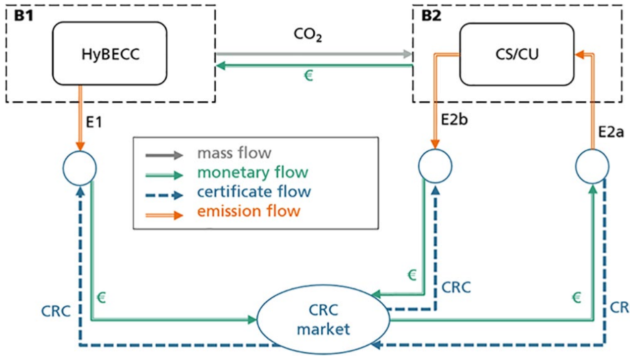

FIGURE 8 Basic model for regulatory systems based on carbon removal certificates (CRCs) at the example of HyBECCS processes (Abbreviations cf. Figure 3)

certificates from the market, negative emission paths can also be ensured. Potential buyers of CRCs are thus government or private institutions aiming to build up a negative emission budget through the reduction of CRCs. The second group who could be obliged to purchase CRCs are emitters of unavoidable emissions. It is, however, important that the unavoidability of GHG emissions is regularly questioned in the light of technological progress. It must be avoided that the CRC offsetting hinders or decelerates innovation for GHG mitigation. Furthermore, the priority of avoiding GHG emissions should be secured by excluding the offsetting of avoidable (fossil) emissions with CRCs, as it would prolong the lifetime of fossil utilities. Moreover, the offsetting of CRCs with fossil GHG emissions would have the same GHG balance as the CCS of fossil carbon dioxide: Both are, at a maximum, GHG-neutral, but would occupy potentially scarce CO$_2$ storage capacities (Azapagic et al., 2018). Such GHG-neutral or -positive uses of storage capacities would increase the costs of NETs: Storage sites would be scarce, potentially less accessible, and thus more expensive to access when the economically best locations are already used for the storage of avoidable, GHG-neutral, or -positive CO$_2$. This would limit the total potential of HyBECCS and NETs in general. CRC offsetting with avoidable GHG emission thus has to be ruled out, such as CCS of avoidable fossil CO$_2$, both ideally by the avoidance of such avoidable CO$_2$ emissions in the first place. In the proposed offsetting mechanism for HyBECCS, potentially avoidable GHG emissions (of the HyBECCS process) are offset against CRCs. It should be discussed if such offsetting is allowed, in the interest of the NET implementation, whether the GHG emission internalization should happen via offsetting of process emissions against emission reduction certificates from renewable energy projects, or if a ratio for emission reduction certificates and CRCs should be introduced for NETs (Geden, 2021). The approach presented above gives an example of how an incentive scheme for the generation of negative emissions might look like aiming to present a basis for discussion of how to solve the externalities of NETs in a positive way.

5 | DISCUSSION AND LIMITATIONS

It must be clearly stated that there is no claim to the completeness of the described methods for a final techno-economic and ecological evaluation of HyBECCS projects. However, the evaluation basics and specifics are provided in order to enable a uniform evaluation of these approaches. Using those basics and discussing the elaborated KPIs LCCNH or LCNE, a review of the TEA and EA results should be carried out in order to check the completeness, reliability, and consistency of the model, assumptions, data quality, and outputs. Therefore, an uncertainty and sensitivity analysis should be conducted to identify the most influential input indicators. (Zimmermann et al., 2020). Based on the technical evaluation and the uncertainty and sensitivity analyses, targeted technical optimization can be carried out to improve efficiency in terms of energy consumption and biomass conversion as well as the economics and ecological aspects of the HyBECCS plant (Zimmermann et al., 2020). The LCCNH (and LCNE) can only serve as a benchmark to price scenarios and projections for external costs and benefits of HyBECCS processes into cost calculations as long as they are not internalized and reflected as actual internal costs in the calculations.

