Synergies of green hydrogen and biobased value chains deployment

Synthesis Report

Contribution of IEA Bioenergy Tasks 44, 45, 40, 33 and 34 to the Inter-Task Project (ITP) Synergies of green hydrogen and biobased value chains deployment

IEA Bioenergy: Task 44 Flexible Bioenergy and System Integration

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Synthesis Report

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Preface

According to the International Energy Agency (IEA), fuels in the form of hydrogen, hydrogen-based fuels, and bioenergy will have to meet 24% of global final energy demand in 2070 in the Sustainable Development Scenario (SDS), particularly in the areas where direct electrification is difficult (IEA, 2020). The statistics show that all these fuels need to ramp up quickly to meet the targets. Bioenergy is a limited but a very diverse energy carrier and required for various applications (industry, transport, high-temperature heat, negative carbon emissions etc.). The future scenarios typically see bioenergy in combination with carbon capture and storage/utilization (CCS/U). The SDS describes that 20% of hydrogen use in 2070 will be in the production of synthetic fuels from hydrogen and CO_2 for the aviation and further 10% used for ammonia production (IEA, 2020). While most of the hydrogen is produced from natural gas today, the demand for renewable hydrogen is increasing. The main interest has so far been in electrolytic hydrogen from wind and solar electricity (IEA, 2021).

In addition to electrolytic hydrogen, there are also great opportunities to convert biomass to renewable hydrogen, so-called biomass-based hydrogen or biohydrogen. This option is currently a rather overlooked opportunity for providing renewable hydrogen and there is a need to make information and data available on biohydrogen production and utilization options. Furthermore, there are many biobased processes either in demand for renewable hydrogen (e.g. synthetic renewable fuels, biorefining) or that could benefit from renewable hydrogen integration for improving the quality of products (e.g. boosting biomethane production). In addition to process level synergies between hydrogen and biobased value chains, system level synergies and services are expected to take place, such as increased flexibility, use of joint infrastructure and provision of long-term storage options. Different synergies could benefit the economic deployment of both bioenergy and renewable hydrogen-based fuels, and the overall energy system demands.

Biohydrogen and renewable hydrogen in biobased processes

Biomass-based hydrogen or biohydrogen pathways should be considered as an important complement to water electrolysis as many of the biogenic pathways may provide great benefits such as:

- Non-intermittent, fossil-free, large-scale hydrogen production, i.e. 24/7.
- Mitigation of the demand for fossil-free power.
- Process integration opportunities to reach more energy efficient production systems.
- Co-production of other value-added commodities such as biocarbon, biochar, biomethane etc.
- Carbon dioxide removal if CCS is applied or biochar produced.

Adding renewable hydrogen to biobased value chains represents another strong link between hydrogen and biomass/bioenergy. In principle, renewable hydrogen integration into biobased value chains can be done to 1) replace conventional, fossil hydrogen use, 2) upgrade the quality of products, or 3) produce (additional) products and by-products.

Within the IEA Bioenergy strategic Inter-task project “Synergies of green hydrogen and biobased value chains deployment” the focus is on the value chains directly linked to bioenergy, i.e., biomass as a source of hydrogen production (biohydrogen) and biobased processes utilizing renewable hydrogen. Representative examples are showcased to describe the potential role of biobased value chains linked to the hydrogen economy, and to create a clearer overall picture of the promising value chains and their potential for future applications.

In this report, we summarize and synthesize the assessment work done in the inter-task project for different case studies either reflecting on the production of hydrogen from biomass or the renewable hydrogen uptake in biobased processes. We provide a concise presentation of the overall results and put these into a broader context and discuss further research needs. In section 1, we present a brief overview on the case studies that were subject of the study[1], followed by a summary of different services provided from hydrogen and biobased value chains deployment as perceived in energy system modelling in section 2 and a summary of the environmental performance of the different case studies including the description of the Life Cycle Assessment methodology applied and developed in section 3. Section 4 concludes with a forward-looking discussion into issues on the need of further research.

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[1] On the description of the different case studies there are separate reports available (Lundgren 2025 and Funke 2025).

Summary

Over the duration of the IEA Bioenergy triennium 2022 to 2024, a consortium of IEA Bioenergy Tasks – 32, 33, 34, 36, 37, 39, 40, 42, 44 and 45 – collaborated on an inter-task project called Synergies of green hydrogen and biobased value chains deployment. Hydrogen is a very cross-cutting topic and the strategic inter-task project is a collaborative effort of the IEA Bioenergy TCP Tasks and also in collaboration with the Hydrogen TCP.

The objective of the project was to identify and assess technologies for producing hydrogen from biomass as well as synergies in the deployment of renewable hydrogen and biobased value chains that can enhance the use of biobased value chains in the energy system.

The descriptions of technologies and concepts - including 1) technology readiness and economic fundamentals and 2) climate effects and role in the energy system - are done through case studies. This serves to increase the visibility of the topic area of biomass and hydrogen as well as to share the state-of-the-art knowledge of promising applications.

In the report on hand considerations on the current and prospective role of biomass and hydrogen within the energy system and the climate effects for supporting the decarbonization of the energy system have been analyzed. With regards to energy system models, the objective was to understand to what degree renewable hydrogen and in particular biohydrogen value chains are integrated into these models and roadmaps, and what systemic benefits they are anticipated to offer. The key outputs are an overview of the current and prospective role of these value chains in energy system models summarizing the status and future needs and expectations. From the overview on different energy system models, it can be learnt that the production and use of biohydrogen is not foreseen within the majority of projections. In some cases, the role of biohydrogen is small even in the most optimistic scenarios. The provision of renewable hydrogen is thus far entirely considered via electrolysis from VRE sources.

Moreover, climate effects assessment studies of selected biohydrogen and hydrogen in biobased processes, recognizing methodological questions and the main factors influencing the GHG balance calculations of the studied value chain concepts have been conducted.

All the biobased systems outperformed their fossil counterparts regarding the impact category Global Warming Potential (GWP), but were rather performing poorly in the impact categories terrestrial acidification (TA), and freshwater eutrophication (FE). The electricity-mix is one dominant parameter that significantly influenced the environmental performance of the biomass systems. Hence, although biomass integrations with renewable hydrogen or e-fuels may be attractive from product yields and diversification perspectives, less resource-intensive green electricity supplies will be critical for their satisfactory holistic environmental performance. The overall findings suggest that, regardless of the region, the biobased systems may play a vital role in reducing carbon emissions in the energy sector.

With focus on the biohydrogen value chain relative to the GWP and FE, the biochar credit (i.e., pulverized coal displacement) is a key deciding factor regarding the best-performing biohydrogen route. Regarding fossil-based hydrogen replacement results show, that biohydrogen is a superior choice to PEM hydrogen from an environmental viewpoint. Relative to fossil-based hydrogen, the studied biohydrogen systems could lead to substantial reductions in GWP. Therefore, process energy efficiency enhancements and sustainable green electricity supplies are essential for the holistic environmental success of the biohydrogen systems.

Overview on case studies and technologies for producing hydrogen from biomass and value chains combining renewable hydrogen into biobased processes

Biobased value chains can be closely linked with renewable hydrogen industry by either providing renewable hydrogen from biomass resources (also referred to as biohydrogen) or adding renewable hydrogen from electrolysis to biobased value chains. In order to shed some light on the status quo of deployment and the role of biohydrogen as well as the overall renewable hydrogen use in biomass processes within the energy system various existing concepts and projects have been presented in more detail. Here, in particular, the techno-economic performance and the role within the energy system have been presented by means of case studies.

Thus, a selection of 15 different case studies has been made addressing either 1) technologies producing hydrogen from biomass (biohydrogen) or 2) biobased processes that consume renewable hydrogen (e.g. for boosting biofuels production). The discussion on promising concepts for consideration and evaluation for suitability as future application had been done as part of an expert workshop. There, among others, deployment perspectives of biohydrogen have been presented and criteria for selecting certain pathways defined (Hennig et al., 2023a)

The technologies selected for case studies are presented in Table 1. As it can be noted, the technologies represent various pathways and products where hydrogen and biomass are linked to each other. The various technologies and concepts are of different technology readiness and the majority of concepts position at Technology Readiness Level (TRL) 6 to 7. While the presented projects and activities are located in Europe and South America, many of the technologies utilize feedstock types that make them applicable in other regions as well. Further details on the individual case studies are presented in the following paragraphs, and each case study can be found in the two accompanying case study reports (compare Lundgren et al. 2025 and Funke et al. 2025):

Table 1 The selected case studies for consideration of biohydrogen production and renewable hydrogen use in biobased processes.

Project/Company	Country	Technology	Products/by-products	TRL - weakest link	TRL - weighted average
Case studies on hydrogen from biomass					
Torrgas Technology BV	NL	Medium/large-scale gasification	A tar and nitrogen free syngas for production of methanol, H2, SNG, SAF and biochar as soil improvement or in the (chemical) industry	5	7
Cortus AB, WoodRoll®-technology	SE	Small-scale gasification	Biochar, H_2, SNG	5	7
RISE & Indienz AB	SE	Anaerobic digestion	H_2 and methane	5.8-6.7	4

Hytron/NEA	BR	Alcohol reforming	H_2	6-7	7.2-7.8
Nissan	BR	Onboard alcohol reforming	H_2, electricity	6-7	6.5-7.3
Hycamite Oy	FI	Thermo-catalytic decomposition (or pyrolysis)	H_2, solid carbon in different forms for wide range of applications, e.g., graphitic carbon for battery storage	6	6.7
Case studies on H_2 uptake in biobased value chains					
Skærbæk	DK	Biomass combustion with CCU	Heat, electricity	5	7
LTU Green Fuels	SE	Hybrid biomass gasification and electrolysis process	Methanol/DME	4-5	6-7
reFuels	DE	Green refineries with focus on fuel production	SAF, Marine fuels, Road transport fuels	5	6-7

Electrochaea	DK	Biological methanation	Heat	8-9	8-9
Pilot-SBG	DE	Catalytic methanation	BioLNG Fertilizer, HTC products like biochar	4	7-8
HyFuelUp	PT	Dual Fluidised Bed – Sorption Enhanced Reforming Gasification + Fluidised bed methanation	Bio-LNG	5	6-7
Lignin valorisation (HDO)	IT	Upgrading/ hydrodeoxygenation of lignin	Aromatic monomers/BTX/phenols/cycloalkanes	3-4	5-6
Silvagreen Fuel	EU	Upgrading of HTL oil	HTL oil	4-5	7-8
PTG-HEFA	DE and other regions	PTG-HEFA-SPK	HEFA-SPK, HVO-Diesel, naphtha	9	9
Omega Green advanced biofuel plant	PY	Electrolytical hydrogen in HVO plants	HVO, HEFA-SPK, green naphtha	9	9

BIOMASS AS A SOURCE OF HYDROGEN

Thus far, hydrogen based on electrolysis is dominating the area of renewable hydrogen provision, however less focus is put on biomass-based hydrogen production pathways. These pathways should be considered as an important complement to water electrolysis as many of the biogenic pathways may provide great benefits such as:

- Non-intermittent, fossil-free, large-scale hydrogen production, i.e. 24/7.
- Mitigation of the demand for fossil-free power.
- Process integration opportunities to reach more energy efficient production systems.
- Co-production of other value-added commodities such as biocarbon, biochar, biomethane etc.
- Carbon dioxide removal (negative CO_2-emissions) if CCS is applied or biochar produced.

Biohydrogen is an additional hydrogen production route to the well-known process via electrolysis, using renewable electricity. There are numerous production pathways to convert different types of biomass resources to biohydrogen. Overall, the pathways can be divided into two main groups, thermochemical and biological technologies (Lundgren et al. 2025):

- **Thermochemical conversion processes** include technologies as pyrolysis, hydro- and solvothermal liquefaction, and gasification followed by required downstream upgrading such as reforming, separation etc.

- **Biological conversion processes** include technologies water-gas shift reactions promoted by micro-organisms, photo-fermentation and dark fermentation, anaerobic digestion followed by biogas/biomethane reforming, fermentation to alcohols followed by reforming, and bio-photolysis with photosynthetic organisms.

For exploring hydrogen production routes based on biomass, different conversion pathways have been chosen. The case studies utilize existing projects of companies or institutions showing different TRL. The information and data stems from within the IEA Bioenergy Network or from associated contacts. Detailed case study descriptions with information on the technology, status of project realization and its drivers, barriers and framework conditions as well as a techno-economic assessment are provided in dedicated case studies reports (Lundgren et al. 2025). Information on the environmental performance and the role of biohydrogen within the energy system is presented and discussed in this report.

The biohydrogen technologies chosen as case studies presented in Table 1 include gasification, anaerobic digestion, alcohol reforming, and thermocatalytic decomposition. These technologies use a wide variety of feedstocks to produce hydrogen; torrefied biomass, woody biomass, wastewater, ethanol, and methane. Thus, many of the technologies can be adapted to utilize local feedstocks. The feedstocks can be of lower grades, such as wastewater or agricultural residues, or higher quality such as bioethanol and biomethane. Many processes generate additional value-adding commodities such as biochar and biocarbon, increasing resilience and likely also improved economic performance. All the production concepts are still under development, many of them having reached TRL of 7. The weakest link associated to many of the concepts is related to complete integrated operation.

The levelized cost of hydrogen (LCOH) estimation for biohydrogen technologies ranges from 3 to 8 €/kgH_2. Although the estimations have a high level of uncertainty due to the low TRL levels, the economic performance for biomass-based hydrogen seems promising. While hydrogen production via electrolysis is generally seen as the most economically feasible option to produce renewable hydrogen, biohydrogen could reach equal or even lower production costs, particularly in regions where large biomass resources are available.

Production of hydrogen from biomass can potentially be integrated with capturing of biogenic carbon which would lead to so-called 'negative CO_2-emissions' when stored with high permanence. This would allow to extract atmospheric CO_2, which is temporarily stored in the biomass, and its removal from the carbon cycle if carbon capture and storage is applied or biochar produced. Thus, this type of biohydrogen value chain could be a part of a broader carbon dioxide removal portfolio, as there is a wide scientific consensus that these technologies are needed to reach global climate goals (IPCC 2022). Consequently, the result is the availability of renewable hydrogen with a net negative carbon footprint, which offers potential for financial rewards via Carbon Credits.

