Bioenergy in a Net Zero Future

Summary and conclusions from the IEA Bioenergy workshop held on 19 October 2023 in Lyon (France)

Workshop organized by IEA Bioenergy in collaboration with ADEME, the French Agency for Ecological Transition

GAYA demonstration plant, south of Lyon © TBM-Technology Based Magic

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1.Key messages from the workshop

- **Modern bioenergy is one of the pillars of the energy transition.** In the IEA Net Zero Emissions by 2050 roadmap (NZE), modern bioenergy is projected to triple from now to 2050, while at the same time traditional uses of biomass are phased out. Altogether, bioenergy represents 15-20% of total energy needs in 2050 in the IEA NZE roadmap. The demand for biomass would be within conservative estimates of biomass potentials.

- **A reduced contribution of bioenergy - i.e. excluding or reducing below current levels - would cause dramatically increasing system costs to achieve the 2050 climate targets.** This would lead to much higher challenges to balance intraday and seasonal fluctuations related to the high share of variable renewables in the energy system; make it much more expensive to provide fuels for difficult to abate transport sectors; and imply much higher levels of Direct Air Capture (DAC), which is far more expensive than capturing biogenic CO_2 from bioenergy systems.

- **Feedstock mobilization is one the main challenges for bioenergy deployment.** This requires setting up efficient collection systems; investing in biomass crops, particularly on marginal/abandoned lands; and developing approaches with local biohubs to facilitate logistics. On technology side, it is also critical to support the development and deployment of advanced technologies that can cope with wide ranges of (low quality) biomass feedstocks.

- While substantial amounts of sustainable biomass are available and/or can be mobilized, the resource base still has its limits. To maximize the GHG emission reduction impact, prioritisation of certain bioenergy applications may be required to make the best use of the available biomass feedstocks. **Connecting bioenergy systems with CO_2 capture (BECC) strongly enhances the carbon efficiency and value of biomass towards net zero energy systems.**

- The captured biogenic CO_2 from bioenergy systems can be used for permanent storage (BECCS), or for the production of additional renewable chemicals and fuels, when combined with renewable hydrogen (BECCU). The **growing demand for e-fuels in the long term for long distance transport will require substantial amounts of biogenic CO_2** (from bioenergy systems) or atmospheric CO_2 (captured through DACC), with biogenic CO_2 being much less costly or energy intensive.

- While GHG emission reduction and moving away from fossil fuels is priority in the next decades, reaching net zero by 2050 and net negative GHG emissions thereafter **requires high amounts of carbon dioxide removal (CDR) from the atmosphere**. Long term storage of captured biogenic CO_2 from bioenergy projects is one of the key CDR options, with the unique advantage that BECCS provides a combination of both carbon storage and renewable energy provision. Large scale BECCS projects are starting to take off and becoming a reality, also in terms of business case, with carbon storage / negative emissions being financially rewarded in markets.

2. Executive summary

Luc Pelkmans, Technical Coordinator, IEA Bioenergy

The IEA Technology Collaboration Programme on Bioenergy (IEA Bioenergy) held its biannual workshop on 19 October 2023 in Lyon (France), in conjunction with its Executive Committee meeting (ExCo92). The workshop on 'Bioenergy in a Net Zero Future' was in hybrid form, with mostly physical and a few remote presentations and was organised in collaboration with ADEME, the French Agency for Ecological Transition.

The workshop consisted of three parts:

1. The role of bioenergy in energy transition strategies, followed by a panel discussion
2. Flexible bioenergy and the use of biogenic CO_2 in future energy systems
3. Promising developments in bioenergy concepts

The workshop had around 80 physical participants in Lyon. More than 200 people followed the workshop online. The PowerPoint presentations and recordings are available for downloading from IEA Bioenergy's website[1].

Role of bioenergy in energy transition strategies

Modern bioenergy is one of the pillars of the energy transition and plays an important role in all sectors: power, heat, industry, and transport. In the IEA Net Zero Emissions by 2050 roadmap (NZE), bioenergy meets between 15 and 20% of total energy needs. This implies that modern bioenergy would need to triple from now to 2050, while at the same time traditional (inefficient and high polluting) uses of biomass are phased out. About 100 EJ of biomass would be needed – compared to a current use of 65 EJ – which falls within conservative estimates of biomass potentials.

In many countries, major demand increases for biomass and biofuels are expected in the coming decades, particularly from industry and transport sectors in their efforts to decarbonize their sectors. This demand will often be difficult to match and temporary gaps between supply and demand may be expected, particularly between 2030 and 2040 as biomass supply chains need to be developed and certain advanced technologies that can cope with a broad range of (lower grade) feedstocks still need to take steps towards market maturity. Next to stimulating such developments, there can/should be a prioritization of biomass uses, the choice of which is highly political, and sector driven. High temperature heat and non-energy use of biomass in industry, district heating networks, and difficult to abate transport sectors are often mentioned as priority use. A priority order can also be determined by the GHG reduction impact that can be reached with a certain amount of biomass. Compatibility with carbon capture and utilization or storage (BECCUS) can be an important factor.

Bioenergy deployment is not on track to meet the intermediate 2030 target of the NZE roadmap. Achieving net zero requires stronger demand policies, diversifying supply chains and expanding advanced biofuels. Nevertheless, trends consistent with net zero are emerging. All major biofuel demand and production centres in North and South America, Europe, and Asia have policies, programs, and funding efforts to expand and diversify feedstock supply. Various supporting policy packages in the United States, the European Union and Brazil were presented in the workshop.

In a panel debate, the main challenges of bioenergy deployment and ways to address these challenges

[1] https://www.ieabioenergy.com/blog/publications/ws30-bioenergy-in-a-net-zero-future/

were discussed.

- Competition with fossil fuel prices is still the main hurdle for biobased fuels, with fossil fuels in several regions even being subsidized to reduce the energy cost for citizens and industries. Long-term and predictable policies – giving perspectives for solutions that fit in a net zero strategy - will be needed to make the financial equation work for low carbon intensity biofuels. Cost-effectivity of policies will be important to achieve a broader decarbonization, with the least cost to society.
- Performance standards for biofuels and other renewable fuels are critically important, particularly when mandate systems are used. Policies should be technology agnostic and consider the carbon intensity of fuels put on the market. This will incentivize producers and distributors of fuels to lower the carbon intensity of the fuels they distribute.
- Low carbon intensity technologies that are available now will need to be accelerated; on top, we need to invest in upcoming technologies. Upcoming technologies - which have a larger feedstock base than conventional biofuels - are vital for the future, and they need additional support on top of market instruments such as tax incentives or mandates to reach market maturity.
- Feedstock mobilization is one the main challenges for bioenergy deployment. Collection systems of biogenic waste and residues need to be improved or set up. Forest management practices that reduce risks for forest fires and infestations in warming climates need to be stimulated and these will provide a growing source of biomass. Moreover, agricultural production of biomass will also be indispensable: we should consider the types of (energy) crops that we can grow in specific circumstances, improve agricultural systems across countries to ease the stress on land use, and address marginal/abandoned lands and learn how to grow crops there with a good business case. Biohubs at the local scale can produce bioenergy intermediates and facilitate the logistics to more central processing sites.
- There is a lot of misinformation and negativity around bioenergy, but also a lack of knowledge about good bioenergy practices and opportunities these provide. Credible sustainability governance is to be applied to tackle the main sustainability risks of certain types of bioenergy. Overall, there should be better marketing and education to explain good bioenergy practice and gain confidence in the broader community and specifically the financial community as deployment means making investments.

Flexible bioenergy and the use of biogenic CO_2 in future energy systems

The flexibility that can be provided by bioenergy systems can be highly valuable to deal with several challenges in a renewable energy system with increasing shares of intermittent renewables such as solar and wind energy. Flexible combined heat and power (CHP) systems, with fast ramp up/down times, can contribute to intraday matching of supply and demand; seasonal mismatches - e.g. with lower production of solar power in winter while electricity demand of heat pumps is highest - can be covered through the use of storable bioenergy carriers, with large spatial and temporal flexibility, e.g. bio-CHPs providing both heat and power in colder seasons. In addition, there are important synergies with hydrogen - biomass based power-to-X (PtX) systems enable value creation to support PV/wind overcapacity.

Connecting bioenergy systems with CO_2 capture (BECC) strongly enhances the carbon efficiency and value of biomass towards net zero energy systems. The captured biogenic CO_2 can be used for permanent storage (BECCS), or for the production of renewable chemicals and fuels (BECCU). A study for the European energy system found that excluding BECC would lead to a 13% higher system cost to achieve the climate targets. Without bioenergy, the expansion of variable renewables, electrolysers, e-fuels, and Direct Air Capture (DAC) would be much more challenging and lead to much higher system costs (up to 20% higher) to phase out fossil fuels and reach the net-negative emissions that will be required in the second half of the century. A similar message can be found in the IEA Net Zero report of 2021: it was found that a 10% reduction in bioenergy use from the IEA's already conservative estimates would add an additional 4.5 trillion USD to the cost of the global energy transition (a 3% increase).

Carbon dioxide removals (CDR) lower atmospheric levels of CO_2 by putting biogenic or atmospheric carbon in long-term storage. When paired with ambitious emissions reductions, carbon removal could make it possible to reach net-zero emissions. Not all carbon capture projects can be qualified as carbon removal. The condition is that atmospheric or biogenic CO_2 is used, and that it is used for long time storage. Supply chain emissions should also be accounted for. The overall governance of CDR is critical: a clear regulatory framework is needed, as well as economic incentives for investment and supporting biogenic CO_2 removal through the creation of demand for negative emissions.

Future deployment of BECCS will require confidence in the GHG mitigation potential associated with its use, both in terms of scientific understanding and treatment under relevant policy. As for all bioenergy systems, impacts in the supply chain (both direct and indirect) need to be accounted for. Accounting approaches for existing bioenergy supply chains have already been developed and these are a good basis. To build experience and ease further BECCS deployment it is best to start with no-regret options, i.e. pathways that have minimal indirect market level effects, such as biomass waste and residues.

Projections to decarbonize difficult to abate transport sectors like aviation and maritime transport mainly rely on a combination of biofuels and e-fuels. These e-fuels rely on renewable hydrogen and most of them need atmospheric/biogenic CO_2 as input. A case study for France concluded that demand side measures in transport are indispensable to avoid excessive demands for renewable power and biogenic CO_2 in these sectors; moreover, a thorough planning and prioritization would be required to avoid conflicts of use for renewable electricity and biogenic CO_2 (which is also needed for negative emissions).

Promising developments in bioenergy concepts

Several projects and concepts were presented in the last session of the workshop, many of them focused on biomass gasification.

Depending on the feedstock type, operating conditions, and the gasification technology syngas produced by biomass gasification is suitable for combined heat and power, biomethane, biohydrogen, liquid biofuels or biochemicals production. While gasification-based CHPs are already deployed at scale, the synthesis of syngas to fuels or chemicals is in demonstration or early commercialization stage. Some examples of developments in France to produce biomethane or Fischer-Tropsch fuels were presented in this session.