Further, for the environmental assessment specifics elaborated, a special focus is on the impact category of global warming potential. This is due to the main objective of the considered HyBECCS technologies for climate protection. However, many important impact categories remain unconsidered. These include, for example, acidification and eutrophication potential or photochemical oxidant formation as well as ozone layer and abiotic depletion according to ISO 14040/44. As HyBECCS represents a BECCS technology, this novel approach is subject to the sustainability criteria of BECCS technologies. Therefore, it should secure food supply, avoid land degradation and land use conflicts, conserve water resources, as well as preserve biodiversity in order to be socially and ethically tenable (Fajardy et al., 2019). The implementation of HyBECCS projects also depends on social acceptance and social compatibility (Gough et al., 2018), since social values are crucial in decision-making (Wainger et al., 2010) and technological development (Buck, 2016). Hence, HyBECCS projects must take place in a socio-ethical context, which is why those impacts need to be assessed in order to determine the full implementation potential of HyBECCS projects (Gough et al., 2018). Therefore, a social life cycle analysis (S-LCA) should be carried out. Furthermore, the deployment of each HyBECCS plant should be aligned with the Sustainable Development Goals (Fajardy et al., 2019). In addition, any other category that influences a social-ethical friendly environment, such as health and safety conditions, local work and employment conditions, fair competition, respect of indigenous rights, infrastructure development, etc. must be investigated within the S-LCA (Benoît Norris et al., 2013). These aspects were not considered in the present work. Thus, guidelines for an S-LCA for HyBECCS approaches need to be elaborated.

6 | SUMMARY AND OUTLOOK

In this paper, fundamentals for the holistic evaluation of HyBECCS process combinations in terms of techno-economic and climatic performance are presented for the first time. Since there is no HyBECCS plant so far, this work provides the theoretical basis for comparing future HyBECCS plants. For this purpose, first, a classification and delimitation of the HyBECCS approach are elaborated. Respectively, the concepts CCS, NET, and CDR apply to the HyBECCS approach as it removes biogenic carbon dioxide from the atmosphere. However, further requirements must be met: Only if the GHG footprint of a specific HyBECCS project is negative, it actually generates net negative GHG emissions and thus qualifies as NET and the generated hydrogen is carbon-negative hydrogen (CNH). System boundaries to be applied and emission streams to be considered are described in order to provide a comparable frame of reference. Thereby, the HyBECCS approach is divided into two system elements, each with an associated subsystem boundary: First, the biohydrogen production with CO_2 co-production and capturing (HyBECC) and, second, the storage or long-term use of biogenic CO_2 (CS/CU). In addition to the emission flows, monetary flows of the system boundaries are defined as a basis for a better understanding of the economic relationships. A special focus was put on the description of interrelationships between climatic and economic aspects by elaborating the double climate protection effect through GHG emission reduction and removal and their resulting possibilities to receive incentives.

In the main part, this basis was used to explain how the economic viability as well as ecological effects, specifically on the climate, can be determined. On the ecological side, firstly, the conditions for positive climate impacts of the HyBECCS technology are discussed. This is done within an eligibility check related to the selection of the basic technology as well as project-specific life cycle impacts. The eligibility check on technology level ensures that the approach considered is suitable for the production of CNH. The theoretical ability for CO_2 removal and the theoretical permanence of the CO_2 storage is evaluated by matching the substrate biomass and the selected CO_2 storage technology via positive lists. These lists should be drawn up and continuously maintained by authorities. Second, if this step is successful, a life cycle assessment is carried out for the specific project proposal and the suitability for generating net negative emissions is verified via the greenhouse gas balance. Special features for the greenhouse gas balancing that apply to the HyBECCS subsystems are elaborated and described. As a key figure for the climatic impact, the emission factor EF was established and defined as the most important indicator for the classification of the HyBECCS approach as NET and the designation of the produced hydrogen as CNH. Eligibility on project level to qualify as NET is proven if the calculated emission factor EF is less than 1. The EF can be estimated ex-ante based on the project planning, but has to be verified ex-post through on-site measurements during the operation of the HyBECCS plant(s).