BIOBASED PROCESSES CONSUMING RENEWABLE HYDROGEN

Next to hydrogen production from biomass, adding renewable hydrogen to biobased value chains is another strong link between hydrogen and biomass/bioenergy that can be considered. In principle, renewable hydrogen integration into biobased value chains can be done to 1) replace conventional, fossil hydrogen use, 2) upgrade the quality of biobased products, or 3) produce (additional) biobased products and by-products. The options differ in the degree of technological and process adaptation and development required. Adding renewable hydrogen vividly shows the potential synergies between renewable hydrogen and biobased value chains that can create various benefits (compare Figure 1):

- **Improving existing fuel infrastructure (A)**: The use of renewable hydrogen in carbon-based production to produce hydrogen-derived liquid fuels makes storage, transport, and utilization more convenient than gaseous or liquid hydrogen.

- **Synergies through process integration (B)**: Combining electrolysis with biofuel production enhances infrastructure efficiency, lowers logistics costs, and improves heat flow management. This facilitates decentralized renewable energy use and provides local chemical energy storage, potentially reducing hydrogen costs.

- **Enhancing carbon efficiency (C)**: Incorporating renewable hydrogen into biomass conversion processes significantly enhances carbon-to-fuel efficiency and, in some cases, improves the quality of the final products. Further on, renewable hydrogen can be used for upgrading product gases from gasification to liquid biofuels, biogas to biomethane, and pyrolysis oil to stabilized oil.

- **Facilitating liquid and gas co-production (BECCU) (D)**: Using bioenergy with carbon capture (BECC) in heat and power generation, renewable hydrogen is essential for utilizing the captured CO_2 (BECCU). This enables the co-production of liquid and gaseous carbon products alongside heat and power generation.

When looking into the role of CO_2 capture in concepts of renewable hydrogen uptake in biomass conversion processes, capturing could be beneficial either through efficient process integration and/or due to high CO_2 concentrations in the off-gases. This is relevant for, e.g., biological methanation processes (also compare Funke et al. 2025). While these are general benefits from integration of CO_2 activation in biobased value chains, the actual cost of available CO_2 will always be determined by additional factors, such as cost of electricity, scale of realization, local infrastructure, and contaminants in the off-gas (Funke et al. 2025).

In many established biobased value chains, such as hydrotreated vegetable oil (HVO) and hydroprocessed esters and fatty acids (HEFA), hydrogen is essential for producing high-quality transportation fuels. This creates a fundamental link between hydrogen economy and biobased value chains. These value chains can serve as energy carriers for both transportation and storage of hydrogen. However, there are significant differences between technologies typically used for hydrogen transport and storage. In most cases, hydrogen is integrated into the production of a final product rather than used as an intermediate hydrogen carrier.

Overall, the transition to a hydrogen economy, or even the substantial addition of hydrogen as an energy carrier, necessitates significant infrastructure for production, transport, and storage. Various technologies exist for hydrogen transport and storage, each with its own performance to assess suitability for future applications.

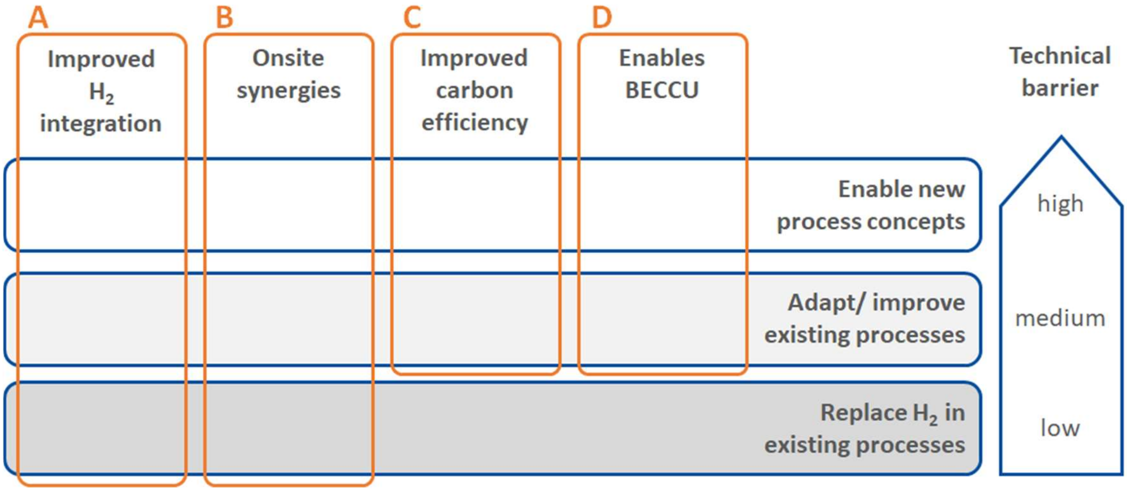

Figure 1 Overview of potential benefits (A-D) and level of technical barrier for integration of renewable hydrogen in biobased value chains (Funke et al. 2025)

Synergies and services from renewable hydrogen and biobased value chains deployment from a system perspective

Energy system models and roadmaps are important tools for envisioning and guiding the transition to low-carbon energy systems. Many countries have developed comprehensive scenarios to carbon neutrality, incorporating bioenergy and hydrogen to explore their roles in achieving decarbonization targets. A general perspective of the role of different technologies and value chains is provided by, e.g., Integrated Assessment Models (IAMs) and international roadmaps, such as the IEA's *Net Zero by 2050*. This chapter aims to compile insights from various national and international modelling studies to understand to what degree renewable hydrogen and in particular biohydrogen value chains are integrated into these models and roadmaps, and what systemic benefits they are anticipated to offer (Hennig, C. et al. 2023b). In this respect also the role of renewable hydrogen and bioenergy within the energy system and a possible interplay between these two low-carbon energy carriers will be addressed.

INTERNATIONAL ENERGY SYSTEM MODELS AND ROADMAPS

The Net Zero by 2050 roadmap provides a comprehensive global framework for achieving net-zero emissions by mid-century (IEA, 2023). First published in 2021, the updated roadmap from 2023 considers the recent developments in technologies, markets, and policies and describes what is needed from policymakers and other stakeholders all around the world for the Net Zero target to become reality.

One cornerstone of the Net Zero Emissions by 20250 Scenario (NZE) is the expansion of hydrogen as a versatile energy vector. Hydrogen is integrated across power, transport, and industrial sectors, with a significant shift toward renewable hydrogen produced via electrolysis powered by renewable electricity. By 2050, hydrogen use is projected to account for nearly 10% of global final energy demand, which is driven by substantial increases in renewable electricity production. Figure 2 presents the cumulative electrolyzer capacity growth by 2050, which must grow to 590 GW by 2030 and reach about 3,300 GW by 2050.

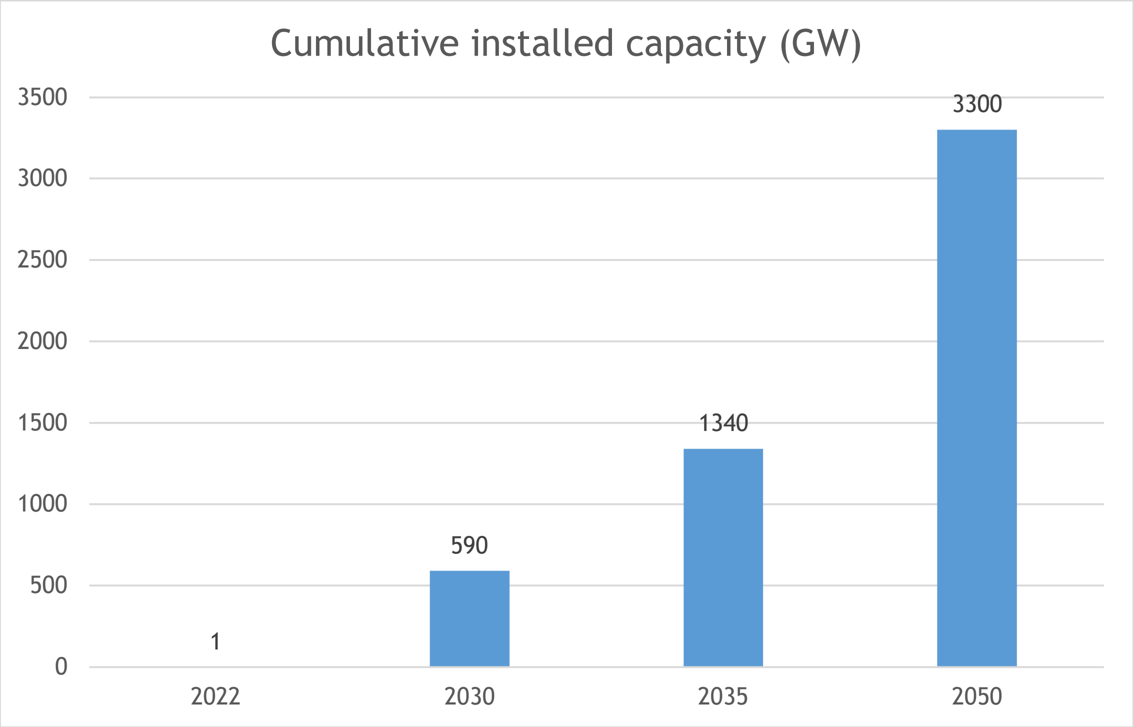

Figure 2. The cumulative installed electrolyzer capacity milestones set in the IEA NZE Scenario (IEA, 2023).

Bioenergy complements hydrogen within the NZE as a flexible and renewable resource, especially through its integration into bioenergy with carbon capture and storage (BECCS) systems. BECCS is identified as essential negative emissions technology (NET), which enables low-carbon energy production and CO_2 removal simultaneously. By 2050, modern bioenergy is projected to reach 100 EJ, with BECCS capturing approximately 1 Gt CO_2 annually, especially from power generation and biofuel production. Gaseous bioenergy, such as biogas and biomethane, supports decarbonization via direct substitution for the fossil natural gas in power generation and industrial heat, while it can also provide renewable carbon feedstock for hydrogen-derived fuels. However, the production and use of biohydrogen is not foreseen within the projections. The provision of renewable hydrogen is entirely considered via water electrolysis.

The interplay between hydrogen and bioenergy is emphasized in synthetic fuel production, where biogenic CO_2 is utilized alongside hydrogen to produce e-fuels for hard-to-abate sectors like aviation and maritime. Hydrogen and bioenergy can be combined in multiple ways and can contribute to energy system flexibility through long-duration storage and sector integration. Within the NZE the seasonal balancing is strengthened by growing underground hydrogen storage capacity, which is anticipated to grow from 70 TWh in 2030 to 1200 TWh by 2050.

While ambitious, the NZE highlights significant barriers to realizing its targets, including the high upfront costs of hydrogen infrastructure, limited availability of sustainable biomass, and the need for coordinated policy frameworks. These challenges underline the importance of addressing resource availability and political priorities, as well as regional disparities in technology adoption to achieve a balanced and just energy transition.

Integrated Assessment Models (IAMs) are tools that represent the complex interactions between economic, social, and environmental systems to provide policy-relevant insights into global environmental challenges and sustainable development. They integrate knowledge from multiple disciplines to quantify human-environment interactions and often focus on energy-land-economy-climate linkages. These models help decision-makers to evaluate trade-offs, uncertainties, and sustainable transformation pathways both at global and regional levels (IAMC, n.d.). IAMs play an important role in, e.g., in the Intergovernmental Panel on Climate Change (IPCC) work to assess and quantify the complex effects of climate change.

The fast development of technologies and trends in energy transition can pose a challenge for these modelling activities. Renewable hydrogen has gained significant interest as a clean energy carrier and is anticipated to play a strong role particularly in decarbonizing the transport and industrial sectors. To support this momentum, energy system modelling can and will keep providing policy-relevant insights of decarbonisation pathways, in which an accurate representation of the impactful hydrogen and bioenergy value chains is important.

Within the international research community, the representation of hydrogen in energy system modelling has been studied in the IEA ETSAP community, and also together with the IEA Bioenergy Technology Collaboration Programme (TCP). An initial debate and analysis on the role of renewable hydrogen and in particular biohydrogen in energy system modelling took place as part of a joint workshop organized by IEA ETSAP and IEA Bioenergy in November 2023[2]. Dodds et al (2022) compared the hydrogen energy systems across the TIMES energy system models within the ETSAP community and presented guidelines for hydrogen supply chains representation. Specifically, it focused on the improvement of the ETSAP-TIAM model, but it discusses the considerations regarding hydrogen end-uses, production, and delivery systems and their level of detail depending on the geographical scope of the model, which are applicable to other models as well.

Out of the 10 models studied, 7 considered biomass-based hydrogen production. Biomass with CCS was considered in four. The report recommends that the minimum set of technologies regarding hydrogen production from biomass should be biomass gasification, both with and without CCS, and biomethane Steam Methane Reforming (SMR) with CCS. There is considerable variation in cost and performance assumptions for different technologies between the models, and in many cases the data is difficult to obtain. As the costs of several technologies are not well understood thus far, the consideration of various hydrogen end-use and production technologies, such as biohydrogen production, has been limited. The challenges related to data availability were further emphasized during the joint workshop organized by IEA ETSAP and IEA Bioenergy in November 2023. The workshop highlighted the importance of better valuing flexibility and more accurately representing biomass-hydrogen value chains and reflecting on their costs. It also underscored the need for improved data integration in energy system models to enhance the representation of bioenergy and renewable hydrogen from biomass, reduce uncertainties, and improve predictive accuracy. With the help of this IEA Bioenergy study a better understanding on the costs for producing biohydrogen has been created. The results show that the production costs for biohydrogen are on comparable levels to hydrogen from water electrolysis (compare Lundgren et al. 2025).

A meta-analysis by Ghaboulian Zare et al. (Ghaboulian Zare et al., 2025) reviewed 50 studies (2003-2024) to examine the role of hydrogen within IAMs. The review examined the

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[2] https://iea-etsap.org/index.php/workshops-meeting/winter-november-2023; https://iea-etsap.org/workshop/online_winter_dec2020/S5-02_paul_dodds_etsap_workshop_hydrogen_project_dec2020_v1.pdf

characteristics of hydrogen integration across 12 IAM families by analysing the configurations of hydrogen value chains, the embedded assumptions, and the modelling uncertainties.