A promising development in gasification concepts is to valorise the CO_2 from the syngas, which is currently not used. Converting this biogenic CO_2 in combination with renewable hydrogen to additional products can lead to very high carbon efficiencies, with over 90% of the carbon of the biomass input ending up in the final products. Similarly in ethanol projects, the high concentration CO_2 co-product from the fermentation process can be further utilised to make full use of the carbon contained in the biomass input.

Alternatively, this CO_2 can also be captured and stored. Gasification could be directed to hydrogen production, with most of the energy going to hydrogen and most of the carbon ending up in biogenic CO_2 that can be captured and stored. When these negative emissions are rewarded at 100€/ton CO_2 or more, the cost for producing bio-hydrogen would in many regions be lower than hydrogen produced from solar cells or wind power.

Large scale BECCS projects are starting to take off and becoming a reality, also in terms of business case. Ørsted Bioenergy in Denmark will capture and store 430,000 tons of biogenic CO_2 annually from two district heating CHP plants from 2026 onwards. The CO_2 will be injected into offshore permanent geological reservoirs in the Norwegian part of the North Sea. The carbon removal certificates from BECCS will be sold through bilateral offtake agreements. The project will enable taking the first step in establishing a large-scale CO_2 hub for storage and utilisation.

3. Workshop

3.1 SESSION 1: THE ROLE OF BIOENERGY IN ENERGY TRANSITION STRATEGIES

This session was moderated by Dina Bacovsky, BEST (Austria) and Chair of the IEA Bioenergy TCP; and Emilie Machefaux, ADEME (France).

Dina Bacovsky welcomed all participants in Lyon, as well as online, on behalf of IEA Bioenergy. IEA Bioenergy is one of IEA's Technology Collaboration Programs, with participation of 24 countries from across the globe plus the European Commission. IEA Bioenergy is a high-level international platform where experts exchange with experts to advance sustainable bioenergy deployment and make systemic assessments. She reminded everyone that the transition will require an unprecedented change in the energy system. The role of bioenergy is an essential one, providing around 20% of total energy supply in 2050. Bioenergy will provide 3-fold contributions: (1) substitute fossil fuels and reduce greenhouse gas emissions, (2) provide flexibility in the energy system which will be dominated by variable renewables, (3) provide negative emissions through the capture and storage of biogenic CO_2.

Emilie Machefaux also welcomed the workshop participants and presented some of the background of ADEME, the French Agency for Ecological Transition. ADEME participates in the development of national and local policies, in support of the Ministry; its areas of work are climate change, renewable energy, energy management and the bioeconomy. ADEME and French stakeholders have been involved in energy transition work for a long time; France participates in 17 IEA Technology Collaboration Programs, one of which is IEA Bioenergy. In 2020, ADEME published a foresight exercise 'Transition 2020' to explore what is needed achieve carbon neutrality by 2050, which confirmed the essential role of biomass in the French energy system. The demand for biomass will have a strong increase to meet all uses, so there will be a challenge to increase harvests in agriculture and forestry without unbalancing systems (such as carbon storage). We need a systemic vision on the availability of resources and the expected uses of biomass. Biomass is a renewable but limited resource; planning will be important to meet local and national needs.

Emmanuel Goy is from the regional office of ADEME for the region Auvergne Rhone-Alpes. The region is as big as Austria and is the region with the biggest amount of standing wood in France. It also has several poor air quality zones; wood energy plays a significant role in air quality, mainly because of fireplaces and old stoves. Open fireplaces are banned in some areas. ADEME, together with the local authorities, gives subsidies to replace open fireplaces and old stoves with new efficient and clean devices. This also reduces wood consumption for the same amount of heat produced, so it saves the wood resource. ADEME also supports centralized district heating systems; the last big wood boiler that was financed in this region is a 50 MW_{th} biomass plant, with high efficiency and low emissions. It provides district heating for parts of the city of Lyon and its surroundings.

3.1.1 Bioenergy in iea’s net zero roadmap

***Jeremy Moorhouse**, Renewable Energy Division, International Energy Agency (IEA)*

The IEA Net Zero Emissions by 2050 (NZE) roadmap was updated in September 2023[2]. In this roadmap, energy sector CO_2 emissions are reduced 65% by 2035 and reach net zero by 2050, with residual emissions of 1.7 Gt balanced by atmospheric removals of the same magnitude. Energy-related greenhouse gas emissions should peak by 2025 and decline by nearly 40% from today to 2030. Proven solutions available today deliver over 80% of what is needed this decade.

Modern, sustainable bioenergy accounts for more than half of all renewable energy supply today. In the net zero scenario it expands in all sectors thanks to its compatibility with existing infrastructure and global availability. Modern bioenergy is the single largest source of new, low-emitting energy supply in the net zero scenario to 2030. Total biomass supply grows from 65 to 100 EJ by 2050, with growth in solid, liquid, and gaseous supplies. It plays an increasing role in industry and transport, but also in power generation – while only representing 5% of power generation in 2050, it is crucial to balance the grid with high dominance of variable renewables like solar and wind energy; moreover, bioenergy systems combined with carbon capture and storage (BECCS) provide negative emissions.

Bioenergy plays an important role in all sectors and is one of the pillars of the energy transition. **While traditional uses of biomass are phased out, modern bioenergy use in the NZE roadmap nearly triples to 2050, meeting almost 20% of total energy needs and becoming the second largest source of energy supply (after solar energy)**.

Global demand of around 100 EJ biomass in 2050 is within the assessed sustainable potential, and is a conservative figure compared to other estimates. There are enough sustainable supplies that can be mobilized - by 2050 there would be no overall increase in cropland use for bioenergy production and no encroachment on forested lands from current levels.

[2] Available at: https://www.iea.org/reports/net-zero-roadmap-a-global-pathway-to-keep-the-15-0c-goal-in-reach

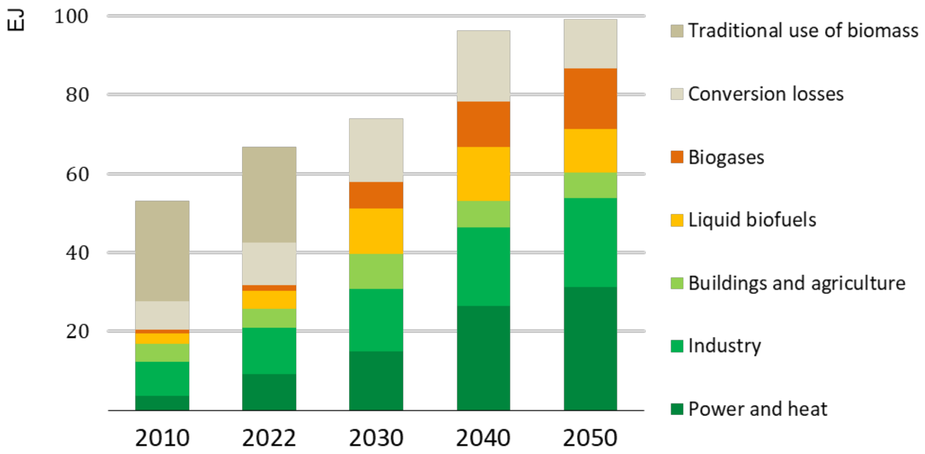


Figure 1: Primary bioenergy use by sector and economic grouping in the NZE Scenario, 2010-2050. (Source: IEA, 2023)

Is bioenergy on track to meet these targets? The answer is no. The phase out of traditional uses of biomass needs much stronger acceleration. In terms of biofuels, these only expand in a limited number of countries; in particular, the United States, Brazil, Indonesia, India, and Canada drive 80% of new biofuels demand in the next 5 years. Feedstock supply is crucial – we already start to see constraints in the supply of fats and oils. Achieving net zero requires stronger demand policies, diversifying supply chains and expanding advanced fuels.

However, trends consistent with net zero are emerging. All major biofuel demand and production centres have policies, programmes, and funding efforts to expand and diversify feedstock supply. New projects based on novel feedstocks may account for near 20% of new biofuel supply to 2030.

To overcome the barriers to deployment, we need to identify and develop markets with high potential for biofuels production; expand access to feedstocks; accelerate technology deployment to commercialize advanced biofuels; seek consensus on performance-based sustainability assessments and frameworks; and enhance international collaboration efforts.

3.1.2 The challenges of biomass closure of the French climate-energy strategy

__Christophe Kassiotis__, General Directorate for Energy and Climate Change, Ministry of Energy Transition, France

The national low-carbon strategy in France states that GHG emissions are to be reduced by 55% by 2030 and carbon neutrality should be reached by 2050. This implies that the annual rate of GHG reduction needs to be doubled.

The French energy transition has three pillars: (1) energy savings, (2) electrification and (3) mobilisation of thermal renewable energy - with a central role for bioenergy.

Considering the increasing demand for biomass to substitute fossil fuels, the climate strategy analysed if there can be a balance between biomass supply and demand in the coming decades. A hierarchy of uses will be necessary in the longer term, and potential conflicts with other objectives (e.g. food self-sufficiency, biodiversity, or carbon sinks) are to be considered. The background for the analysis is the combination of different sector models and iterations. Considering that France has one of the largest agricultural and forestry areas in Europe, only domestic biomass production is considered, no imports, except for a limited share of liquid biofuels.

The figures below show preliminary results of the modelling exercise for the French climate energy strategy. In a high mobilisation scenario (see figure), the supply of biomass resources is expected to increase from around 170 TWh today to 310 TWh in 2050. **Most of the increase will be in agriculture, notably through the recovery of crop residues, intermediate crops, lignocellulosic crops, and livestock effluents.** In terms of forest biomass or wood outside of forests there will only be a slight increase; a reduction of the bioenergy share in harvests is offset by a net increase in the recovery of wood products at the end of life.