On the economic side, particularities for the determination of profitability were explained. Special focus was placed on determining internal capital and operating costs, initially without taking into account external effects and incentive systems. The selection of appropriate methods for estimating capital cost with respect to the current degree of the project definition and data availability is elaborated within this part. Afterward, peculiarities concerning the HyBECCS approach with respect to political regulatory measures and interrelationships between economics and ecology are outlined. Based on this, two key performance indicators (KPIs) are determined: The levelized costs of carbon-negative hydrogen (LCCNH) and negative emission (LCNE). Both KPIs allow deciding whether a specific HyBECCS project is economically viable when compared to the LCOE of competing technologies for the provision of negative emissions, hydrogen, or energy, in general. It furthermore allows the comparison of HyBECCS projects with different hydrogen or energy provision technologies and NETs. This is especially important to ensure that the biological transformation process of modern economies is efficient, minimizing the depletion of scarce resources such as energy, non-waste biomass, land, potentially CO_2 storage sites, and, ultimately, money. The guidelines for the KPI determination furthermore give first indications of how to optimize the GHG balance of a HyBECCS project. For instance, the design of the HyBECCS project as a “waste to hydrogen” plant, using waste or residuals as biomass feedstock, may significantly reduce the process emissions, allowing for a higher output of net negative emissions footprint (DIN e.V. DIN EN ISO 14044: Umweltmanagement - Ökobilanz - Anforderungen und

Anleitungen (ISO 14044:2006 + Amd 1:2017 + Amd. 2:2020); IE; Thrän & Pfeiffer, 2013). These holistic target KPIs can be calculated based on the total production costs and GHG balance. Both the negative emissions and the co-generated biohydrogen contribute to limiting global warming. However, only the internalization of these external benefits and the external costs of GHG emissions can turn innovative technologies such as HyBECCS into viable business cases. This particularity is reflected by the LCCNH. The LCCNH should represent the value to be optimized in order to achieve higher sustainability. However, this KPI depends strongly on political framework conditions, which must be taken into account.

In order to reach the GHG reduction targets set by governments worldwide, existing carbon pricing schemes have to be expanded and sharpened, as well as incentive schemes for negative emissions need to be disseminated. As shown in this paper, both of them affect the economic viability of HyBECCS. It is important to underline that the complete internalization of all GHG emissions and negative emissions – as proposed here – is important to give a realistic picture of the real costs of energy provision and climate protection. The still missing or incomplete internalization of external costs of conventional technologies hinders the implementation of novel, climate-friendly approaches such as HyBECCS, giving the presented assessment approaches a speculative component. Only realistic carbon price levels will have the needed steering effect on the individual decision process of operators and investors to direct investment into eco-friendly and efficient options like HyBECCS (OECD, 2021). The implementation of regulations to account for all GHG emissions of all processes should thus be the aim on a global level and the basis for future negative emission incentive schemes. This paper increased the understanding of these regulation´s impact on the economics of HyBECCS systems, and evaluability, as well as comparability, have been initiated via suggestions for basic frameworks and metrics. The work can be understood as an initial standard that enables meaningful comparison of HyBECCS systems. However, it needs to be confirmed by implementing the assessment approaches on real plants.

Furthermore, the innovative concept of HyBECCS with its novel product carbon-negative hydrogen calls for a more detailed categorization of hydrogen. On-going initiatives work on the establishment of a uniform threshold of GHG intensity for hydrogen to qualify as "green" or "low-carbon" (certifhy; Hinicio; Newborough & Cooley, 2020). However, as the GHG footprint of "green" hydrogen from different sources and projects varies significantly, the "theory of colors" always falls short of introducing real transparency. Imposing a product declaration stating the specific GHG intensity of hydrogen (e.g., in kg-CO_2eq/kgH_2) would allow such transparency. Besides the economic steering effect of the monetary internalization schemes introduced in this paper, such transparency could give an important impulse for the dissemination of CNH. Moreover, in order to safeguard the economic integrity of HyBECCS, efforts need to be directed toward the integration of scientific evidence on the risks of specific CO_2 storage technologies into a regulatory framework. The same applies to the definition of a minimum time horizon of storage for carbon utilization applications. Further needs for regulations will appear during the future development of the HyBECCS concept. Thorough monitoring, reporting, and verification (MRV) standards need to be elaborated and generally adopted so that market mechanisms, such as a CRC market exemplary described above, can lead the world on emission pathways toward the 1.5°C target.

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CONFLICTS OF INTEREST

The authors declare no conflict of interest.

AUTHOR CONTRIBUTIONS

Writing, J.F., S.Z., and M.G.; supervision, R.M. and A.S. All authors have read and agreed to the published version of the manuscript.

ORCID

Johannes Full https://orcid.org/0000-0002-0748-7689

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