Regarding the sectoral coverage of the IAMs, a categorization framework was established to assess the representation of hydrogen across various dimensions of energy systems. Furthermore, the review explored different production pathways, including electrochemical, thermochemical, and biochemical routes. Hydrogen production and end-use were the most consistently modelled components, while distribution and storage received less attention, appearing in only approximately 15 and 10 studies, respectively – despite their critical role in large-scale hydrogen deployment. While electrochemical hydrogen production was included in most studies, biochemical pathways are addressed in roughly half. The level of detail for biochemical pathways varied: for instance, MESSAGE-ix includes several types of biomass gasification, with and without CCS.

Across 541 scenarios that limit global warming to 2°C or lower, biohydrogen contributes approximately 14% (10 EJ/a) of projected global hydrogen production (70 EJ/a) by 2100. Stricter temperature targets were observed to correlate positively with increased hydrogen production. However, these production volume estimates exhibit considerable uncertainties, as evidenced by significant differences between median and average values, along with the presence of outliers. While the level of detail varies considerably between IAMs, the general consensus among the studies was that hydrogen can play a significant role in decarbonization, particularly in the transport and industry sectors.

EUROPEAN ENERGY SYSTEM MODELS AND ROADMAPS

The NEGEM[3] project assessed the realistic and sustainable potential of Negative Emission Technologies and Practices (NETPs) for meeting the 1.5 °C goal outlined in the Paris Agreement. It combined qualitative and quantitative approaches to evaluate technologies such as BECCS, DACCS, biochar, soil carbon sequestration, and enhanced weathering, integrating them into global and European energy system models (TIMES-VTT and Pan-European TIMES) (Lehtilä et al., 2023). Three scenarios were developed:

- 1.5C-Tec: Rapid technological advances and global cooperation
- 1.5C-Env: Environmental limits on NETPs due to planetary boundaries
- 1.5C-Sec: Regional self-sufficiency and geopolitical fragmentation.

Achieving the 1.5 °C target requires employing NETPs on a gigatonne scale. The investments in NETPs reach the highest levels after 2060, but significant amounts of BECCS, biochar, and soil carbon sequestration take place already in 2040. Bioenergy with Carbon Capture and Storage (BECCS) is widely applied across the energy sector, capturing 200 – 360 GtCO_2 by 2100, describing the significant attributed to BECCS. Global biomass use increases from 60 EJ today to 90 – 120 EJ by 2100, with the highest reliance in the 1.5C-Tec and 1.5C-Sec scenarios. The trajectories align with the IEA NZE scenario but also highlight risks: climate-induced yield reductions, competing biomass resources demand, e.g., for materials and chemicals, and stricter sustainability criteria may constrain bioenergy deployment.

Electricity demand reaches 140 – 180 PWh globally by 2100, which is partially both driven and

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[3] https://www.negemproject.eu/

enabled by hydrogen: an expanding hydrogen economy and increase e-fuels production increase the electricity demand. The various types of energy storages included in the model, such as Power-to-X, batteries, and pumped hydropower, also enable a high degree of electrification in the energy systems.

The more detailed European modelling within the NEGEM project highlights a heavy reliance on BECCS and DACCS to meet net zero target in EU by 2050. For example, in the 1.5C-Env scenario, direct emissions are cut by 76% compared to 1990 levels, but the remaining 24% of the reduction is achieved using NETPs, as direct emission cuts become increasingly costly. By 2050, NETPs contribute 1.1–1.4 $GtCO_2$ removal per year (cumulatively 35 $GtCO_2$ by 2065), where BECCS and DACCS dominate the technology portfolio, followed by afforestation, enhanced weathering, soil carbon sequestration (SCS), and biochar. With regards to hydrogen the results suggest that hydrogen production from biomass becomes cost-competitive in some European countries (e.g., Norway and Spain) due to high carbon prices but has a proportionally smaller role compared to global levels because of the assumed limited availability of sustainable biomass resources in Europe.

Markkanen et al (2024) further analyzed the NEGEM scenarios for Europe, with particular emphasis on the risks of over-reliance of CDRs. The results suggest that even deep CO_2 cuts alone are insufficient to achieve carbon neutrality by 2050, even with high ETS1 CO_2-prices. DACCS emerges as the dominant CDR technology here, despite its high cost and energy demand, assuming severe constraints on sustainable biomass availability for BECCS. The biomass use in EU-31 ranges from 4 to 6.2 EJ/a, where the Environmental-scenario employs the least and Security-scenario the most biomass. Biohydrogen is assumed to become cost-competitive in 2040 with higher importance in the Security-scenario and when fewer NETP options are available. However, the role of biohydrogen is small even in the most optimistic scenarios, reaching approximately 0.1 EJ/a. In general, biomass use shifts from heat and power toward biogas and biofuels with CC. In the Security-scenario, biofuels with CC reach 1.2 EJ/a by 2050, whereas in technology-driven scenario, biogas with CC reached 2 EJ/a, with biofuels playing a smaller role (0.5 EJ/a).

While IAMs and roadmaps such as IEA's NZE provide long-term projections for hydrogen and bioenergy integration, modelling and identifying the bottlenecks on a more practical level is necessary to ensure these transitions can take place. One such example is the **Ten-Year Network Development Plan** (TYNDP). It is a biannual initiative by ENSTO-E and ENTSOG that maps European electricity and gas grid development in alignment with EU climate goals. It is often used as a basis for energy system modelling in Europe; in particular, the National Trends scenario has been developed to correspond the national energy and climate plans, which serves as a good starting point for further research.

The Scenario Methodology Report outlines the modelling framework, including hydrogen integration starting from 2022 and expanded further in the 2024 iteration (ENTSO-E & ENTSOG, 2024). The latest modelling incorporates hydrogen in e-fuel production (e.g., e-diesel, e-kerosene, and synthetic methane) via coupling with biogenic CO_2. The e-fuel potential is linked to the availability of biogenic CO_2 in Europe. On the demand side, the model considers hydrogen use in industry and transport, but also to a lesser extent in residential heating. In transport, a flat demand profile is assumed for industry and heavy-duty vehicles, while for aviation, the seasonal supply needs for hydrogen are derived from the historical kerosene profiles. The potential hydrogen sources in the modelling include natural gas with or without CCS, electrolysis, and by-products from industrial processes.

While according to the TYNDP modelling biomass combustion for electricity generation declines, biomethane production is projected to increase from 375 TWh today to 980-1250 TWh by 2050. Hydrogen use expands from industry into more various uses, such as in transport and residential sector. This growth takes place particularly via e-fuels, with demand reaching 800 TWh by 2050, which equals current gasoline consumption. By then, Europe's gas supply is projected to be fully decarbonised, low-carbon hydrogen being dominant in the beginning and gradually replaced by renewable hydrogen by 2050. Electrolysis capacity is expected to approach 400 GW by 2050, which significantly increases renewable electricity demand alongside direct electrification.

Regarding hydrogen flexibility, the TYNDP modelling approach was set up to allow flexibility from various sources, such as large-scale underground hydrogen storages, steam methane reforming (SMR)/autothermal reforming (ATR), e-fuel production, import terminals, and demand side response. The flexibility needs by 2050 in order to balance supply and demand is set up to 180 TWh. However, the report does not specify the timescale of flexibility — whether it refers to short-term, weekly, or seasonal balancing — which is an important distinction. Moreover, the report advises that flexibility sources may not deliver as expected due to technical or economic reasons, underestimating the importance of hydrogen storage facilities. The hydrogen storage capacity need is very sensitive to flexibility limitations, with storage capacity requirements potentially increasing significantly under scenarios of limited conventional hydrogen production and imports.

Overall, TYNDP 2024 remarks that hydrogen introduces both new flexibility opportunities but also challenges. Electrolysis-based production adds weather-dependent variability to the energy system while emerging heating applications introduce temperature-dependent variability for hydrogen demand. The model projects low operational hours for hydrogen power plants, highlighting their role specifically as backup capacity during low renewable output periods.

SUMMARY

All studies on energy system models emphasize the central role of renewable hydrogen and bioenergy in transitioning to low-carbon energy systems. Renewable hydrogen is recognized for its versatility across sectors like transport, industry, and power, while bioenergy's adaptability and compatibility with existing infrastructure makes it a near-term enabler of the energy transition.

Both resources are seen as important for enhancing energy system flexibility, especially under high shares of variable renewable energy (VRE). Hydrogen offers temporal and seasonal balancing through its capability to store renewable electricity, balancing grid fluctuations, and providing dispatchable backup capacity during low RE periods. Bioenergy complements this through its steady and dispatchable availability, with applications ranging from biogas in power generation to biogenic CO_2 use in synthetic fuels.

The energy system models and roadmaps also converge on the potential role of hydrogen in decarbonizing hard-to-abate sectors such as aviation, maritime, and heavy industry. Bioenergy is seen to complement these efforts, particularly through BECCS and biomethane production, and also offering sustainable carbon inputs for hydrogen-derived e-fuels and helping offset residual emissions. In turn potential competition between biomass use for the hydrogen economy and for providing negative emissions via BECCS can arise.

Environmental impacts of biomass-based hydrogen production chains and renewable hydrogen use in biobased value chains

OVERVIEW ON CASE STUDY VALUE CHAINS

This section focuses on the environmental impact assessment of a number of promising case study value chains from the inter-task project Synergies of green hydrogen and biobased value chains i.e., methanol, hydrogen, and biocrude (compare Lundgren et al. 2025 and Funke et al. 2025 and Table 1), which are summarised in Table 2. The case study value chains and the life cycle assessment (LCA) approach employed in the environmental assessment are briefly described in the following sections. More details can be found in the available reports available.[4]

For the environmental impact assessment, only a selection of the total set of case studies covered in the work packages 2 (Hydrogen from Biomass) and 3 (Hydrogen uptake in biobased processes) of this inter-task project was further analysed. The selection of case studies was based on amongst others on choosing a wide variety of different routes and the willingness and ability of industrial partners to provide input data. In addition, in this chapter we only present the results of the case studies that had the same biomass feedstock (namely wood chips) as input and a limited set of final products as output: bio-methanol and/or biogenic hydrogen (and biocrude and /or biochar as byproducts). This was done in order to enable an easy comparison of results for the different conversion routes. In addition, hydrogen production via pyrolysis using biomethane (Hycamite case study) and via anaerobic digestion using e.g. waste water streams (Bioflex case study) were also investigated. The corresponding results on the environmental impact assessment are available in a separate publication (Martínez-Arce, 2025; Martínez-Arce & Styles, 2024).

Table 2 Case study biobased value chains and LCA parameters

	Case study 1 | Based on HTL	**Case study 2 | Based on Gasification, Torrgas Technology**	**Case study 3 | Based on Pyrolysis + Gasification, Cortus WoodRoll® Technology and Torrgas Technology**
Biomass and Hydrogen	**Hydrogen uptake in biobased processes**	**Hydrogen uptake in biobased processes**	**Production of Hydrogen from Biomass**
Products and by-products	**HTL-oil, biochar**	**Biohydrogen, bio-methanol, biochar**	**Biohydrogen, bio-methanol, biochar**
Targeted product	**Advanced biocrude fuel**	**Bio-methanol**	**Biohydrogen**
Feedstock(s)	Wood chips	Wood chips	Wood chips

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[4] Detailed process descriptions are available in three master’s theses (Martinez, 2024; Gonzales, 2024; Maran, 2024). See: https://studenttheses.uu.nl/handle/20.500.12932/48080; https://www.diva-portal.org/smash/record.jsf?pid=diva2%3A1897973; https://urn.kb.se/resolve?urn=urn:nbn:se:kth:diva-354068

Process routes	**R1**: HTL + H_2T of the obtained bio-oil to produce biocrude. **R2**: HTL + H_2T + PEM [1] + CCU to produce biocrude & methanol.	**R1**: Two-stage gasification of torrefied biomass + hydrogenation of carbon oxides into methanol using H_2 from syngas & WGS. **R2**: Gasification + full hydrogenation of the carbon oxides (additional H_2 from PEM electrolyser). **R3**: HTL + H_2T + PEM + CCU to yield biocrude & methanol (Similar to the ABF-R2, biocrude by-product).	**R1**: Pyrolysis + Gasification of wood chips + PSA + WGSr + PSA **R2**: Two-stage gasification of torrefied wood chip + WGSr + PSA
Product(s)	R1: Advanced biocrude (biocrude only); biochar by-product. R2: Advanced biocrude (biocrude + methanol); biochar as by-product.	R1: Bio-methanol, biochar by-product. R2: Bio-methanol; biochar by-product. R3: Methanol + biocrude; biochar by-products.	R1: Biohydrogen; biochar & ash by-products. R2: Biohydrogen; biochar by-product.
Technology scope / developer	R1 & R2: Process simulation (Lozano Sanchez et al., 2024).	R1 & R2: Pilot demonstration (Torrgas Nederland BV). R3: Process simulation (Lozano Sanchez et al., 2024).	R1: Pilot demonstration (WoodRoll® technology- Cortus AB company). R2: Pilot demonstration (Torrgas Nederland BV).
Conventional fossil-based reference systems	Diesel from petroleum refinery (for biocrude) [2], SMR of natural gas (for methanol) [3]	SMR of natural gas (Ecoinvent database) [3]	SMR of natural gas (Ecoinvent database) [4]

NB: HTL- Hydrothermal liquefaction, H_2T- hydrotreating, PEM- proton exchange membrane water electrolyser, PSA-Pressure Swing Adsorption, CCU- carbon capture and utilisation, SMR- steam methane reforming, WGS- water-gas shift unit, ABF- Advanced Biocrude Process.

[1] Background data for the PEM electrolyser modelling were sourced from Krishnan et al. (2024), with further methodological details described by Padi et al. (2025).

[1] The adopted Ecoinvent v3.10 dataset (i.e., Diesel, at refinery/RER S) is a multioutput crude-oil refinery process (i.e., petrol, unleaded, bitumen, diesel, light fuel oil, heavy fuel oil, kerosene, naphtha, propane/ butane, refinery gas, secondary sulphur and electricity) in which the impacts from wastewater treatment, process emissions and direct discharge to rivers are allocated to the various products. (NB: 'RER S' denotes a dataset representing Europe, with the process classified under a system model variant).

[2] Evaluated via the 'Methanol, at plant/GLO U' dataset from Ecoinvent v3.10. In the process, SMR of natural gas generates syngas for methanol production. It was assumed that CO_2 is unutilized, and the derived hydrogen is burned in-house. The analysis considers impacts from raw materials, processing energy, catalysts, emissions to air and water, and plant infrastructure.