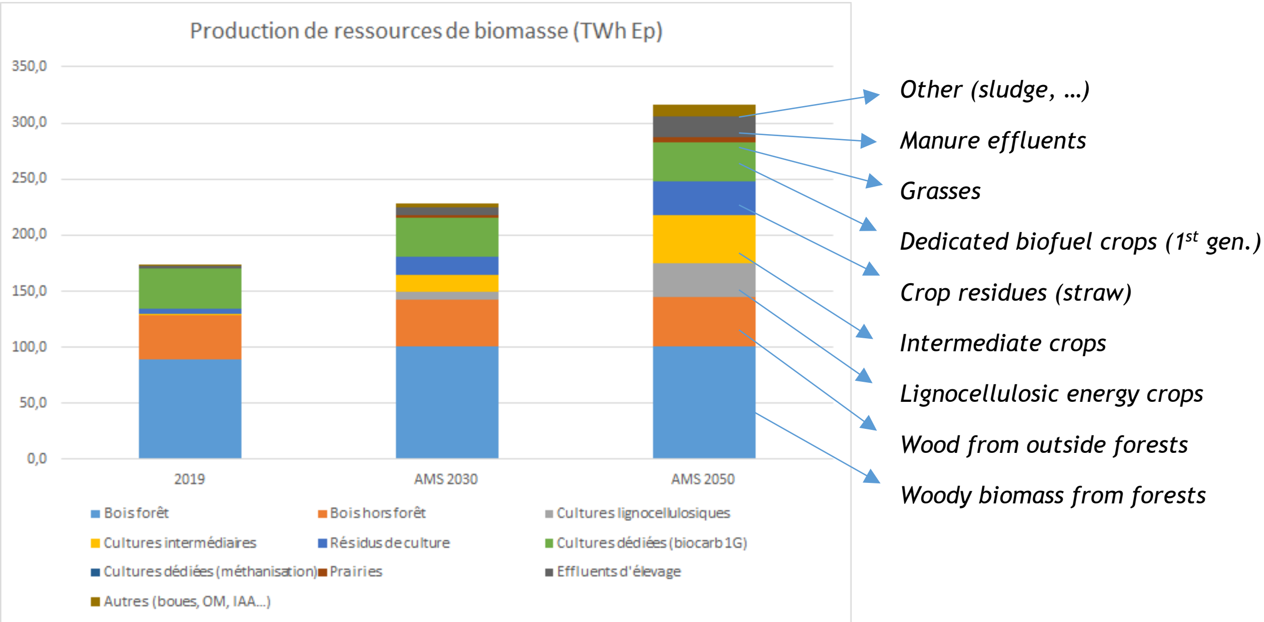


Figure 2: Biomass supply in France - results of 2nd modelling run (optimistic assumptions); 1 TWh = 3.6 PJ. (source: French Ministry of Energy Transition, 2023) – Preliminary modelling results!

When looking at the supply-demand comparison, it turns out that there is a slight deficit towards 2030 (mainly for gaseous biofuels), and a major deficit towards 2040. This is particularly related to the growing demand for liquid biofuels to decarbonize transport sectors. After 2040, demand from transport will decrease again due to increasing electrification in road transport, with demand remaining from hard to electrify sectors such as aviation and maritime transport. Anyway, liquid biofuels production is assumed to double from now to 2050, so consistent efforts will be needed to increase their production.

Figure 3: Balance between supply ('offre') and demand for biogas (left), solid biomass (middle) and liquid biofuels (right). (source: French Ministry of Energy Transition, 2023) – Preliminary modelling results!

In terms of solid biomass there may be a surplus compared to demand. Part of this is already assumed to be used for the production of liquid biofuels via gasification type projects.

Demand for renewable gas will see a strong growth up to 2050, coming towards the same order of magnitude as demand for solid biomass and liquid biofuels.

There will need to be a prioritisation of biomass uses, the choice of which is a highly political and sector driven. High temperature heat and non-energy use of biomass in industry, as well as heat networks come forward as priority use; for transport there is diversification between air and marine transport on the one side, with higher priority, and road transport on the other side, with lower priority, particularly for light duty vehicles.

3.1.3 Bioenergy in Canada's net-zero future

***Oshada Mendis**, Office of Energy Research and Development, Natural Resources Canada*

Canada has a large potential to leverage bioenergy to achieve climate change goals. It has six principal types of biomass feedstocks, with forest related biomass being the dominant feedstock potentials in Provinces like British Columbia and Quebec, and agriculture related biomass being dominant in Provinces like Alberta, Saskatchewan, and Manitoba (see figure).

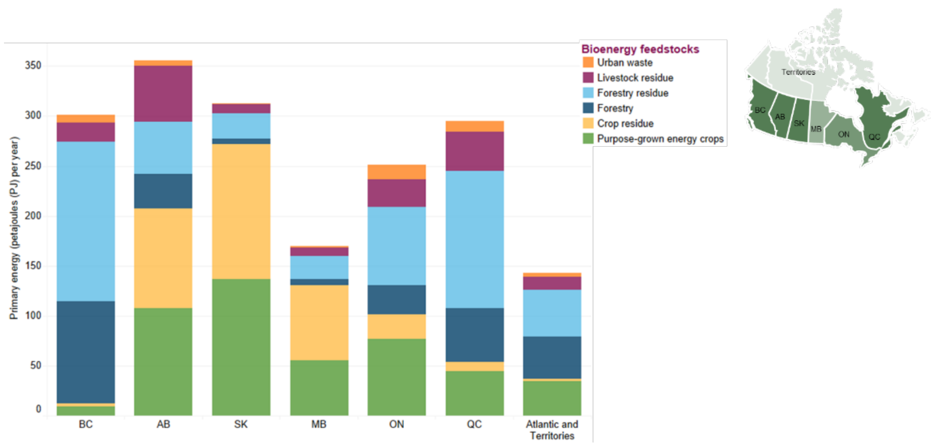


Figure 4: Biomass potentials in the provinces of Canada. (Source: CER, 2023)

Even with this substantial potential, choices will have to be made. It is important to expand the knowledge to advance bioenergy, with techno-economic and environmental assessments of modern bioenergy pathways, feedstock availability and delivered cost, and market assessment/utilisation in regional contexts. Artificial Intelligence can be applied to combine different aspects. The main objective in the presented analysis carried out by CanmetEnergy is to optimize GHG reductions in industrial facilities, considering technical and economic constraints, in which a multi-criteria approach can be applied with weight factors.

A case study for the province of Quebec showed that demand for biomass in industrial projects could be almost four times higher than supply. So, there is not enough biomass to cover all identified fuel switching projects. The **focus will be on 'high-impact GHG applications', meaning that best use is made of low-cost biomass and investment capital**. A priority order / order of merit will depend on specific analysis criteria/objectives. Next to maximizing GHG reductions, compatibility with BECCS is also an important factor.

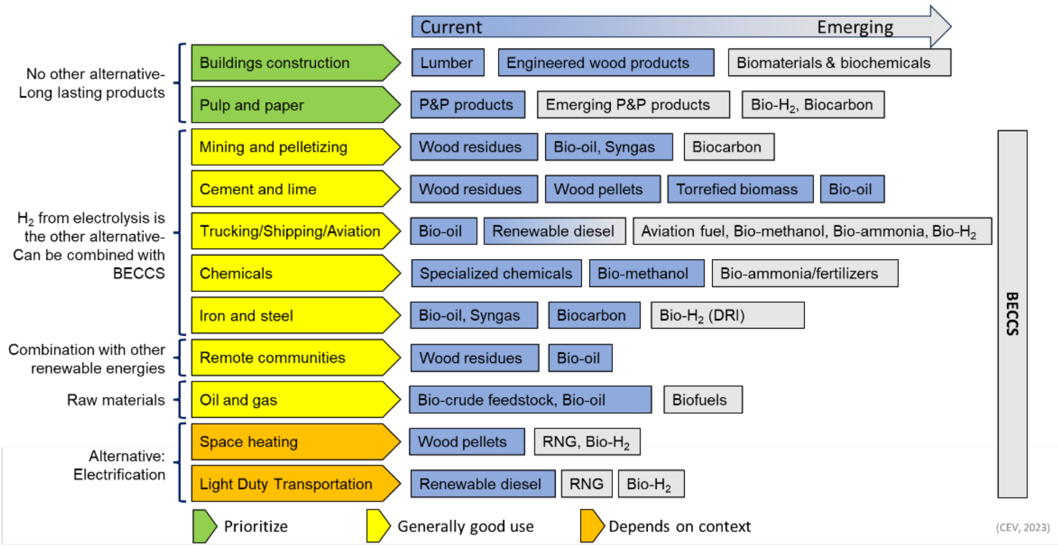


Figure 5: Order of merit for biomass in industrial decarbonisation. (Source: CEV, 2023)

The following three contributions were given as introduction to the panel debate, showing an overview of policies in the US, EU, and Brazil to support the development and deployment of bioenergy/biofuels.

3.1.4 US Bioenergy opportunities

***Jim Spaeth**, Bioenergy Technologies Office, United States Department of Energy*

There are several government programs and laws in the US that support the development and deployment of bioenergy/biofuels, from lab-scale developments to market roll-out. Some of the main examples:

- The ‘**Sustainable Aviation Fuel (SAF) Grand Challenge**’ is a government-wide initiative led by the US Departments of Energy (DOE), Agriculture (USDA), and transport (DOT) to expand the domestic production of SAF to meet 100% of domestic demand for aviation fuel. The near-term goal is 3 billion gallons by 2030 (20% CO_2 reduction); the long-term goal is 35 billion gallons by 2050.
- The **Bipartisan Infrastructure Law** (BIL) of November 2021 and the **Inflation Reduction Act** (IRA) of August 2022 together invest more than 450 billon USD in the US energy system, particularly for the deployment of clean technologies.
- **Clean Fuel Tax Credits** are extended for road biofuels - such as renewable diesel or other second-generation biofuels - or introduced for sustainable aviation fuel. A technology neutral Clean Fuels Production Tax Credit based on well-to-wheel lifecycle GHG emissions will be introduced from 2025.
- The Office of Clean Energy Demonstrations (OCED) supports the delivery of clean energy technology demonstration projects, in partnership with the private sector. 10 billion USD is scheduled for ‘carbon capture, direct air capture and industrial emission reduction’.
- The Bioenergy Technology Office (BETO) provide an annual funding of 250 million USD to support R&D, pilot, and demonstration projects from TRL 2 up to TRL 7. The higher the Technology Readiness Level (TRL), the more input from the private sector is expected.
- The existing loans programs of the DOE Loan Programs Office are expanded, tripling the loan authority for innovative energy technologies (40 billion USD).
- The Department of Transport has a FAST-SAF grant programme for projects that produce, transport, blend or store sustainable aviation fuel (244.5 million USD).