[3] The adopted dataset from Ecoinvent (i.e., Hydrogen, gaseous, low pressure {RER}| hydrogen production, steam methane reforming | Cut-off, U') entails an SMR of natural gas to yield syngas for hydrogen recovery via PSA. Hydrogen yield is enhanced via water-gas-shift reactor with no syngas by-product formation. All process electricity and heat are supplied internally via natural gas. (NB: 'RER' indicates a dataset with European geographic coverage).

Definition of the biomass feedstock supply chain for environmental assessment

In the following, detailed information on the input data and assumptions used for the assessment is provided. The biomass feedstock supply chain (BFSC) encompasses pre-processing activities (i.e., wood harvesting, and recovery and forwarding of logging residues for chipping), transport of the wood chips to depots for temporary storage, and further transport to the final processing facility. The wood chips are derived from Norwegian spruce (Picea Abies) logging residues. It was assumed that only 80% of the referred residues are recovered to comply with soil health and carbon demands (Thiffault et al., 2016). Biomass losses during the chipping and temporary storage were assumed to be 3.6% and 8%, respectively (Hammar et al., 2015; Lindholm et al., 2010), resulting in net wood chip production of 106.3 m^3/ha. Methane emissions to the atmosphere during temporary wood chip storage are estimated to be 1.44 kg/ton dry mass (DM) based on a conservative assumption that methane accounts for 2.35% of the carbon emitted during wood chip storage (Alakoski et al., 2016; Kuptz et al., 2020).

In the BFSC, the logging residues are forwarded for chipping. The chipping facility is presumed to be sited close to the forest to reduce logistics costs (Johansson et al., 2006). Productivity and diesel fuel consumption of the forwarder are estimated at 6.1 Mg DM/EO and 11 L/EO respectively (where EO is an effective operational hour) (Lindholm et al., 2010). The chipping is carried out using a mobile chipper, which has a productivity of 90 m^3/EO, and a diesel fuel consumption rate of 3.9 L/Mg DM. Lubricant oil demands of the forwarder and chipper were estimated at 6% of their respective diesel fuel demands (Berg & Lindholm, 2005). A transport distance of 30 km was assumed for the first phase of the BFSC, representing average road transport distance from the forests to the logging company's depots. The second phase covers road transport from the wood chip depots to the final processing facility, presumed to be 100 km apart. The detailed set up of the individual biobased value chains of the considered case studies is presented below.

Case study 1: Advanced biocrude (ABF) value chain

Advanced biocrude process route 1

The ABF process route 1 (ABF-R1) on HTL is adapted from the study of Lozano Sanchez et al. (2024), and involves biomass liquefaction and refinement (BLR), and heat recoveries (Figure 3). The BLR process consists of hydrothermal liquefaction (HTL) and hydrotreating (H_2T) operations. The HTL process involves the thermochemical decomposition of the wood chip feedstock at 400°C and 300 bar in the presence of water using a homogeneous catalyst (K_2CO_3), which yields bio-oil, carbon-rich gases (i.e., HTL gases), an aqueous stream, and biochar residue. Other chemicals are used for pH control (NaOH) and products separation (methyl-ethyl ketone (MEK). The HTL gas is subjected to heat recovery for self-use. The biochar is designated for pulverized coal replacement in steel manufacturing process, while most of the aqueous stream is recirculated with the biomass feedstock to the HTL reactor with the remaining sent for wastewater treatment (WWT). The bio-oil is subjected to H_2T process (at 400°C and 150 bar in the presence of a Mo-Al_2O_3 catalyst), involving the use of H_2 in excess to upgrade the quality and stabilize the bio-oil to produce a refined product termed drop-in biocrude. Mainly water, CO_2 and CH_4 are produced during biocrude hydrotreating, generating a gaseous mixture (H_2T gases) that contains primarily the excess H_2 (94 vol.%) and an aqueous stream sent for WWT. The H_2 input to the H_2T reactor is supplied via H_2 recovery and recycling from the H_2T gases (i.e., gas recovery), which is augmented with H_2 from a PEM electrolyser. The gas recovery is achieved using a combination of Pressure Swing Adsorption (PSA) and Membrane (MEMB) separation technologies. The PSA unit recovers ≈75% of the H_2 from the H_2T gas, while the MEMB unit achieves 97% H_2 recovery rate from the gas discharge from the PSA. The gas effluent from the MEMB unit is added to the HTL gases for heat recovery prior to its discharge into the atmosphere.

Advanced biocrude process route 2

The ABF process route 2 (ABF-R2) models Bioenergy with Carbon Capture and Utilization (BECCU), thus incorporates CO_2 capture and conversion to methanol into the ABF-R1 process (Figure 3). Hence, in the ABF-R2, CO_2 in the carbon-rich HTL gases is captured and converted into methanol via hydrogenation process using H_2 from the PEM and gas recovery system. The carbon capture is achieved via the commercial Selexol^{TM} process, i.e., a solvent absorption process using dimethyl ethers of propylene glycol (DEPG) as solvent. The gas effluent from the Selexol^{TM} process consists of up to 20 vol.% H_2, which is sent for H_2 recovery in the gas recovery system. The discharge from the gas recovery system is sent for heat recovery. Methanol synthesis from the captured CO_2 and H_2 occurs at 220°C in the presence of a Cu/ZnO/Al_2O_3 catalyst. The process generates gases (i.e., mainly C1-C4 hydrocarbons) that are handled in the gas recovery system. Liquid effluent from the methanol system is sent for WWT along with the aqueous streams from the HTL and H_2T systems.

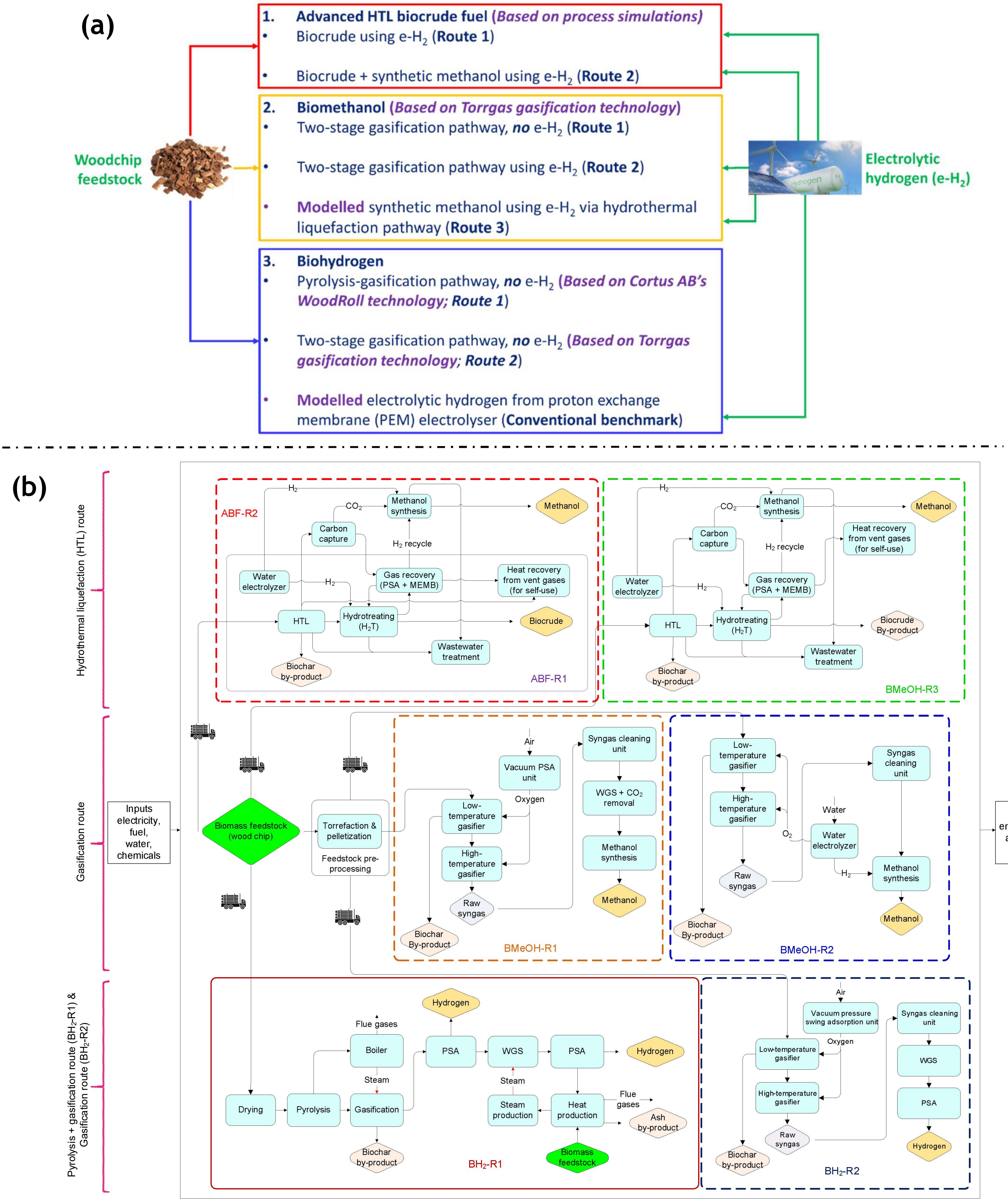

Figure 3 (a) Simplified schematics of the studied process case studies showing the 'hydrogen uptake in biobased processes' and 'hydrogen production from biomass' pathways, (b) Process flow diagrams of the studied biobased value chains and system boundary of the LCA

Case study 2: Bio-methanol (BMeOH) value chain

Bio-methanol process route 1

The bio-methanol process route 1 (BMeOH-R1) entails conversion of torrefied and pelletized wood chips via a two-step gasification technology developed by Torrgas Technology BV in the Netherlands (Figure 3). The BFSC comprises of torrefaction and pelletization of the wood chips in a torrefaction plant annexed to the wood chip depots, and transportation of the torrefied and pelletized biomass to the bio-methanol facility.

The torrefaction involves thermal treatment of the wood chips in an inert environment at 1 atm and 200-300°C, resulting in torrefied wood and volatile compounds (Kota et al., 2022; Prins et al., 2006). Pelletization of the torrefied wood then follows, involving compacting of the torrefied wood under elevated temperatures to enhance the biomass energy-density and reduce transport cost (W.-H. Chen et al., 2015; Niu et al., 2019). In the Torrgas gasification technology, the torrefied wood pellets are first processed in a low-temperature gasifier at 700°C using oxygen produced from a vacuum pressure swing adsorption (VPSA) system to yield biochar and hydrocarbon-rich gas (Figure 3). The biochar is cooled and collected for use as coal replacement in steel manufacturing. The hydrocarbon-rich gas is further processed at 1,200°C in a high-temperature gasifier to yield a nitrogen-free syngas devoid of tar impurities, thereby enhancing the gas purity and quality (Figure 3). A gas cleaning unit is used to remove harmful contaminants from the syngas, ensuring it meets the methanol catalyst specifications for the downstream methanol conversion (Xiao et al., 2021; Zhang et al., 2022). A water-gas shift (WGS) unit and CO_2 removal unit are then applied to produce the required H_2/CO ratio for the syngas conversion to methanol. The methanol production from the syngas involves exothermic hydrogenation of the carbon oxides in the presence of chromium-, copper-, or zinc-oxide based catalyst following the reactions shown in Eqs. 1 and 2, thus favoured by high pressure and low temperature conditions (Rauch et al., 2016).

$$CO + 2H_2 \leftrightharpoons CH_3OH \qquad \Delta H^\circ = -90.5\ \text{kJ/mol} \qquad (1)$$

$$CO_2 + 3H_2 \leftrightharpoons CH_3OH + H_2O \qquad \Delta H^\circ = -49.5\ \text{kJ/mol} \qquad (2)$$

Bio-methanol process route 2

The bio-methanol process route 2 (BMeOH-R2) is similar to the BMeOH-R1 process, except for slight modifications in the gasification and methanol conversion stages allowing for an increased hydrogen content (Figure 3). Methanol synthesis from syngas typically requires an optimal H_2-to-CO molar ratio of 2:1. Thus, a PEM water electrolyser was incorporated to augment the hydrogen content of the syngas, enabling the attainment of stoichiometric balance with the CO and CO_2 for complete conversion into methanol (Porter et al., 2022). The PEM electrolyser generates H_2 from a water electrolysis reaction (i.e. splitting of water into H_2 and O_2 molecules using electric energy) (Bhandari et al., 2014). The oxygen by-product from the water electrolysis is used in the gasification unit, thereby obviating the need for an oxygen-supplying VPSA unit (Figure 3).

Bio-methanol process route 3

The bio-methanol process route 3 (BMeOH-R3) is the same as the ABF-R2 process, except that the methanol from the CCU serves as the targeted product and the biocrude and biochar are considered to be by-products (Figure 3).

Case study 3: Biohydrogen (BH_2) value chain

Biohydrogen process route 1

The biohydrogen process route 1 (BH_2-R1) is based on the proprietary WoodRoll© process developed by the Swedish company Cortus AB for producing of syngas. In brief, the biomass feedstock undergoes a series of operations, which include drying, pyrolysis, and gasification, to yield hydrogen-rich syngas and residual biochar/ash solids (Figure 3). The process data were provided by Cortus AB, the process descriptions below are adaptations from literature and have been presented to provide a general idea of the unit operations (Cortus AB, 2024).

One of the latest syngas technologies is the multi-stage gasification system, where the process is controlled to achieve sequential pyrolysis and gasification reactions in different zones of the reactor (Heidenreich & Foscolo, 2015). This ensures the removal of the volatiles during the pyrolysis stage for optimal operations of the gasification process, allowing for high feedstock conversion rates and hydrogen-rich syngas with a small amount of residual biochar and ash by-products. In principle, the process begins with the drying of the wood chip at 100°C, followed by pyrolysis in an oxygen-free environment at 280-1000°C, resulting in biochar and gaseous product comprising of permanent gases (i.e., CO, CO_2, CH_4, H_2, and light hydrocarbons) and condensable vapours (i.e., bio-oil) (Dhyani & Bhaskar, 2018; Jahirul et al., 2012). The gaseous product is combusted in a boiler to generate thermal energy for the pyrolysis/gasification units (W. Chen et al., 2019). In the next stage, i.e., the steam gasification step, the carbonaceous biochar is thermally decomposed into a gaseous mixture (syngas) in the presence of steam at high temperatures (750-1300°C) (Tezer et al., 2022; Y. Wang et al., 2023). The relevant associated reactions are illustrated in Eqs. 3 and 4 (Encinar et al., 2001). Although catalytic gasification has been tested to increase the hydrogen yield, the uncatalyzed process could still produce hydrogen at high rates (Encinar et al., 2001).

The syngas is treated in a PSA system to recover hydrogen with >99% purity. The resultant tail gas is rich in carbon-monoxide, thus combined with steam from a biomass-fired boiler for processing into additional hydrogen via the WGSr system, while the gas effluent from the WGSr system is processed via a PSA unit to recover hydrogen with >99% purity (Figure 3). The WGSr is a moderate exothermic reversible reaction of carbon monoxide and water vapour to form CO_2 (Eq. 5) (W.-H. Chen & Chen, 2020).

$$C_{(s)} + H_2O_{(g)} \rightarrow H_{2\,(g)} + CO_{(g)} \qquad (3)$$

$$CO_{(g)} + H_2O_{(g)} \rightarrow H_{2\,(g)} + CO_{2\,(g)} \qquad (4)$$

$$CO_{(g)} + H_2O_{(g)} \leftrightharpoons H_{2\,(g)} + CO_{2\,(g)} \qquad (5)$$

Biohydrogen process route 2

The biohydrogen scenario 2 (BH_2-R2) pathway couples syngas production via the Torrgas two-step gasification technology with hydrogen recovery from the syngas (Figure 3). The BH_2-R2 aims to explore the potential environmental impacts of pursuing hydrogen production from gasification as compared with the interest in bio-methanol. Therefore, the BH_2-R2 adapts the BMeOH-R1 process. In the adapted scheme, the raw syngas from the high-temperature gasifier is treated for hydrogen recovery in a process similar to the hydrogen process model by Antonini et al. (2020), entailing steam methane reforming and hydrogen recovery from the derived gaseous products via a PSA system. The process model assumes the hydrogen yield is boosted via an endothermic WGSr unit where carbon monoxide reacts completely with steam to form CO_2 and hydrogen (see Eq. 4). The heat demand of the steam is supplied through natural gas combustion in an industrial furnace.

LCA METHODOLOGY

For all the case studies listed above and their respective process routes a life cycle assessment has been performed. The LCA was conducted using SimaPro v10.0 software following the ISO 14040 and 14044 methodology (ISO, 2006b, 2006a), which consists of four steps: (i) goal and scope definition, (ii) life cycle inventory (LCI), (iii) life cycle impact assessment (LCIA), and (iv) interpretation of results.

Goal and scope definition

This LCA study aims to evaluate the environmental impacts of alternative wood chip-based biofuel production systems and compare their environmental performances to conventional fossil-based alternatives. The objective is to contribute to frameworks for identifying sustainable conversion pathways and support data-driven decision-making in selecting sustainable biobased value chains. A consequential LCA (cLCA) framework which estimates how the environmental burdens of a system could change as a consequence of a decision was adopted (Brandão et al., 2024). A cradle-to-gate scope was evaluated, beginning with forest logging residues as input to the BFSC and ending with the products and emissions leaving the biofuel production facility. Accordingly, the studied system boundary comprises the BFSC and biofuel production facility (Figure 3). The by-products (i.e., biochar, biocrude, and ash) were credited in the system boundary. Impacts from the biomass feedstock transportation and infrastructure (building, machinery) were considered in the assessment. The temporal and geographical scopes were specified as 2030 and Western Europe respectively. The technological scope comprises combinations of recent pilot demonstration plants and process simulations (Table 2). A functional unit (FU) of 1 GJ biofuel was considered. In the ABF-R2 process where both biocrude and bio-methanol are produced, the FU was defined as 1 GJ ABF with the biocrude and methanol accounting for 76% and 24% of the energy content respectively (Lozano Sanchez et al., 2024). All biofuel production systems were compared with their conventional fossil-based reference systems (see Table 2).

Life cycle inventories

Primary LCI data for the BFSC were obtained through direct communications with stakeholders of the forest industry (i.e., Södra Skogsägarförening- Sweden's largest forest owners' association), while those for the biofuel production processes were obtained from pilot demonstration plants (see Table 2**Fehler! Verweisquelle konnte nicht gefunden werden.**). When data was unavailable, secondary data was sourced from scientific literature and industry reports. Biogenic carbon emissions from the biofuel value chains were presumed to be carbon-neutral since the forest carbon stocks are stable under current harvest rates in Sweden (O'Sullivan et al., 2016).

The primary and secondary LCI data were supplemented with background data from the Ecoinvent v3.10 database (i.e., consequential system process datasets). Electricity supplies to the biofuel processes were modelled as the 2030 marginal mix of Western Europe following the protocols of Vandepaer et al. (2019) and Krogh et al. (2024) (for further info pls see Table 4 in the Appendices. In the biofuel process models, the data on infrastructure (i.e., buildings and process equipment) are first approximations derived from pilot demonstration plants or process models.

Multi-product system approach

To handle the multi-product biofuel systems in the cLCA, the substitution method was adopted to avoid partitioning of the systems based on an arbitrary criterion (Brandão et al., 2024). In the approach, the by-products from the multi-product biofuel systems are credited via avoided impacts from producing functionally equivalent conventional alternatives (Brandão et al., 2024). The associated assumptions are as follows:

- Biochar by-product from the BMeOH, ABF, and BH_2 value chains were credited as pulverized coal replacement. A conservative assumption of 1:1 replacement ratio was considered due to their comparable chemical compositions (C. Wang et al., 2015).
- Wood ash by-product from the BH_2-R1 is rich in potassium and phosphorus nutrients (Kuokkanen et al., 2009; Naylor & Schmidt, 1989). Thus, the associated avoided impact was assessed in terms of displaced phosphorous (P_2O_5) and potassium (K_2O) inorganic fertilizer productions (Rosenberg et al., 2010).
- Biocrude by-product from the BMeOH-R3 was credited in terms of fossil-diesel replacement due to their comparable purity, and chemical and physical properties (Dimitriadis & Bezergianni, 2024; Lozano Sanchez et al., 2024). A conservative biocrude-to-diesel replacement ratio of 1:0.9 was assumed based on the slightly lower carbon content and heating value of biocrude (≈75% and 40 MJ/kg, respectively) compared to petroleum diesel (≈83-87% and 43 MJ/kg, respectively) (Cheikhwafa et al., 2024).
- The cradle-to-gate scope implies an exemption of the use and end-of-life phases in the LCA. Thus, the climate savings from the biogenic carbon embedded in the carbon-neutral biomass-based fuels versus their respective fossil options were evaluated as the differences in their CO_2 emissions from combustion (i.e., 67 kg CO_2/GJ (ABF-R1), 52.4 kg CO_2/GJ (ABF-R2) and 62.5 kg CO_2/GJ (BMeOH)) (IPCC, 2019).[5]

Impact assessment

The LCIA was based on the characterization factors of the ReCiPe 2016 midpoint (World-H) method (Yadav et al., 2020). Three relevant impact categories were chosen, namely global warming potential (GWP), terrestrial acidification (TA), and freshwater eutrophication (FE) (Osman et al., 2021; Popp et al., 2014; Wu et al., 2018).

ENVIRONMENTAL PERFORMANCE OF THE DIFFERENT VALUE CHAINS

Environmental performance of the advanced biocrude (ABF) value chains

The integration of CCU-methanol in the ABF-R2 enhanced the biomass resource use efficiency (i.e., total fuel yields), resulting in reductions in the associated environmental impacts by 26.6% versus the ABF-R1 (Figure 4). However, the CCU-methanol incorporation could increase the

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[5] Assuming the carbon in the fuel will be oxidized into CO_2. Hence, the embedded CO_2 is calculated as: $CO_{2\ embedded} = C_{product} * OF * 44/12$; where $C_{product}$ is mass of carbon in the fuel, and OF is the oxidation factor assumed to be 1 (IPCC, 2019). Carbon contents of the biocrude (in the ABF) and bio-methanol (BMeOH) were valued at 37.5% (Sebos, 2022) and 75% (Cheikhwafa et al., 2024), respectively.

overall impacts (ABF-R1 vs ABF-R2, Figure 4). Biochar by-product provides little credit to the GWP, TA, and FE impacts (Figure 4), which could be explained by the low amounts produced (0.62 kg/GJ ABF). In both the ABF-R1 and ABF-R2, the ABF production section dominates the impact contributions at 65.4-81.8% (GWP), 75.3-86.7% (TA), and 96.3-99.2% (FE) (**Fehler! Verweisquelle konnte nicht gefunden werden.**).

In the ABF-R1, the HTL+H_2T section accounts for 55.7%, 58.9%, and 51.5% of the GWP, TA, and FE impacts respectively, followed by the PEM electrolyser with 40.9% (GWP), 32.5 (TA), and 47.1% (FE). Chemical demands for HTL and H_2T catalysts and process heat supplies via natural gas combustion contributed the most to the HTL+H_2T impacts (i.e., respective contributions of 47.3% & 44.7% (GWP), 84.6% & 15.1% (TA), 1.6% & 90.7% (FE)).

Conversely, in the ABF-R2, the PEM electrolyser dominated the impacts with 65% (GWP), 57.5% (TA), and 77.1% (FE). This can be attributed to the higher use of electricity by the PEM electrolyser, which accounts for 97.2% (GWP), 93.3% (TA), and 80.5% (FE) of the PEM impacts. These numbers are comparable with previous reports where the electrolyzer infrastructure contributes minimal to the impacts (e.g., 4% in wind-based electrolytic hydrogen) (Bhandari et al., 2014). Electrolytic hydrogen impacts have been demonstrated to be highly dependent on the electricity-mix, with wind and fossil-dominated grids exhibiting the least (≈1 kg $CO_{2\ eq}$/kg H_2) and highest (31 kg CO_2 eq/kg H_2) respectively (Bhandari et al., 2014). In this study, the PEM impacts were evaluated to be ≈5.9 kg CO_2 eq (GWP), 0.007 kg SO_2 eq (TA), and 0.003 kg P eq (FE) per kg H_2 produced, which compare fairly with reports for renewable electricity-powered electrolytic hydrogen (e.g., ≈1-4 kg CO_2 eq/kg H_2) (Bhandari et al., 2014). Thus, the higher impacts of the PEM in the ABF-R2 in comparison to the ABF-R1 could be primarily due to the larger size required to supply the demands of the CCU-methanol in the ABF-R2.

Compared to the fossil alternatives, both the ABF-R1 and ABF-R2 are advantageous with regards to lowering the GWP and TA impacts but perform poorly in the FE category where the catalyst chemicals, heat, and electricity supplies dominate the impacts. Hence, the environmental concerns of ABF production lie mainly in the operation phase via catalyst chemicals, heat, and electricity supplies.

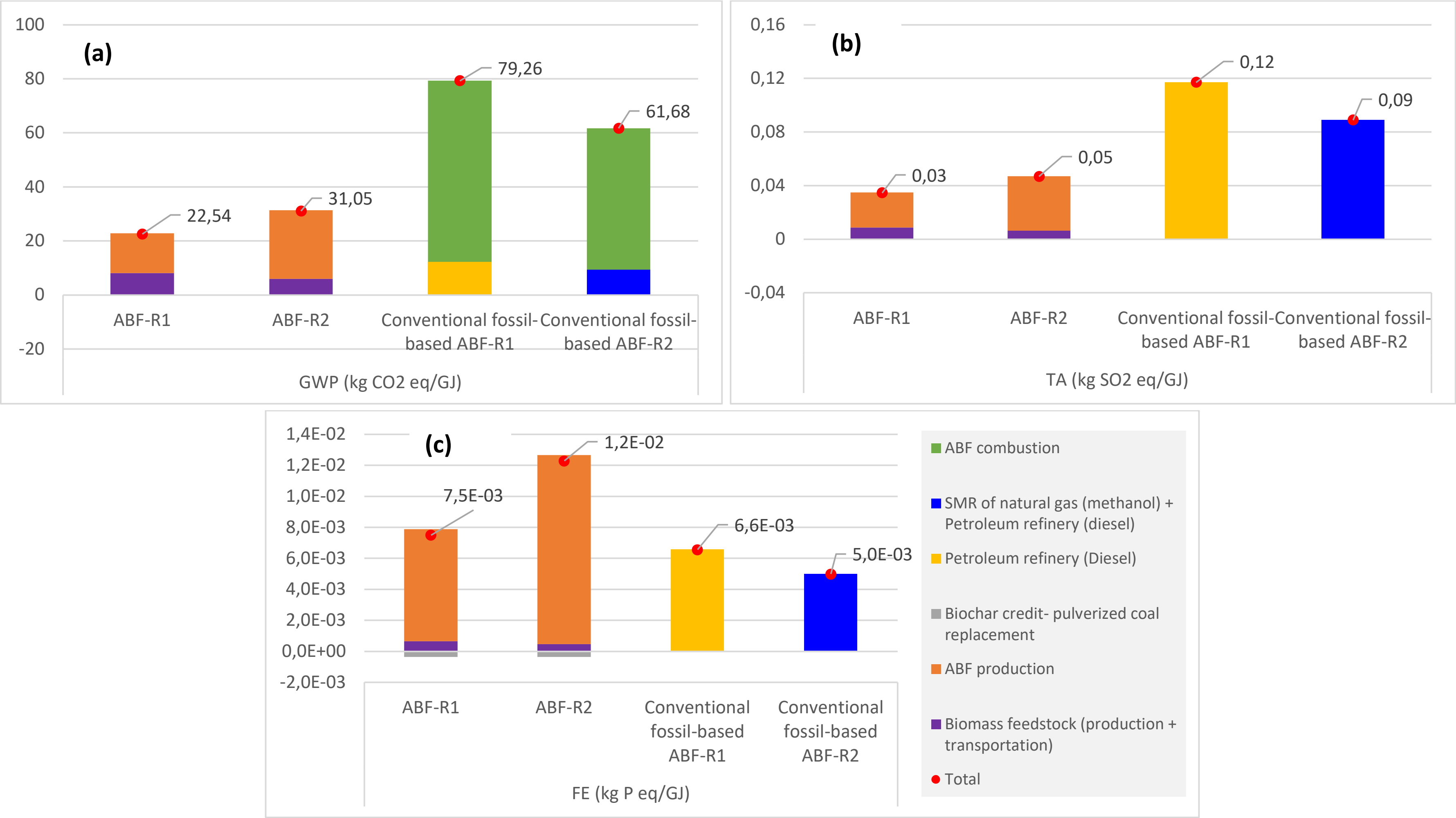

Figure 4 Environmental impacts of the advanced biocrude process routes and the conventional fossil-based alternatives

Environmental performance of the bio-methanol (BMeOH) value chain

Figure 5 presents the results on the environmental impacts of the three bio-methanol routes. In the BMeOH-R1, the biomass feedstock dominates the GWP (83.3%) and TA (92.6%) categories, while biochar credit and methanol production dominates the FE (60.6% savings). For the BMeOH-R2, the methanol production section leads in the GWP (76.8%) and FE (88%, minus credits), while the biomass feedstock leads in the TA (65%). In the BMeOH-R3, the methanol production section contributes the most to the GWP (81%, minus credits) and FE (96%, minus credits), but the TA is dominated by the credit from biocrude by-product (61% savings).