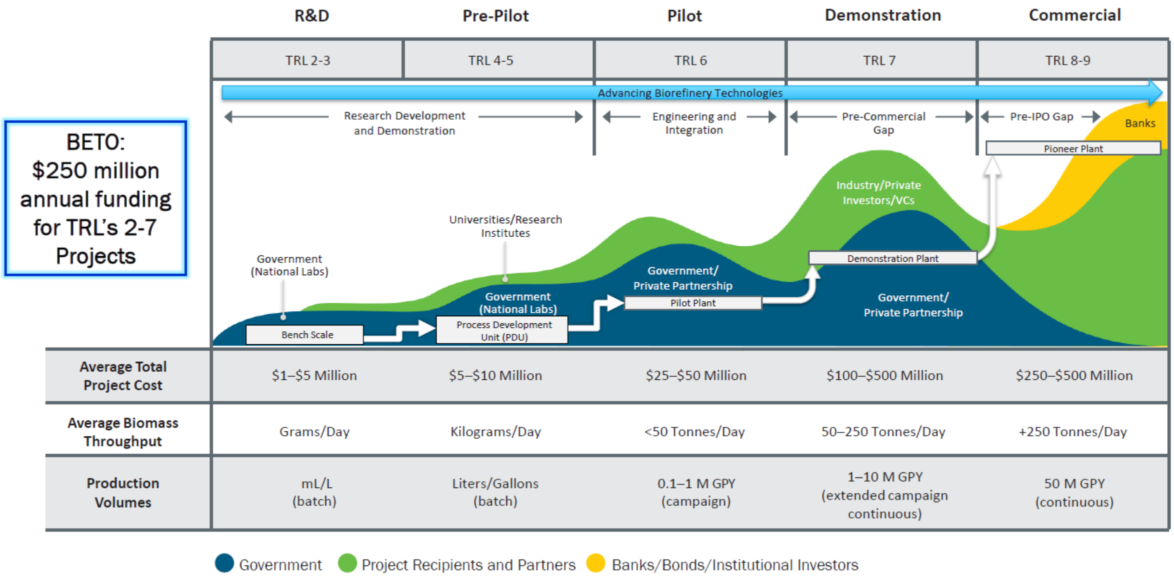


Figure 6: Support of bioenergy projects over the TRL scale. (Source: US DoE – BETO Office)

3.1.5 EU policies, relevant for bioenergy deployment

***Maria Georgiadou**, DG Research and Innovation, European Commission*

The main initiatives at European level impacting bioenergy deployment are:

- The **'Fit for 55' implementing regulation**, containing a package of regulatory initiatives, aiming to collectively reach 55% GHG reduction by 2030 in the EU. Several regulatory initiates have a direct or indirect relevance for bioenergy. The Fit for 55 package includes revisions of the Renewable Energy Directive, Effort Sharing Regulation, Emission Trading System, LULUCF regulation, Energy Taxation Directive and CO_2 emission standards to bring them in line with the targets of the European Green Deal. The package also includes specific targets to replace fossil fuels in aviation (ReFuelEU Aviation) and maritime sectors (FuelEU Maritime), see figure below.
- **REPowerEU** was implemented in reaction to the energy crisis after the invasion of Russia in Ukraine to diversity energy sources, accelerate the clean energy transition and save energy. One of the actions is a Biomethane Action Plan to double the target of EU biomethane production to 35 billion m^3 per year by 2030.
- The EU **Net-Zero Industry Act** aims to support strategic net-zero technologies that have significant potential for rapid scale-up. Sustainable biogas/biomethane and carbon capture and storage are some of the strategic technologies.
- The **Strategic Technologies for Europe Platform** (STEP) aims to boost investments in critical technologies in Europe and leverage EU funds to investments in the EU, among others through the Innovation Fund and Horizon Europe, and covers clean energy and renewables.
- The Hydrogen and decarbonized gas markets package proposes revised and new rules to lower the carbon footprint of the gas market. The goal is to shift from fossil natural gas to renewable and low-carbon gases.

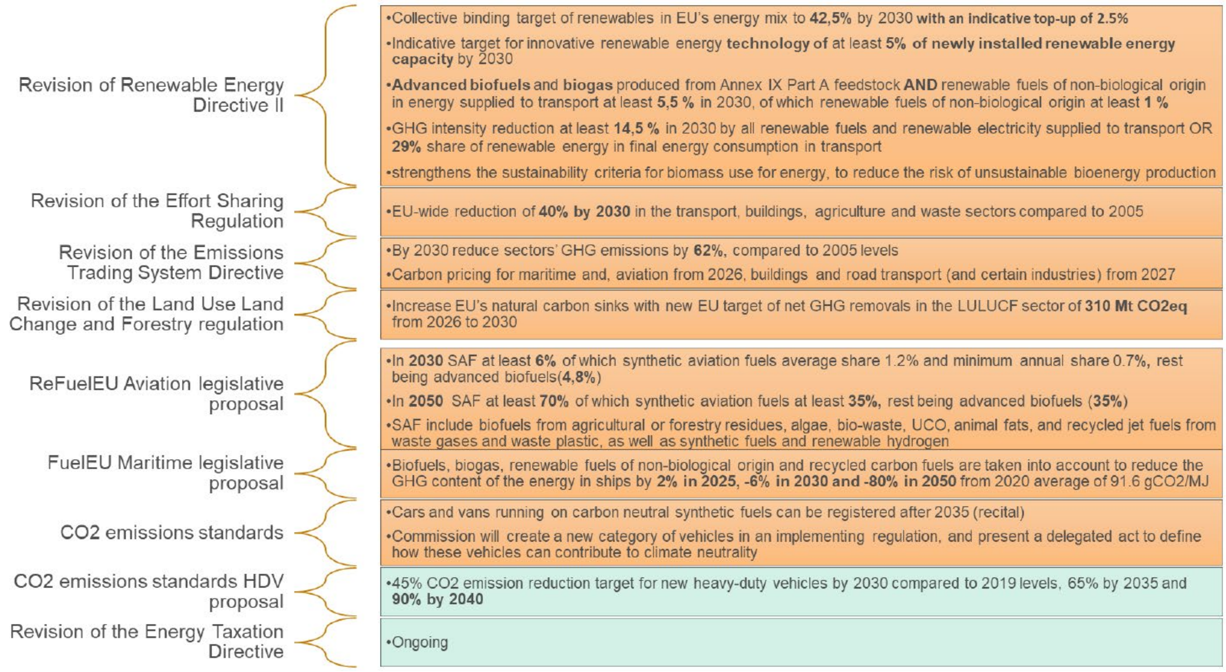
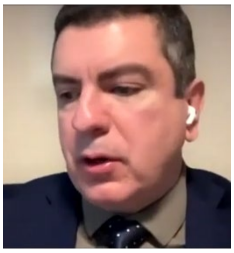


Figure 7: Regulatory initiatives in the Fit for 55 Package[3] with relevance for bioenergy. (Source: European Commission)

3.1.6 The Brazilian policies for biofuels

***Marlon Arraes Jardim**, Biofuels Department, Ministry of Mines and Energy, Brazil*



Brazil has favourable conditions to produce bioenergy due to the availability of agricultural land and a suitable climate for the cultivation of raw materials such as sugar cane, corn, or soy. These have consolidated Brazil's expertise in the sector of biofuels.

RenovaBio is the centre of the national biofuels policy in Brazil. It contains national targets for reducing emissions in the fuel market. The basis is individual certification of biofuel production on a life cycle basis; biofuel producers receive an efficiency score in terms of net emissions per unit of energy. Decarbonization Credits (CBIOs) issued by the biofuel producer must be purchased by distributors on the stock exchange market. One CBio corresponds to a reduction of one ton of CO_2 equivalent, in comparison to fossil fuel emissions. The CBIOs acquired will be the only way to prove compliance with the goals.

[3] More information available at: https://www.consilium.europa.eu/en/policies/green-deal/fit-for-55-the-eu-plan-for-a-green-transition/

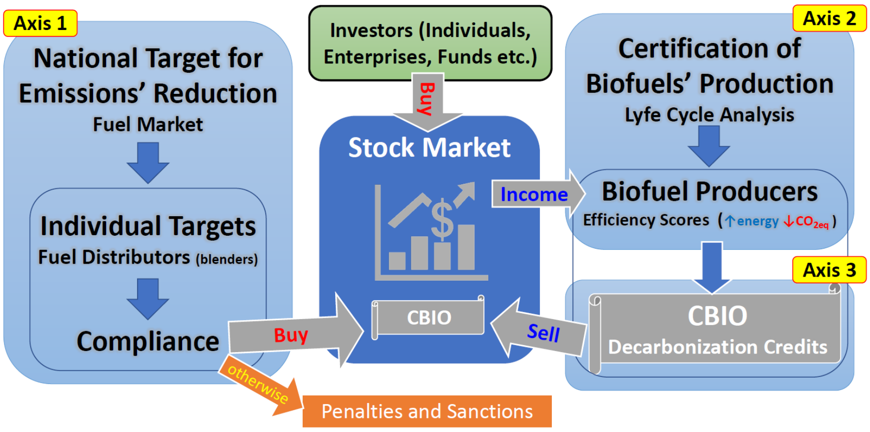


Figure 8: Schematic overview of the RenovaBio concept, with the three axes. (Source: Brazilian Ministry of Mines and Industry)

The 'Fuel of the Future' legislative initiative aims to integrate the National Biofuels Policy (RenovaBio), the Rota 2030 Program (well-to-wheel emission targets for the automotive industry), the Air Pollution Control Program for Motor Vehicles (PROCONVE), and the Brazilian Vehicle Labelling Program.

Next to that it includes:

- The National Sustainable Aviation Fuel Program (PROBIOQAV) sets targets for reducing CO_2 emissions for air operators, in their domestic operations, through the use of SAF. It contains a minimum CO_2 reduction target of 10% by 2037. The impact of such a target on air flight tickets would be between 3 and 10%.
- The CO_2 Capture and Storage Technology Regulation allows the voluntary use of CCS technologies by companies regulated and supervised by the ANP.
- The National Green Diesel Program (PNDV) puts volumetric mandates for green diesel to reduce the country's external dependence on Diesel.
- An evaluation program on the technical feasibility of expanding the limits of anhydrous ethanol mixture in gasoline from 27.5% to 30%.

The alignment and integration of biofuel related policies is fundamental to ensure the necessary investments and to comply with Brazil's international climate commitments.

3.1.7 Panel debate on effective policies and strategies to support the role of bioenergy

*This session was moderated by **Paul Bennett**, SCION (New Zealand) and **Birger Kerckow**, FNR (Germany). All presenters of Session 1 participated.*

Main conclusions of the panel debate:

Challenges of bioenergy deployment and ways to address them

Competition with fossil fuel prices is still the main hurdle for biobased fuels. Governments are always worried about fuel prices for consumers, sometimes implementing tax reforms in the opposite direction, favouring fossil fuels to reduce energy prices for their citizens and industries. There is a need to have different perspectives and provide incentives for long term solutions that fit in a net zero strategy. Long-term policies will be needed to make the financial equation work. The perspective of a **cost-effective programme** aims to make the broader decarbonisation possible, with the least cost to society. Not all countries/regions can afford large subsidies. Without substantial budgets, mandates are the best approach to advance the energy transition.

In mandate systems, **performance standards** are critically important, so that lower carbon intensities are rewarded. In that sense, **policies should be technology agnostic and consider the carbon intensity of fuels put on the market**. This will incentivize producers and distributors of fuels to lower the carbon intensity of the fuels they distribute, which puts biofuels/bioenergy with low carbon intensity on a level playing field.