The incorporation of PEM hydrogen into the gasification system increased the methanol yields, resulting in lower biomass feedstock impacts per GJ methanol (BMeOH-R1 vs BMeOH-R2, Figure 5). This highlights the efficient use of biomass carbon resources in the BMeOH-R2 system. However, the feedstock impacts from the gasification routes (BMeOH-R1 & R2) are higher than from the HTL route (BMeOH-R3) (Figure 5), which can be attributed to the additional wood-chip torrefaction step in the gasification routes. The torrefaction step contributes the most to the feedstock impacts at 88% (TA) and 54% (FE), with the torrefaction step's electricity and process operations representing its major contributors (i.e., 73% GWP/86% FE and 94% TA, respectively). Similarly, the process electricity demands dominated the impacts from the gasification methanol production sections (i.e., 57.6-87.6% GWP, 73-90% TA, and 82-93% FE). The justifications for the electricity impacts are as previously explained for the PEM and biomass feedstocks in the ABF routes.

Hence, out of the three bio-methanol routes explored, the two-stage gasification route (BMeOH-R1) is the most promising technology pathway for environmental impact mitigations in the methanol industry. Although the integration of the gasification system with PEM hydrogen (BMeOH-R2) increased the methanol yields, owing to the sufficiency of hydrogen for complete conversion of the carbon oxides into methanol, environmental impacts from the associated resource demands (mainly electricity) outweigh the high-product benefit. However, except for the FE, the HTL technology route (BMeOH-R3) could boost the environmental performances with PEM (BMeOH-R3 vs BMeOH-R2, Figure 5), which is mainly due to the significant credits derived from the biocrude by-product (i.e., fossil-diesel displacement) (BMeOH-R3, Figure 5).

Overall, the result from this study compares favourably with values in literature. For instance, the GWPs of the bio-methanol systems (15.3-23.15 kg CO_2 eq/GJ) and fossil-methanol system (102.2 kg CO_2 eq/GJ) (Figure 5) are similar to values reported for waste wood-based methanol (10-22.6 kg CO_2 eq/GJ) and natural gas-based methanol (91-101.6 kg CO_2 eq/GJ) respectively (IRENA and Methanol Institute, 2021). Hence, with a renewable electricity-mix supply, the life cycle GWP of bio-methanol is expected to be less than half the conventional natural gas methanol's. Conversely, compared to the fossil system, the poor performance in the TA and FE categories for some of the bio-methanol systems (Figure 5) could be attributed to the combined effects of the high electricity demands and electricity-mix of the bio-methanol routes, as explained above.

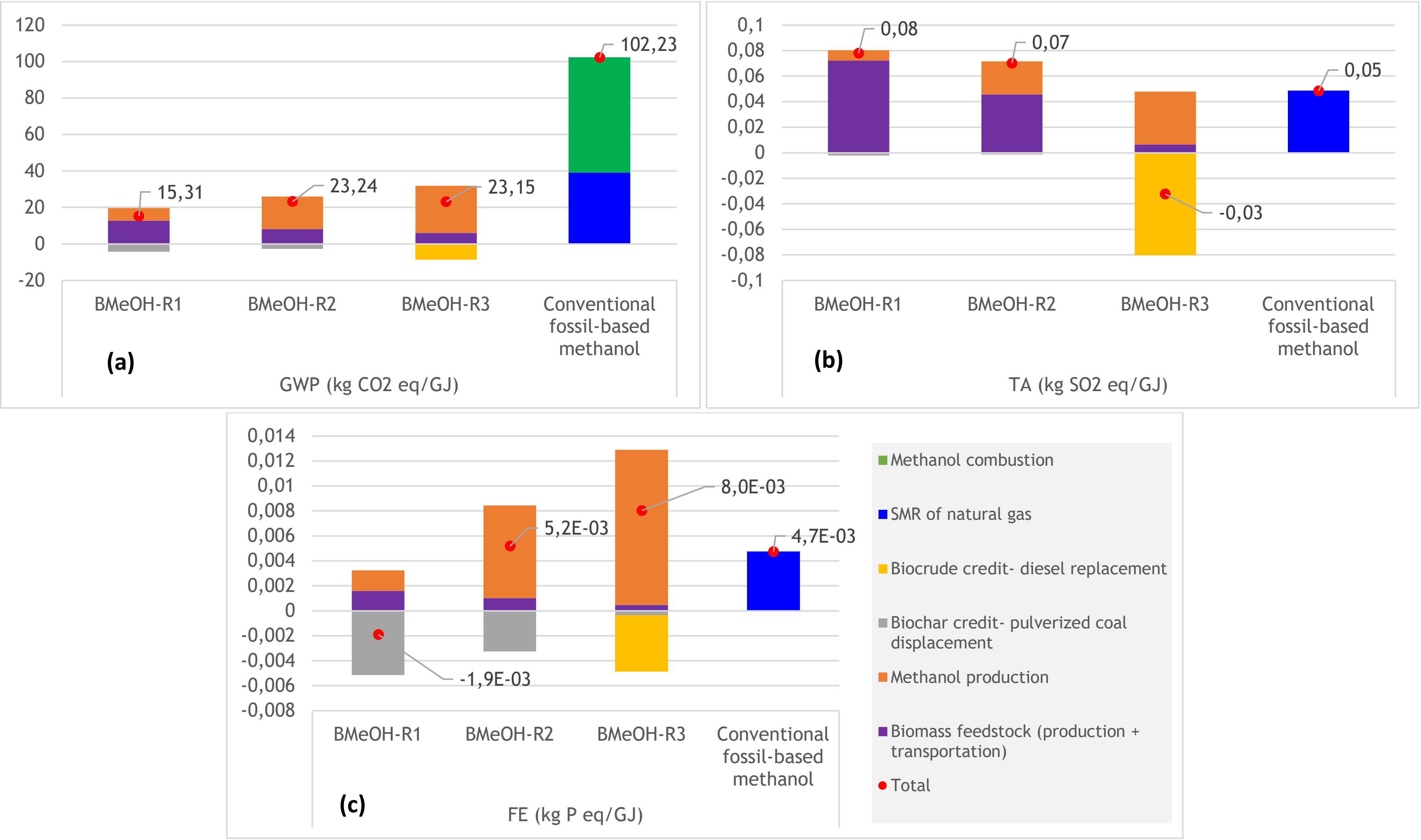

Figure 5 Environmental impacts of the bio-methanol process routes and the conventional fossil-based alternative.

Environmental performance of the (BH_2) value chain

The environmental performance of the biohydrogen via pyrolysis and gasification routes are presented in Figure 6. For the two biohydrogen routes, the contributions from the syngas + hydrogen production sections to the GWP and FE impacts are comparable (Figure 6). The slightly higher GWP and FE impacts from the biomass feedstock of the BH_2-R2 compared to the BH_2-R1 (12.9 vs 10.9 kg CO_2 eq/GJ) can be attributed to the extra torrefaction step in the BH_2-R2, which is dominated by the electricity demands as previously explained for the bio-methanol routes. Therefore, relative to the GWP and FE, the biochar credit (i.e., pulverized coal displacement) is a key deciding factor regarding the best-performing biohydrogen route (Figure 6). For instance, the biochar credits of -1.43 and -4.3 kg CO_2 eq/GJ for the BH_2-R1 and BH_2-R2 respectively led to reductions in their overall GWPs to 17.75 and 16.34 kg CO_2 eq/GJ respectively (Figure 6). Per the magnitudes of the credits, a high biochar yield from the BH_2-R2 is implied. The high temperature operations of the BH_2-R1 process in comparison to the BH_2-R2 may explain the yield disparity (Encinar et al., 2001; Peterson & Brown, 2020; Sessa et al., 2021).

Regarding the TA impacts from the BH_2-R1 and BH_2-R2, irrespective of the notable differences in the contributions from the syngas + hydrogen production sections and biomass feedstock, their net effects are comparable, culminating in similar TA impacts (0.09 kg SO_2 eq/GJ) (Figure 6). In the BH_2-R1, the syngas production section dominates the TA impact (72%) (Figure 6). Of this impact, the electricity demands and infrastructure account for 67% and 17% respectively. Conversely, in the BH_2-R2, the TA impact is dominated by the biomass feedstock (82.5%) (Figure 6), where the torrefaction process and biomass transport infrastructure/diesel account for 83.2% and 11% respectively. The high contributions from the torrefaction process are mostly due to its electricity demand/mix, which accounts for 94% of the TA impact.

Regarding fossil-based hydrogen replacement, biohydrogen is a superior choice to PEM hydrogen from an environmental viewpoint. Relative to fossil-based hydrogen (i.e., SMR of natural gas, Table 2), the studied biohydrogen systems could lead to substantial reductions in GWP (81-83%), although with adverse consequences from the perspectives of TA impacts (Figure 6). As explained above, these environmental drawbacks are governed by the electricity demands and mix. Therefore, process energy efficiency enhancements and sustainable green electricity supplies are essential for the holistic environmental success of the biohydrogen systems. In contrast, the biohydrogen systems are superior to the conventional PEM hydrogen as regards environmental performances, except for the TA impact (Figure 6). Like the electricity drawbacks of the biohydrogen processes, the electricity-intensive PEM operations and electricity-mix could explain its weak environmental performances. Hence, with a greener electricity-mix supply, biohydrogen is a more environmentally friendly option than PEM hydrogen and thus presents a more sustainable pathway to advancing green hydrogen exploits.

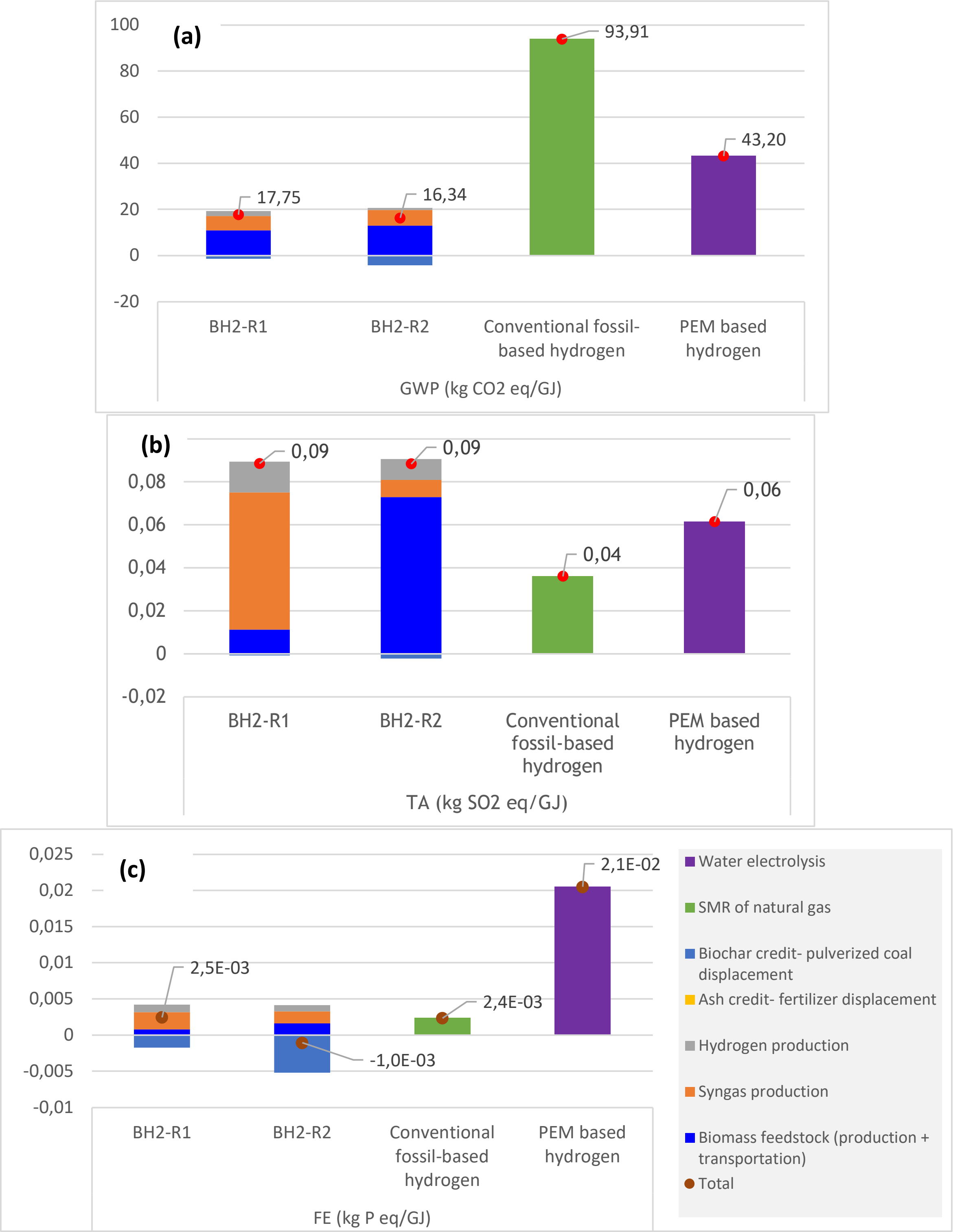

Figure 6 Environmental impacts of the biohydrogen via pyrolysis and gasification process routes and the conventional fossil/PEM based alternatives.

Comparative performance analysis of the biobased value chain systems

A comparison of the seven process routes was conducted to identify the most effective approach to utilizing scarce biomass resources for sustainable biofuel and biohydrogen deployment. From the relative impact results (i.e., normalizing the highest impact category to 100% and expressing all other impacts relative to this reference value; Figure 7), the ranking of the routes in decreasing order are:

(i) GWP: BMeOH-R1, BH_2-R2, BH_2-R1, BMeOH-R3, ABF-R1, BMeOH-R2, ABF-R2,

(ii) TA: BMeOH-R3, ABF-R1, ABF-R2, BMeOH-R2, BMeOH-R1, BH_2-R2, BH_2-R1, and

(iii) FE: BMeOH-R1, BH_2-R2, BH_2-R1, BMeOH-R2, ABF-R1, BMeOH-R3, ABF-R2.

Hence, variations in the ranks can be perceived at the individual impact category level, which could imply possibilities of environmental trade-offs amongst the routes. For instance, while the BMeOH-R1 outperformed the other routes in the GWP, and FE categories, the BMeOH-R3 led the routes in the TA category (Figure 7).

However, a combined impact assessment (Figure 7) shed light on the holistic environmental potentials, revealing insights into the superiority of the BMeOH-R1, followed by the BH_2-R2, BMeOH-R3, ABF-R1, BH_2-R1, BMeOH-R2, and ABF-R2. Thus, it can be rationalized that under conditions of green electricity supply and limited biomass resource availability, the bio-methanol conversion via the BMeOH-R1 technological pathway represents the most effective strategy for a sustainable bioabased value chain and hydrogen deployment from an environmental performance point of view.

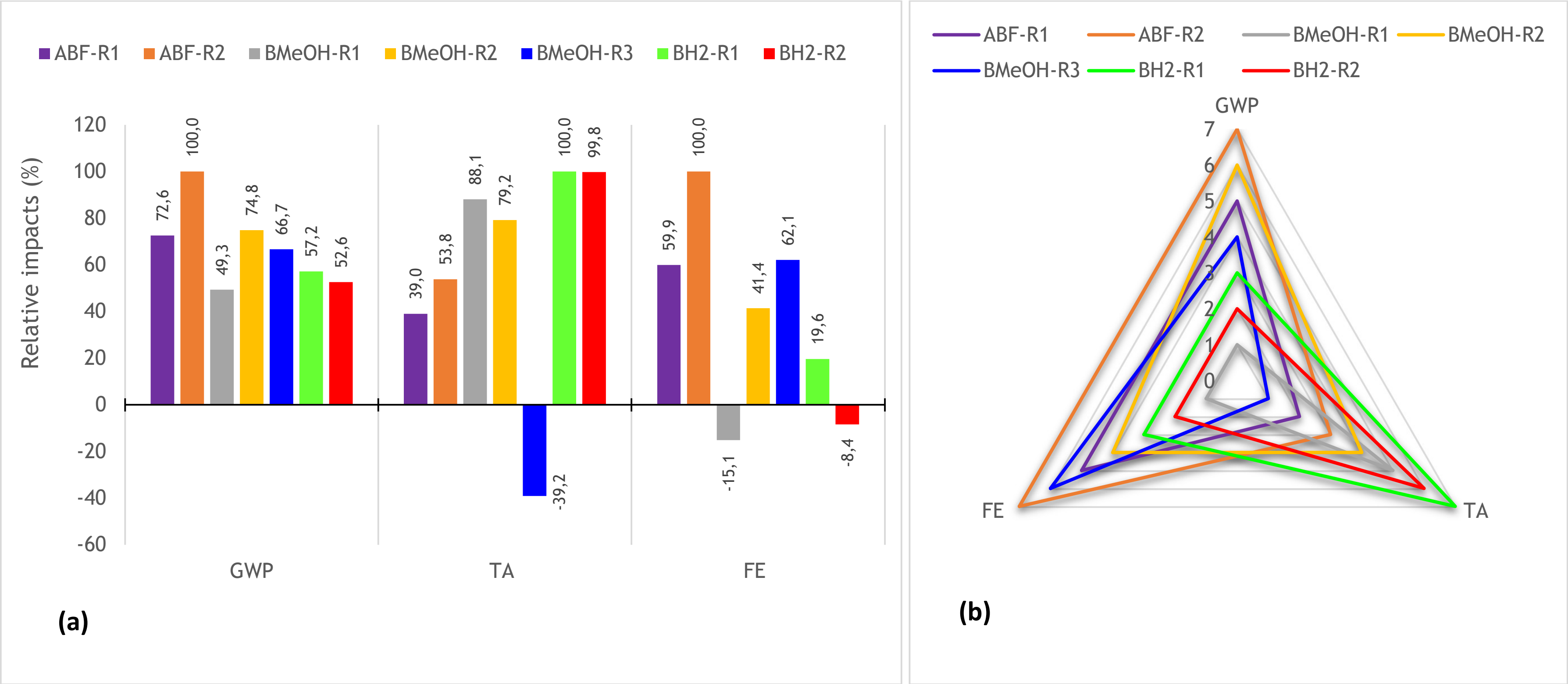

Figure 7 Comparative performance of the biofuel process routes. (a) Percentage relative impacts, and (b) Ranking of the biofuel routes on equal impact weighting basis (NB: 1 and 7 represent best and worst performances, respectively).

ASSESSING IMPACT OF THE DIFFERENT VALUE CHAINS FOR DIFFERENT REGIONS

Understanding the environmental performance of the presented value chains if applied in different world regions is key for the significance of the overall carbon emissions reductions provided. This also supports the transferability to other geographical regions and use in global scenarios as factor for reducing carbon emissions. Therefore, in the following an approach for identifying the impacts of the biobased value chains using LCA and the tool PREMISE for future projections is presented. Hence, the LCA data is combined with background data from TIMER, the energy model of IMAGE, an integrated assessment model to assess the global environment. This additional information supports a better understanding of the benefits and trade-offs of the various conversion routes under various scenarios; with regard to climate change mitigation benefits and other impact categories.

Assessment approach

Environmental ramifications of implementing the biobased value chains in different geographical settings were conservatively evaluated by altering the process electricity mix to the 2030 marginal mix of the following countries representing different world regions: the USA, Brazil, India, China, and South Africa, which were simulated using the 2020 and 2030 generation mix data from the IMAGE model (PBL, 2024) (see Table 3).

Table 3 2030 marginal electricity-mix projections for the studied geographical regions

	2030 marginal electricity mix (%) [1]				
Electricity technology	**USA**	**Brazil**	**China**	**India**	**South Africa**
Oil	1.2	-	-	-	1.6
Natural gas	-	23.3	35.8	5.1	0.1
Solar PV	56.4	30.2	34.1	71.7	18.2
Solar CSP	-	0.1	-	-	0.2
Wind	37.0	25.7	13.1	11.0	68.1
Hydro	-	6.1	10.9	3.9	8.2
Biomass	-	13.0	1.8	6.4	0.2
Nuclear	-	0.6	1.2	-	-
Other	5.4	1.0	3.1	1.9	3.4
Carbon profile (kg CO_2 eq/MJ) [2]	0.029	0.052	0.105	0.047	0.038

[1] Electricity supplies to the biobased value chains were modelled as the 2030 marginal grid mix of the geographical regions of Western Europe, projected using 2020 baseline data from the IMAGE model (PBL, 2024), following the protocols of Vandepaer et al. (2019).
[2] Values for the simulated marginal-mix using Ecoinvent v3.10 background datasets.

Geographical electricity-mix impacts

The potential geographical electricity-mix impacts on the environmental performances of the biofuel routes were evaluated via relative impact assessments and a combined-impacts ranking (see Figure 8).

Per the relative impact results, the geographical electricity-mix could significantly influence the environmental performances of the biofuel production systems (relative impacts ≥30%), except for the ABF-R1 system where the impact was minimal (relative impacts ≥92%) (Figure 8). Furthermore, from the combined-impacts ranking (Figure 8), the geographical impact increases in the order of WE, USA, Brazil/India, South Africa, and China. Therefore, the electricity-mix is a sensitive parameter that could significantly influence the environmental life cycles of the considered biofuel production systems.

Relative to climate impacts of fossil-based fuels, the simulated carbon profiles of the geographical marginal electricity-mix (i.e., 0.029-0.105 kg CO_2 eq/MJ; Figure 9) are well below the critical values that could result in turn-arounds in the benefits of the biobased value chains, except for the ABF-R2 system that exhibited possibilities for a turn-around at a grid emission factor of ≈0.079 kg CO_2 eq/MJ (Figure 9). For instance, relative to the PEM hydrogen and fossil-based hydrogen, the turning-point grid emission factors for the BH_2 routes were found to be ≈0.15-0.17 kg CO_2 eq/MJ and ≥0.4 kg CO_2 eq/MJ respectively (Figure 9). Similarly, the turning-point emission values for the BMeOH routes were established at ≥0.165 kg CO_2 eq/MJ (Figure 9). It must be noted that the steepness of the climate impact plots of the biobased systems in Figure 9 correspond to their sensitivity to the grid carbon profile. Accordingly, the BMeOH-R1 and ABF-R2 can be said to be the most and least sensitive biobased systems (respectively) to the grid carbon profile (Figure 9), which aligns with the magnitudes of their electricity demands. Hence, the overall findings suggest that, regardless of the region, the biobased systems may play a vital role in reducing carbon emissions in the energy sector. Overall, the findings indicate that the biobased value chains exhibit robustness in outperforming their fossil alternatives under various electricity mix scenarios, including those with relatively high carbon-intensities.

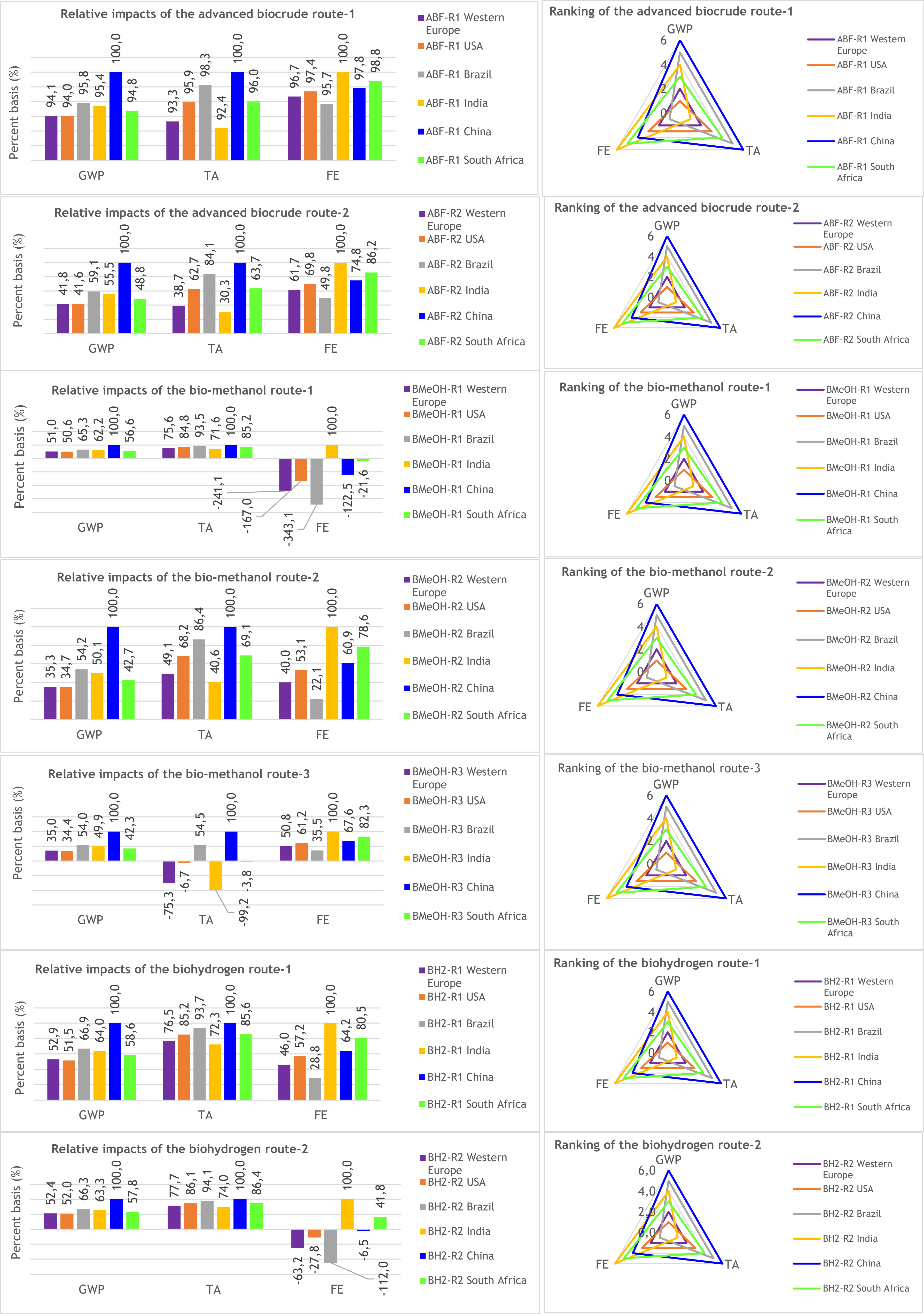

Figure 8 Geographical marginal electricity impacts on the performances of the biofuel production systems (NB: The ranking is based on equal weighting of the environmental categories, i.e., 1 and 6 represent best and worst performances, respectively)