We need to accelerate low carbon intensity technologies that are available now and invest in upcoming technologies. The energy mix today is different from 2030 and 2050. We will have more biofuels and biogas in a future system with less overall fuel and gas consumption. **Upcoming technologies are vital for the future**. The main challenge for advanced biofuels – which have a larger feedstock base than conventional biofuels - is deployment, they do not pick up as fast as expected. **Newer technologies need additional support to reach market maturity.** Demonstration programmes are needed to prove new technologies at scale and bring them to market maturity, i.e. to bridge the 'valley of death' between technology development and market deployment, thereby continuously improving their process efficiency. Overall, broadening the feedstock base with advance technologies needs a solid strategy and a clear strategic roadmap, with aligned policies, which do not contradict each other.

There is a **lot of misinformation and negativity** around bioenergy. Bioenergy is a broad field and can be complex; there are many things that opponents can lash out to and generalize their criticism to the broad field of bioenergy. Sustainability governance to tackle the main sustainability risks and better marketing of good bioenergy examples are needed to handle misinformation and build support of citizens. Apart from an anti-bioenergy sentiment brought up by certain advocacy groups, there is a lack of knowledge and information about bioenergy in the broader community and the financial community. Financing will be key to market deployment, but many people in the financial community are not aware of the opportunities of different types of bioenergy. So, there should be a huge educational component to explain good bioenergy practice and gain confidence.

Overall, international collaboration is important to share knowledge, help each other and address those challenges.

Mobilizing feedstocks

Feedstock mobilisation is one the main challenges for bioenergy deployment. Large amounts of biomass will be required, going from a current use of 65 EJ (including traditional biomass uses) to an estimated 100 EJ by 2040-2050 in the IEA Net Zero roadmap.

The **knowledge of the types and amounts of biomass supplies** that are available and/or can be mobilized in different regions of the world is central, with an increasing role for digitalisation. On the one hand, there is an increased focus on biomass waste and residues – and technologies that can cope with lower grade biomass. This requires **improving collection systems of biogenic waste and residues** and sharing good practices of efficient collection systems. On the other hand, agricultural production of certain amounts of biomass will be indispensable. We need to assess and **find suitable areas which are fit to produce biomass sustainably** (agro-ecological zoning), considering the reality in many countries – with many countries having large potential to advance their agricultural production. Furthermore, we should consider the types of (energy) crops that we can grow in specific circumstances, improve agricultural systems across countries to ease the stress on land use, and address marginal/abandoned lands and learn how to grow crops there with a good business case.

It is important to bring down costs through economy of scales and the organization of logistics. Some parts of the value chains can be decentralized, with drying and preprocessing to bioenergy intermediates at the local scale, through a **biohubs approach; these biohubs are customized to local conditions where the biomass is available**. This facilitates the logistics to more central processing sites, without transporting water over long distances.

Given the limits of biomass availability it is important to **steer the use of biomass to high impact uses, such as biorefineries and BECCS systems**.

Impact of climate change risks

We already see impacts of climate change in changes of agricultural yields and increased forest fires. It is difficult to determine what will be structural change in agricultural patterns (with longer periods of droughts, heavy rain, …) over the longer term because of annual fluctuations. Forest fires and infestations will get more prevalent and severe as time passes and climates get warmer. Reducing the risk for forest fires requires sustainable **forest management. This also creates a sustainable potential for biomass**, so it helps producing biomass for the energy mix, while reducing the risk of carbon losses in forests.

Climate change gives challenges in the access to renewable and low-carbon energy, e.g. droughts can lead to lower levels of hydropower, too low river levels for logistics, or inability to cool nuclear power plants. The degree of risks related to climate change impacts will depend on **our ability to adapt, and the flexibility in our way to approach the energy mix, with a portfolio of climate neutral energies to mitigate risks**.

Role of artificial intelligence (AI)

Artificial Intelligence (AI) capacity is increasing massively day by day. AI can run countless modelling with high speed and ease. It is new for the biofuels/bioenergy sector, but AI will find its way to reduce the complexity of these systems and optimize solutions. AI can be applied for the collection and mobilisation of biomass, to optimize process conditions in biorefineries based on the biomass composition, or for enhanced engineering in production processes and biofuel appliances.

3.2 SESSION 2: FLEXIBLE BIOENERGY AND THE USE OF BIOGENIC CO_2 IN FUTURE ENERGY SYSTEM

*This session was moderated by **Daniela Thrän**, Helmholtz Centre for Environmental Research - UFZ / DBFZ (Germany) and **Zoe M Harris**, University of Surrey (United Kingdom).*

3.2.1 Considerations on the priority of biomass use in future energy systems

***Markus Millinger**, Chalmers University of Technology, Sweden*

Biomass is a versatile renewable energy source that can be used in all parts of the energy system, but it is a limited resource and usage needs prioritisation. The presented study[4] used a sector-coupled European energy system model to explore the range of cost-effective near-optimal solutions for achieving stringent emissions targets.

Commonly, the 'single cost-optimal solution' in energy system modelling studies is in focus, combined with some sensitivity analyses. However, there are large uncertainties regarding future energy systems, and recent analyses have shown that the technology mix variety of near-optimal solutions when allowing a small system cost increase can be distinctly different from the single optimal solution. The available amount of biomass has been found to affect the manoeuvring space substantially. The overarching goal of this work was to analyse the system cost of variability in biomass supply and biomass technologies in a European energy system adhering to stringent emissions targets.

Excluding biomass residue use in a fossil free energy system adhering to a -110% negative emissions target in Europe (compared to 1990) **results in a 20% higher system cost and a substantially higher and more challenging expansion of variable renewables, electrolysers, e-fuels, and Direct Air Capture (DAC)** compared to if biomass residues are included. The cost increase is estimated at 170 billion € annually, roughly corresponding to total European defence expenses.

Most bioenergy systems in this case are connected with carbon capture (BECC). It matters less whether biomass is used for combined heat and power (CHP), liquid fuel production or industrial process heat, as long as it is combined with carbon capture to provide renewable carbon for negative emissions or for recirculation to synthesize fuels for further use in the energy system. Renewable chemicals and liquid fuels are some of the most challenging parts to decarbonize.

Around 900 million tons of biogenic CO_2 capture in Europe would be cost optimal – this is equivalent to 21% of total GHG emissions in Europe in 2021. If BECC is excluded, this would lead to a 13% higher system cost to achieve the climate targets. It is clear that **BECC strongly enhances the carbon efficiency and value of biomass**.

[4] Preprint of the full article available here: https://www.researchsquare.com/article/rs-3097648/v1

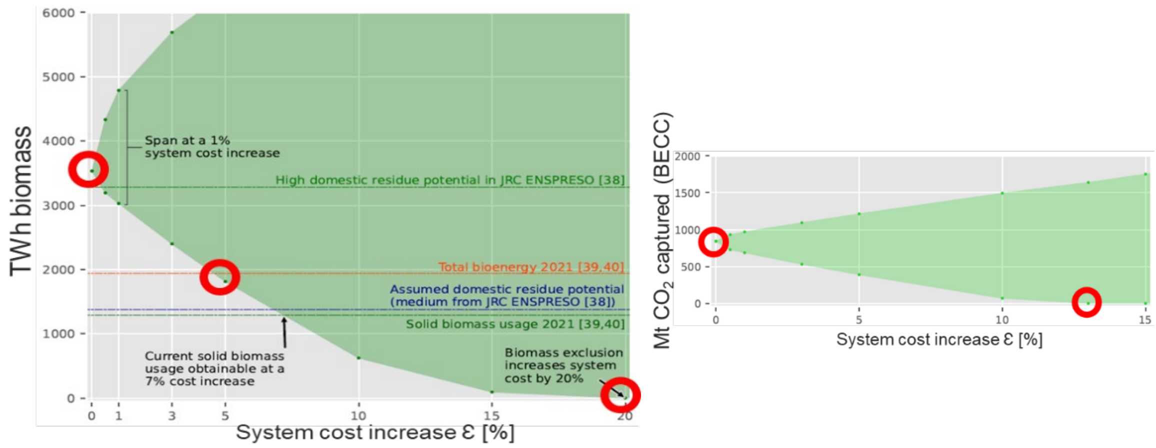


Figure 9: Solution spaces for different biomass usages in a net-negative -110% emissions scenario with an allowed carbon sequestration potential close to what is necessary to achieve the target. The figure maps out the space of feasible solutions (shaded area) for a given allowed system cost increase ε (percentual deviation from the least-cost objective value). (Source: Chalmers University, 2023)

3.2.2 How flexible bioenergy can support the transition to a renewable energy system

***Tilman Schildhauer**, Paul Scherrer Institut, Switzerland*

There are several challenges in a renewable energy system. For example:

1. Intraday mismatch of electricity supply and demand
2. Seasonal (and regional) mismatch of energy supply
3. Defossilization of all sectors: domestic/industrial heat, transport on land, ships, aviation, chemical industry
4. Negative emissions to compensate unavoidable greenhouse gas emissions

Beyond efficiency and demand-side management there are several measures that can be applied for the respective challenges, such as respectively (1) batteries, pumped hydro; (2) water storage in reservoirs (dams); (3) heat pumps, district heating with waste incineration; electrification of cars, trucks, processes; (4) direct air capture of CO_2.

However, these options have their application limits, some require considerable time to deploy, others are very expensive. **Flexible bioenergy is a valuable wild card for all these challenges**.

- Flexible combined heat and power (CHP) systems operating on biogas, liquid biofuel or solid biomass can support the *intraday matching of supply and demand*, through the application of heat storage and flexible power generation, with fast ramp up/down times.
- *Seasonal mismatches* can be covered through the production of storable energy carriers, with large spatial and temporal flexibility. Moreover, CHPs can provide both heat and power in winter times when solar power is low and electricity demand from heat pumps is high. In addition, there are important synergies with hydrogen; biomass based power-to-X (PtX) systems enable value creation to support PV/wind overcapacity.
- Energy carriers can be produced to defossilize difficult to electrify sectors such as industrial heat, or long-distance transport. Moreover, capturing biogenic CO_2 from the processes and combining them with renewable hydrogen can increase the production of renewable gases or liquid fuels that are compatible with fleets and fuel infrastructure.
- The CO_2 captured from biogenic processes can be captured and applied for long-time storage (in the underground, or in buildings), thereby providing negative emissions.

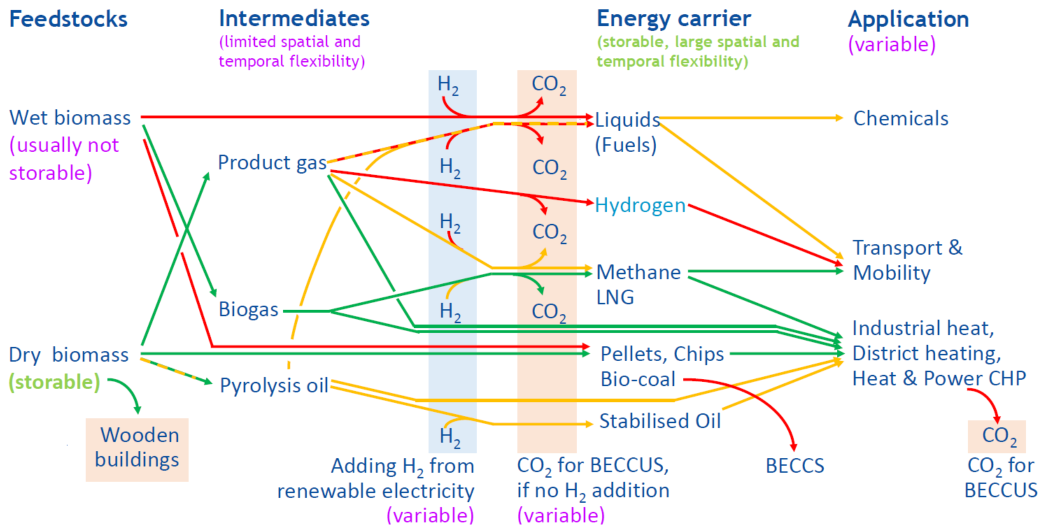


Figure 10: Flexible bioenergy concepts - what to use when and for what? (Source: IEA Bioenergy Task 44)

Flexible biomass systems are no one-size-fits-all solution. There are strong regional differences, e.g. in types and amounts of feedstocks, biomass logistics, availability of district heating or gas grids, synergies with local hydrogen production or with regional CO_2 logistics. Optimal solutions may differ from place to place. There are also variations in time, with the option to valorise biogenic CO_2 via utilization in PtX in summer (when there is excess renewable electricity available from PV systems) and using if for permanent storage (CCS) in winter.

Market regulations and incentives are needed to enable flexibility, without preference for certain technologies, energy carriers or services. Further technology development is needed to increase flexibility and efficiency at small scale. Moreover, **flexibility needs correct representation in system models** to find the overall optimum.

3.2.3 Management of biogenic CO_2: BECCUS

Christiane Hennig, DBFZ, Germany

Carbon dioxide removals (CDR) lower atmospheric levels of CO_2 by putting it in long-term storage. It is important to stress that CDR shall go hand in hand with cutting GHG emissions. All known and proposed methods of carbon removal are either too slow acting, and/or limited in scope, and/or expensive to offset anything like society's current CO_2 emissions. **When paired with ambitious emissions reductions, carbon removal could make it possible to reach net-zero emissions.**

The figure below explains that not all carbon capture projects can be qualified as carbon removal. The condition is that atmospheric or biogenic CO_2 is used, and that it is used for long time storage. The storage of fossil CO_2 leads to a reduction of fossil CO_2 emissions but will never lower atmospheric CO_2 levels. When biogenic or atmospheric CO2 is used through CCU for short lived products (fuels, plastics), it will avoid fossil CO_2 emissions of the conventional fuels/plastics, but it will also not lower atmospheric CO_2 levels.

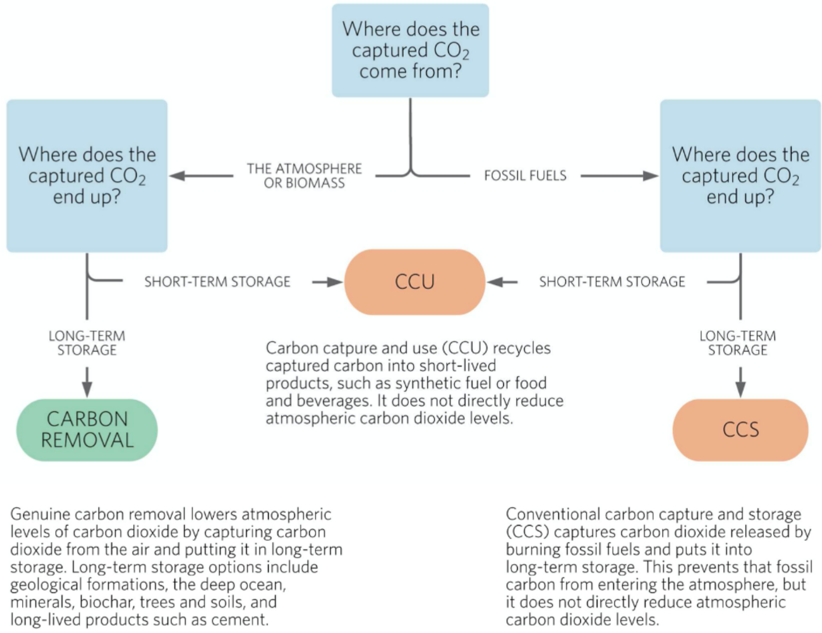


Figure 11: Explainer Carbon Removal. (Source: Institute for Carbon Removal Law and Policy, 2020)

National models in Europe, as well as the EU long-term climate strategy show that for reaching 55% GHG reductions by 2030, net zero by 2050, and net negative GHG emissions thereafter a large deployment of CDR is needed. CCS and CCU at industrial facilities through DACCS and BECCS have been identified as important technologies by the European Commission, as well as in other regions around the world. Denmark, Sweden, and Norway are progressing in their national legislation and support schemes for BECCS; they also drive the discussion on CDR methods at EU level. It is expected that through these initiatives deployment at national levels will progress in the years to come, which can also trigger further debate on EU level. Governance on EU-level still needs to be further developed. This **overall governance of CDR is critical: a clear regulatory framework is needed, as well as economic incentives for investment and supporting biogenic CO_2 removal through the creation of demand for negative emissions.**

IEA Bioenergy aims to provide guidance how to realize BECCS and BECCU deployment by presenting examples (case studies) and describing their successes and challenges; analysing crucial aspects for accelerating deployment (system studies); and supporting good governance to adopt and upscale BECCUS.

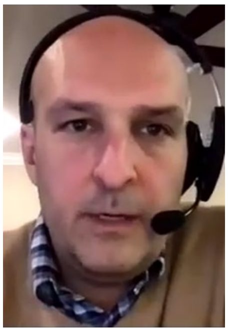
Some central questions:

- Which BECCUS technologies/concepts are (potentially) available?
- What are the requirements/implications for the deployment of BECCUS?
- In a given situation, should biogenic CO_2 be sequestered or utilized?
- How to monetize the carbon negative products that bioenergy can deliver?

Within IEA Bioenergy we have the expertise and link to various „first-of-its-kind“ BECCUS projects and with industries (as for example Hofor, RWE, Ørsted, DRAX) in different parts of the world. Furthermore, we are doing modelling of possible BECCUS applications to understand the concept and its potential for deployment. Summarizing, we can see that countries and regions are moving at different speed when implementing BECCUS concepts. In the past two years the development of BECCS projects has increased significantly, still we are far from the number needed to achieve the targets. Initiatives on BECCUS projects trigger other actors to join which creates BECCUS clusters.

3.2.4 Carbon accounting in BECCS value chains

Christopher Galik, North Carolina State University, USA



Future deployment of BECCS will require confidence in the GHG mitigation potential associated with its use, both in terms of scientific understanding and treatment under relevant policy.

It is important to **consider the full value chain of BECCS projects to assess the full GHG impact**. Project-specific components can either generate net emissions or net removals. For some effects (e.g., feedstock production, energy system market rebound) emissions or removals could include both direct and indirect effects. In the case of BECCS, the feedstock side is highly relevant.

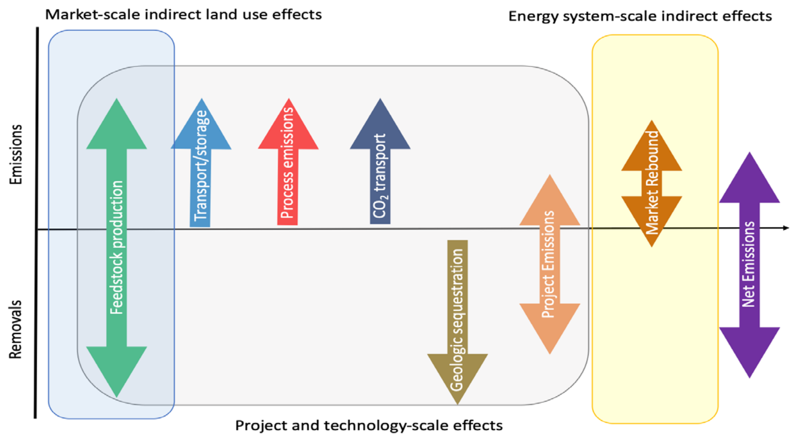


Figure 12: Conceptual diagram of GHG emissions or removals from a BECCS pathway.
(Source: Galik et al., 2023)

Some of the challenges of BECCS are: (1) continuing public distrust — and strong scientific debate — surrounding the accounting of biogenic stocks, including for carbon offsets; (2) multiple layers of reporting, complicating transmission of incentives along an accounting chain; (3) consistent treatment with other CDR options and renewable pathways to avoid implicitly favouring pathways.

Multiple policies exist with the potential to influence the accounting and allocation of removals across a BECCS supply chain. Accounting approaches for existing bioenergy supply chains (biopower, liquid biofuels) have already been developed, for example in the EU RED, the US EPA SAB biogenic carbon assessment process, or the California LCFS, and these are a good basis.

Feedstock transport, energy or fuel production processes, and other direct emissions are generally well-understood, while indirect effects are more difficult to assess. Simplified accounting might be used for pathways that have clear baseline conditions and minimal indirect effects (e.g., waste, residues).

Some recommendations:

- **Build on existing approaches**. The elements onto which accounting pathways are built have precedent. While potentially biasing against new and/or superior approaches, existing approaches have benefits of implementation experience and buy-in.
- Consider taking the easy way out - for now - and **start with 'no-regret' options**. Specific pathways that have clear baseline conditions and minimal indirect, market-level effects (e.g., waste, residues) might provide critical experience and exposure to ease further deployment.

3.2.5 Will there be enough biogenic CO_2 for projected e-fuels demand in France?

Aïcha El Khamlichi, Department of Bioeconomy and Renewable Energy, ADEME, France

The objective of this work was to estimate the needs for electricity and biogenic CO_2 in 2050 for the domestic production of e-fuels for aviation and marine applications in France, based on the e-fuel shares in the recently approved ReFuel EU Aviation and Fuel EU Maritime. Four scenarios were modelled, varying low vs high demand assumptions in the aviation and marine sectors (including national transport/domestic flights and 50% of international bunkers); and conservative vs optimistic technical assumptions (yields, selectivity, …).

Prospective demand of e-fuels by 2050 for aviation would be between 10 and 24 TWh; for maritime it would be between 10 and 30 TWh (*e-methane, e-methanol, and e-ammonia*).

For e-jetfuel, produced via Fischer-Tropsch process from hydrogen and CO_2, between 2.5 and 5 TWh electricity would be needed to produce 1 TWh of jetfuel. For marine e-fuels the ratio would be between 1.5 and 2.5. Overall, this would imply new electricity requirements for e-fuels between 44 and 175 TWh_e per year. These are substantial amounts compared to the projected total electricity production in France in 2050, estimated between 500 and 800 TWh_e.