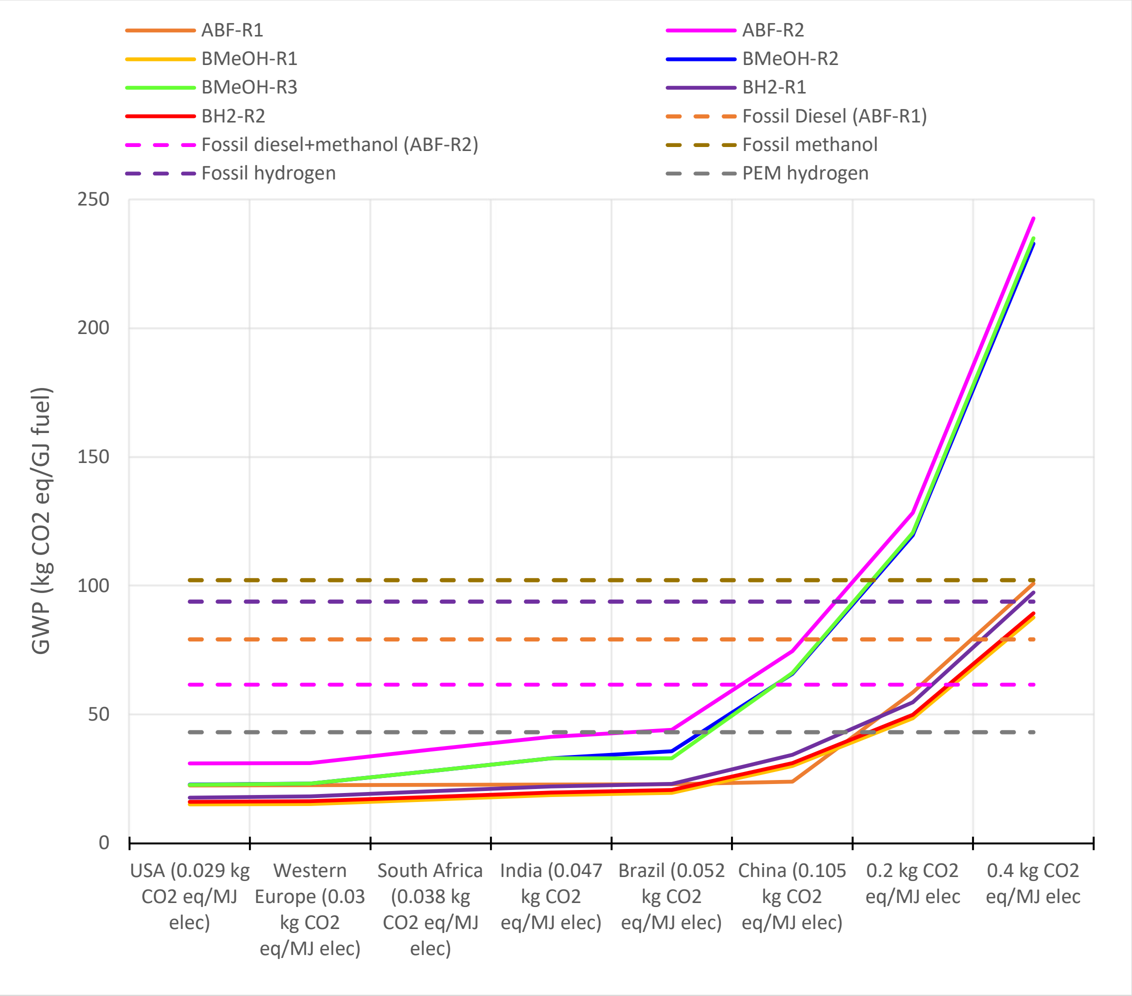

Figure 9 Climate impacts of the biofuel production systems under different geographical electricity mix (i.e., emission factors). The fossil-based fuels are baseline values for the context of Europe (i.e., Ecoinvent v3.10 datasets, see Table 2). The PEM hydrogen system was modelled based on the study of Krishnan et al., 2024 (See Table 2).

Biomass and Hydrogen: what are the implications for the energy system and the climate

GENERAL OVERVIEW

Value chains combining renewable hydrogen and bioenergy are increasingly recognized as mutually reinforcing components of future energy systems. Biohydrogen production offers low-carbon, non-intermittent hydrogen supply, while the integration of renewable hydrogen into biobased processes enhances carbon efficiency, process flexibility, and product diversification and, in some cases, product quality.

This inter-task project intended to 1) create an overall picture and prepare a collection of promising biomass value chains for producing hydrogen and 2) show the effects when adding renewable hydrogen to existing biobased processes and value chains. Effects with regards to process efficiency, additional costs and benefits, and realized products as multi-product system.

Therefore, one work package dealt with the provision of an overview of biomass technologies that can produce renewable hydrogen with a focus on the respective technology and production costs. Actual projects that already try to bring these applications into the market have been highlighted (WP2 report). This WP2 report has discussed several pathways to produce hydrogen from biomass sources, which can also bring wider benefits to the energy systems. The biohydrogen value chains discussed are based on the following technologies:

1. Gasification
2. Anaerobic digestion
3. Alcohol reforming
4. Thermocatalytic decomposition.

Further on, it was the goal to present how renewable hydrogen and biobased value chains support each other, in particular by upgrading biobased processes due to the additional use of hydrogen and reflect on the role of biogenic carbon, potentially also carbon dioxide removal options of such chains. There are many biobased processes either high in demand for hydrogen (e.g., synthetic renewable fuels, biorefining) or that could benefit from hydrogen integration (e.g., boosting biomethane production). This aspect has been covered in another work package (WP3 report).

From energy and climate system perspective, considerations on the current and prospective role within the energy system and the climate effects for supporting the decarbonization of the energy system have been analyzed. With regards to energy system models, the objective was to understand to what degree renewable hydrogen and in particular biohydrogen value chains are integrated into these models and roadmaps, and what systemic benefits they are anticipated to offer. The key outputs are an overview of the current and prospective role of these value chains in energy system models summarizing the status and future needs and expectations.

Moreover, climate effects assessment studies of selected biohydrogen and hydrogen in biobased processes, recognizing methodological questions and the main factors influencing the GHG balance calculations of the studied value chain concepts have been conducted. All findings were summarized in this synthesis WP4/WP5 report.

SYSTEM ASPECTS

Renewable hydrogen has gained significant interest as a clean energy carrier and is anticipated to play a role particularly in decarbonizing the transport and industrial sectors. To support this momentum, energy system modelling can and will keep providing policy-relevant insights of decarbonisation pathways, in which an accurate representation of hydrogen and biobased value chains is important.

From the overview on different energy system models, it can be learnt that the production and use of biohydrogen is not foreseen within the majority of projections. In some cases, the role of biohydrogen is small even in the most optimistic scenarios. The provision of renewable hydrogen is entirely considered via electrolysis from VRE sources. Hydrogen is integrated across power, transport, and industrial sectors, with a significant shift toward renewable hydrogen produced via electrolysis powered by renewable electricity.

The interplay between hydrogen and bioenergy is emphasized in synthetic fuel production, where biogenic CO_2 is utilized alongside hydrogen to produce e-fuels for hard-to-abate sectors like aviation and maritime. Hydrogen and bioenergy can be combined in multiple ways and can contribute to energy system flexibility through long-duration storage and sector integration. The carbon produced can be used in multiple applications, from soil improvement to more demanding applications, depending on the process.

Added value for energy production systems can be seen e.g. in:

- Biomass gasification and thermocatalytic decomposition allowing for co-production of value-added commodities, i.e. biochar, biocarbon
- Negative CO_2 emissions: Biomass and hydrogen value chains can obtain negative CO_2 emissions if coupled with CCS or biochar produced. For example, gasification and biomethane splitting yield biochar and carbon, leading to negative CO_2 emissions whilst also providing opportunities for soil improvement.
- Hydrogen use in biofuel production enables drop-in fuels with high carbon efficiency, which aligns with transport sector decarbonisation by making use of biogenic CO_2.
- Biobased value chains with multi processes and outputs contribute to the flexibility of the system.

These examples show that adding renewable hydrogen to certain biobased value chains could be very beneficial for the process efficiency and also increases the number and variety of products that can be provided, especially biochar. Further on renewable hydrogen can be an enabler for utilizing the captured carbon of a biobased value chain. These characteristics are key for the requirements for the future energy system – allowing for flexibility in the energy system and carbon products as well as negative CO_2 emissions.

Overall, one has to be aware that also a competition between the use of biomass resources for biohydrogen production chains and other biobased value chains predominantly providing negative emissions via bioenergy carbon capture and storage (BECCS) pathways can arise. This aspect needs further consideration. Looking into their individual energy system relevance for decarbonization and within the broader energy policy context will provide more answers.

Limitations in sustainable biomass availability, competitive uses of the biomass resources and development of VRE electricity capacity and costs impact the attractiveness of biohydrogen production and favour electrolytic hydrogen production instead. In this case, the linkages between hydrogen and biomass will occur in applications such as biofuel production and methanation, where hydrogen is feedstock instead of a product.

Key messages

Biohydrogen pathways and **renewable hydrogen to biobased value chains** reveal the following opportunities, shortcomings and trade-offs:

- Biohydrogen is a clean energy carrier that can add flexibility to the energy system
    - Process integration opportunities to reach more energy efficient production and product multi systems
    - Co-production of other value-added commodities such as biocarbon, biochar, biomethane etc.
    - Opportunities Carbon dioxide removal (negative CO_2-emissions) if CCS is applied or biochar produced
- Renewable hydrogen uptake in biomass conversion processes could be beneficial for the process efficiency and also improves the quality of the products
- There is a close link between the hydrogen economy and biobased processes demanding hydrogen
- Energy system models consider mainly renewable hydrogen provision via electrolysis
- Biohydrogen as form of renewable hydrogen is used in some energy system models
- Biohydrogen pathways in energy system models are mainly based on the gasification technology
- Also bioenergy carbon capture and storage pathways in energy system modelling are based on gasification and do not present a wider range bioenergy technologies with carbon capture yet
- Need for a broader set of bioenergy technology pathways for hydrogen production in energy system modelling
- Need for a broader set of bioenergy technology pathways for carbon capture in energy system modelling
- However, bioenergy pathways for biohydrogen and for providing carbon dioxide removal (BECCS) might be in competition for the limited available biomass resources

ENVIRONMENTAL ASPECTS

From the holistic environmental perspective, the bio-methanol value chain BMeOH-R1 represents the best performing route, followed by the biohydrogen production route BH2-R2, BMeOH-R3, ABF-R1, BH2-R1, BMeOH-R2, and ABF-R2. Hence, the bio-methanol production via the BMeOH-R1 technology depicts the most attractive approach for utilizing limited biomass resources for biobased deployment considering hydrogen production. On the other hand, the BH2-R2 and ABF-R1 show potential as feasible instruments for decarbonising the hydrogen economy, respectively.

The LCA results show that the incorporation of e-methanol (using hydrogen from PEM) production into biocrude production systems could impact negatively on the environmental performances (ABF-R1 vs ABF-R2). A similar trend was demonstrated for the bio-methanol yield enhancement via PEM based hydrogen integration, with the exception for the TA impact (BMeOH-R1 vs BMeOH-R2). High electricity demands of the PEM electrolyzer, coupled with the marginal electricity-mix, is the major contributing factor to the result trends above. For biohydrogen, the two-stage gasification technology route (BH2-R2) exhibits superior performances to the pyrolysis + gasification route (BH2-R1), with the by-product biochar yields and associated credit (i.e., pulverized coal replacement) identified as the key differentiating factor.

With focus on the biohydrogen value chain relative to the GWP and FE, the biochar credit (i.e., pulverized coal displacement) is a key deciding factor regarding the best-performing biohydrogen route. Regarding fossil-based hydrogen replacement, biohydrogen is a superior choice to PEM hydrogen from an environmental viewpoint. Relative to fossil-based hydrogen, the studied biohydrogen systems could lead to substantial reductions in GWP. Therefore, process energy efficiency enhancements and sustainable green electricity supplies are essential for the holistic environmental success of the biohydrogen systems. In contrast, the biohydrogen systems are superior to the conventional PEM hydrogen as regards environmental performances, except for the TA impact.

The HTL technology route (BMeOH-R3) could boost the environmental performances with PEM (BMeOH-R3 vs BMeOH-R2, Figure 5), which is mainly due to the significant credits derived from the biocrude by-product. Hence, with a renewable electricity-mix supply, the life cycle GWP of bio-methanol is expected to be less than half the conventional natural gas methanol’s.

The integration of CCU-methanol in the ABF-R2 enhanced the biomass resource use efficiency (i.e., total fuel yields), resulting in reductions in the associated environmental impacts by 26.6% versus the ABF-R1. This highlights the significance of adding carbon capture to such systems.

All the biobased systems outperformed their fossil counterparts regarding GWP, but were performing poorly in the FE (ABF), TA/FE (BMeOH) or TA (BH2) categories. The electricity-mix is one dominant parameter that significantly influenced the environmental performance of the biomass systems. Hence, although biomass integrations with renewable hydrogen or e-fuels may be attractive from product yields and diversification perspectives, less resource-intensive green electricity supplies will be critical for their satisfactory holistic environmental performance. The overall findings suggest that, regardless of the region, the biobased systems may play a vital role in reducing carbon emissions in the energy sector.

Appendices

Table 4 Contributions of each country to the electricity technologies in the 2030 marginal mix projection for Western Europe

Country / Type of electricity [1]	**Natural gas**	**Solar PV**	**Wind**	**Hydro**	**Biomass**	**Nuclear**	**Other**
Austria	2%	2%	2%	7%	2%	-	5%
Belgium	3%	4%	3%	1%	3%	5%	2%
Germany	17%	42%	32%	8%	38%	4%	-
Denmark	1%	1%	3%	-	7%	-	2%
Spain	15%	11%	14%	12%	3%	7%	5%
Finland	1%	-	2%	2%	8%	3%	4%
France	6%	9%	10%	15%	6%	64%	11%
Ireland	2%	-	1%	-	-	-	3%
Italy	21%	3%	5%	13%	6%	-	5%
Luxembourg	-	-	-	-	-	-	-
Netherlands	9%	14%	4%	-	2%	1%	4%
Norway	-	-	2%	20%	-	-	1%
Portugal	2%	1%	3%	5%	3%	-	-
Sweden	-	-	7%	9%	-	7%	43%
Switzerland	-	3%	-	9%	-	3%	-
United Kingdom	21%	9%	11%	1%	22%	6%	16%
Marginal electricity mix [2]	5.61%	71.69%	17.40%	1.10%	1.40%	1.70%	0.10%

[1] The marginal electricity-mix were determined via annual growth rates and capital replacement ratios projected from current policy generation mix data (2020 & 2030) from the ‘Integrated Model to Assess the Global Environment’ (IMAGE) model by PBL (2024). Further details can be found in Krogh et al. (2024).

[2] The carbon profile of the simulated marginal-mix using Ecoinvent v3.10 background datasets is 0.030 kg CO_2 eq/MJ.

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