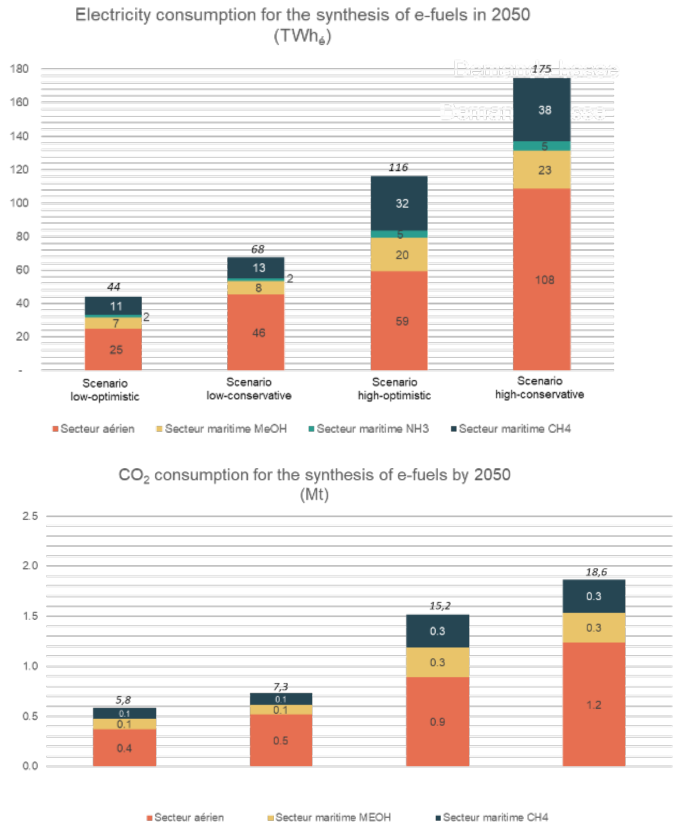


Figure 13: Electricity requirements for e-fuels production by 2050 (left) and biogenic CO_2 requirements (right). 1 TWh = 3.6 PJ (Source: ADEME)

According to RED III, three types of CO_2 are eligible for the production of low carbon fuels (RFNBO): (1) Biogenic CO_2; (2) CO_2 from direct air capture (DAC) (which is very energy intensive); and (3) fossil CO_2 from industries, but only until 2041 (discarded in this work for 2050). It is assumed that biogenic CO_2 would be the main source for carbon-based e-fuels. This would lead to a requirement of 6 to 18 million tons of biogenic CO_2 per year.

In theory, between 11 and 16 million tons of biogenic CO_2 could be captured from large installations (with >200 kt bio-CO_2 emissions per year) which could directly feed an e-fuel production plant. About 32 million tons of biogenic CO_2 could be captured by 2050 from smaller installations (>30kt bio-CO_2 emissions per year) if CO_2 transport networks (pipelines) are developed in France.

Mind that there will be a direct competition with BECCS to obtain negative emissions.

Overall, the low demand scenarios could realistically achieve the decarbonisation targets of aviation and maritime sectors, while having reasonable demands of renewable electricity and biogenic CO_2. In the high demand scenarios, the requirement for renewable power and biogenic CO_2 (just for aviation and marine applications) would be very hard to achieve. Overall energy demand in transport is the first sensitivity factor, so **demand side measures to reduce energy demand in the different transport sectors are a key prerequisite**. On the other hand, **a thorough planning and prioritisation would be required to avoid conflicts of use for renewable electricity and biogenic CO_2**. For example, a threshold for resource allocation could be applied for the production of e-fuels, considering the main energy-climate policies and sectoral strategies. Moreover, a certain share of biogenic CO_2 will be allocated for geological storage (BECCS).

3.3 SESSION 3: PROMISING DEVELOPMENTS IN BIOENERGY CONCEPTS

This session was moderated by ***Chourouk Nait Saidi****, ATEE (France) and* ***Berend Vreugdenhil****, TNO (the Netherlands)*

3.3.1 Diversification of applications downstream of pyrogasification

Marion Maheut*, Lab CRIGEN, ENGIE R&I, France*

Syngas produced by gasification is a good chemical precursor for multiple applications. Syngas quality depends on the feedstock type, operating conditions, and the gasification technology. The syngas purification requirements depend on the targeted applications.

Many gasification technologies are available on the market, suitable for different energy applications such as CHP, heat, SNG, hydrogen, liquid FT-fuels, or chemicals production. ENGIE is testing dual fluidized bed technology at demo-scale, which is suited for capacities between 500 kW_{th} and 100 MW_{th}.

The GAYA platform near Lyon is a cutting-edge R&D and highly automatized demonstration plant to produce bio/low carbon fuels from biomass & waste pyrogasification, with the first focus on producing biomethane/bio-SNG. The process has now been validated at TRL 7-8 and the production chain has successfully been proven to be robust and flexible to convert several feedstocks. This is paving the way towards the industrialisation and market uptake of biomethane production from gasification, with concrete steps to a 20 MW commercial plant in Le Havre (Salamandre project), which is scheduled to be in operation from 2026. The plant will produce, on an industrial scale, a low-carbon synthetic gas that can be injected into the network or used as fuel (synthetic LNG), from solid fuels. Based on 70 ktons per year of non-recyclable waste, up to 11 ktons of synthetic LNG will be produced which will be used as fuel for heavy / maritime transport and intensive industries. The co-produced heat will be used by industries and urban networks.

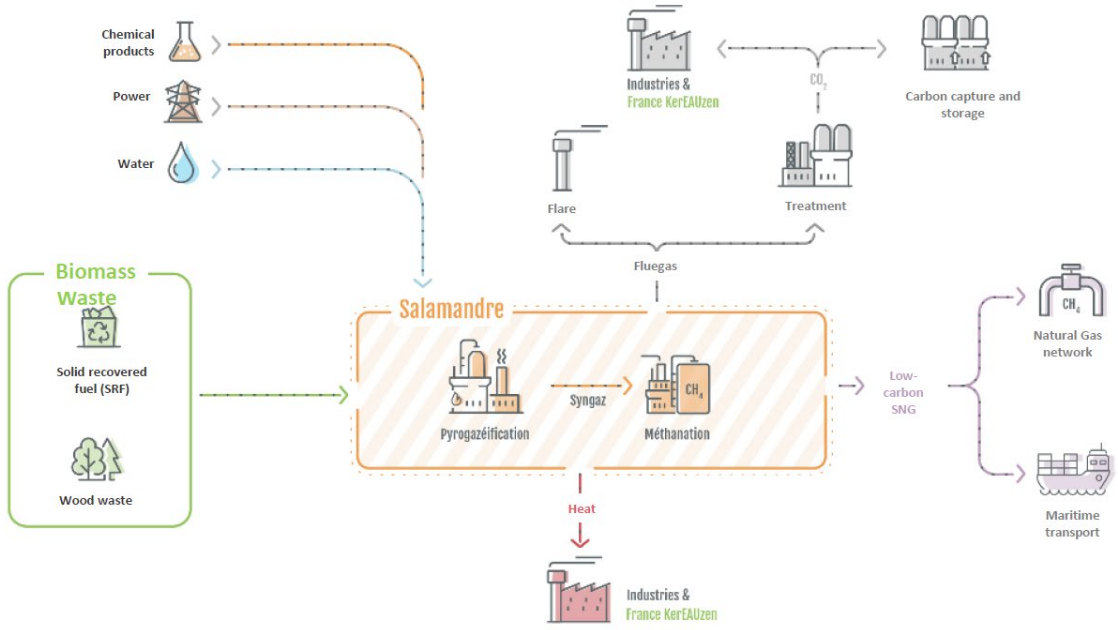


Figure 14: Schematic overview of the Salamandre concept in Le Havre. (Source: ENGIE)

A new initiative is the ‘Butterfly’ project, which is funded by the European Horizon Europe programme. The project will develop a process to produce renewable DME and SNG at a tuneable ratio, depending on the availability of renewable hydrogen (which is combined with CO_2 from the syngas to produce DME). The aim is to improve the biomass-to-fuel efficiency by 15% and achieve up to 97% carbon efficiency.

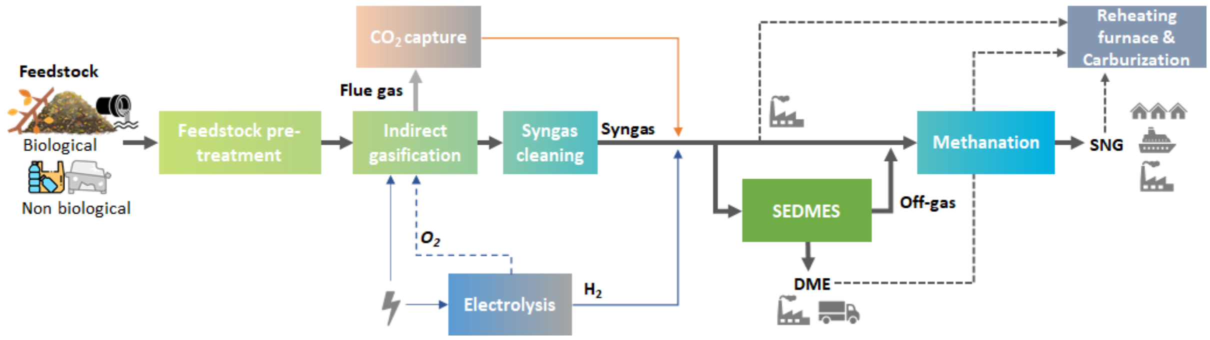


Figure 15: Schematic overview of the concept developed in the Butterfly project. (Source: Butterfly project - Horizon Europe)

3.3.2 Carbon-negative production of hydrogen through biomass gasification

__Joakim Lundgren__, Luleå University of Technology, Sweden

The demand for green hydrogen is expected to skyrocket, starting with the substitution of fossil-based hydrogen in existing applications, and increasing demand for new applications, such as steel industries, new transport fuels, and flexible power generation.

Green hydrogen is usually associated with electrolysis, while other pathways to produce renewable hydrogen, such as hydrogen production via biomass gasification, are often overlooked.

Gasification could be directed to hydrogen production, with most of the energy going to hydrogen and most of the carbon ending up in biogenic CO_2 that can be captured and stored. For every ton of dry biomass gasified, about 0.1 ton of H_2 can be produced together with 1.5-2 ton of CO_2, i.e., 15-20 kg CO_2 per kg H_2.

Hydrogen produced using the steam methane reforming process (SMR) costs between 1 to 2 €/kg without carbon capture and storage, and 1.5 to 2.5 €/kg when paired with carbon capture and storage. For bio-hydrogen the production cost would be around 3 to 4 €/kg (assuming a biomass price of 20€/MWh). However, when the separated bio-CO_2 is stored and negative emissions are rewarded at 100€/ton CO_2, the cost for producing bio-hydrogen would be in the order of 2 to 3 €/kg hydrogen. In many regions of the world this cost – as well as the CO_2 abatement cost - would be lower than hydrogen based on solar cells or wind power.

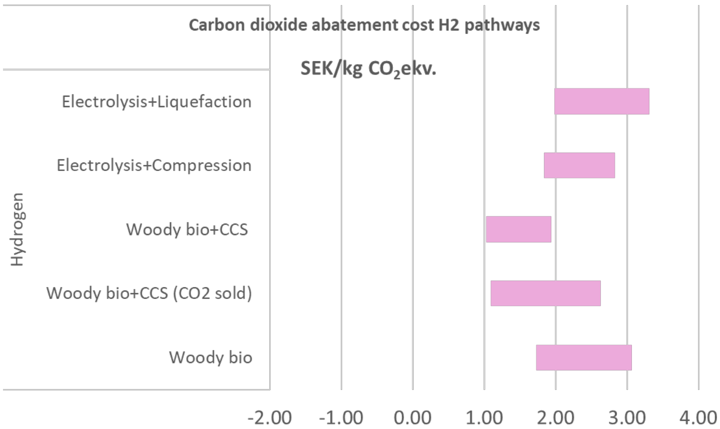


Figure 16: Comparison of CO_2 abatement costs of different renewable hydrogen production pathways – assuming SMR hydrogen as benchmark, CO_2 emission factors of the EU electricity mix and electricity price of 50€/MWh (1 SEK = 0.088 EUR). (Source: Hansson et al, 2023)

Mind also that current developments of CCUS in other applications will lead to lower capital costs, which further reduces the cost of CCUS connected to gasification systems.

Overall, the conclusion is that gasification-based bio-hydrogen deserves much more attention.

3.3.3 Eco-Park de la Barillais - synergy between anaerobic digestion and gasification

***Frédéric Thiollier**, IDEA, France and **Chourouk Nait Saidi**, ATEE (Association Technique Energie Environnement) – Club Pyrogazéfication, France*


New renewable gas production technologies will add a biomethane potential to help achieving the objectives of carbon neutrality by 2050 in France. Next to anaerobic digestion, pyrogasification (using dry lignocellulosic biomass and waste) and hydrothermal gasification (using wet feedstocks) have the potential to produce considerable amounts of biomethane.

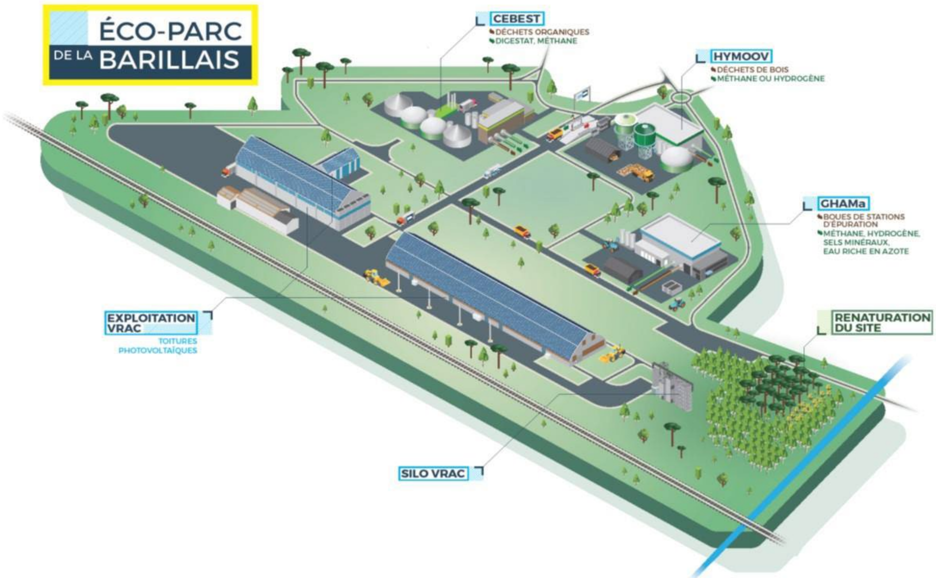


Figure 17: Overview of the Ecopark de La Barillais. (Source: IDEA)

The Ecopark de La Barillais - close to Nantes, in the West of France - started from the reconversion of Seveso wasteland, a former chemical fertilizer storage site. It is now turned into an experimental hub for low-carbon energies. Next to a PV power plant on the roof of a large hangar, three new concepts are being installed on the site, focusing on the production of renewable gas:

1. An **anaerobic digestion** unit (CEBEST): this plant, which was commissioned in April 2022, uses waste from 12 farms and several agro-food industries: manure, slurry, agro-industrial sludge, grease, and grain dust. Each year, 25,000 tons of waste are treated in this way. The plant produces 2.3 million m³ of biomethane per year, which is injected into the local gas network. The digestate co-product of the anaerobic digestion is an organic amendment that can be spread on neighbouring crop fields. In the coming years it is planned to recover and liquefy the CO_2 coming from the methanization process and offer it to market gardeners and industries.

2. **Gasification** (HYMOOV): the company aims to convert dry biomass waste (mostly B-wood waste) into two energy carriers, biomethane and biohydrogen, by 2025.

3. **Hydrothermal gasification** (GHAMa): this technology is less developed, and the GHAMa plant will be the first industrial demonstration project in France. It will treat sludge from wastewater treatment plants and also aims to create synthetic biomethane. Commissioning of the plant is scheduled for 2025.

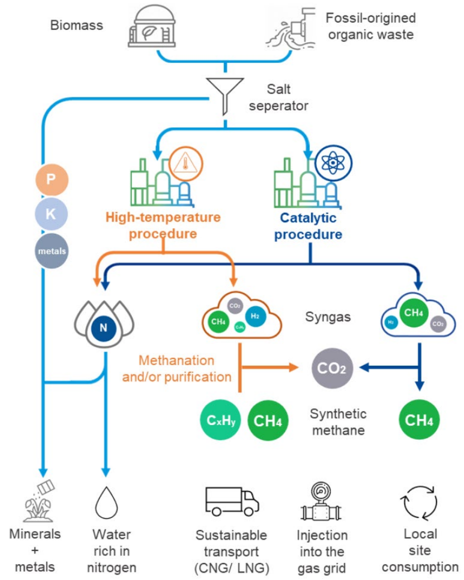


Figure 18: GHAMa hydrothermal gasification concept. (Source: IDEA)

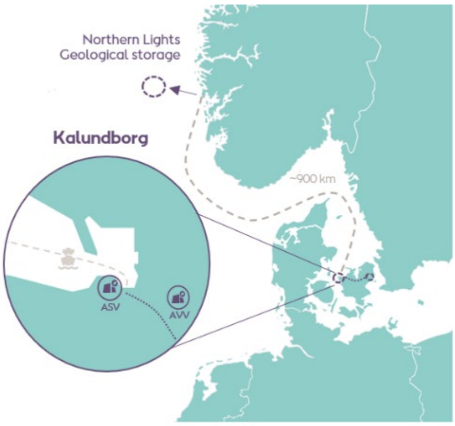
3.3.4. Capturing and storing biogenic CO_2 from biomass CHP plants in Denmark - The Ørsted Kalundborg Hub project

***Christian Bang**, EA Energy Analysis, Denmark*

Danish CO_2-eq emissions were ~45 million tons in 2020 and must fall to ~23 million tons by 2030. Carbon Capture and Storage (CCS) will play an important role to achieve this target. In 2020, the State of Denmark established a market based "CCUS Fund" of 2.1 billion EUR which would be divided into two Tenders. In 2022, the Danish Energy Agency (DEA) launched a first tender from the CCUS Fund, for around one billion EUR, with the objective to actualise reductions of 0.4 million tons of CO_2 yearly from 2026 through CCS. Following the tender process, DEA awarded Ørsted a 20-year contract for its CCS project 'Ørsted Kalundborg Hub'. Ørsted's Danish portfolio includes bioenergy plants (CHPs) as well as offshore wind farms.

The project highlights of the Ørsted Kalundborg Hub are:

- Ørsted Bioenergy will capture and store 430,000 tonnes CO_2 annually from 2026 onwards (initial capture already in 2025).
- It will enable taking the first step in establishing a large-scale CO_2 hub for storage and utilisation.
- Ørsted will establish and hold responsibility for the entire CCS value chain. Construction commenced in June of 2023.



The CO_2 will be captured through amine-based absorption from two biomass combined heat and power plants (connected to district heating), one operating on wood chips, the other on straw. This CO_2 will be liquified for storage and transport to the CO_2 hub in the harbour of Kalundborg. It will be further shipped in liquid form to Norway to be injected into offshore permanent geological reservoirs at 2,600 metres under the seabed in the Norwegian portion of the North Sea (Northern Lights). The carbon removal certificates from BECCS can be sold through bilateral offtake agreements and commodity trading platforms. The project will establish a first-of-kind, large-scale agreement with Microsoft for the offtake of carbon removal certificates.

Figure 19: Location of the assets of the Ørsted Kalundborg Hub project. Source: Ørsted

3.3.5 CO_2 potential of advanced biofuels

Jean-Philippe Héraud, *IFP Energies Nouvelles, France*

Different pathways for advanced biofuels such as cellulosic ethanol or gasification pathways are ready for industrial deployment. Several of these processes have considerable amounts of biogenic CO_2 as side product**. Integration of different technologies will allow to maximize biogenic carbon use in final products.**

Two examples were provided in the presentation.

1. *Advanced ethanol production*

Sugar fermentation processes produce similar amounts of ethanol and (high concentration) CO_2. While this biogenic CO_2 was traditionally vented, it now opens the way to produce more output from the process. The CO_2 could be combined with renewable hydrogen. Through a reverse Water Gas Shift (rWGS) followed by Fischer-Tropsch synthesis and upgrading this can be converted to diesel and aviation fuels. The presentation gave the example of a concept starting from 150 ktons per year of lignocellulosic residues, producing 30 ktons per year of ethanol and 29 ktons per year of CO_2 as side product. With an input of 200 GWh per year of renewable electricity (leading to 4 ktons of hydrogen), this CO_2 can be converted to 11 ktons of Fischer-Tropsch fuels.

2. *Biomass gasification and Fischer-Tropsch pathway*

In the conventional pathway, the syngas coming from the gasification process goes through a Water Gas Shift (WGS) to obtain the right H_2/CO ratio for the Fischer-Tropsch reaction (H_2/CO going from 0.6 to 2.0). This reaction actually converts much of the CO in the process to CO_2. The presentation also gave the example of a concept starting with 150 ktons per year of lignocellulosic biomass, which would produce 30 ktons of Fischer-Tropsch diesel and aviation fuels, and 115 ktons per year of CO_2 as side product.

An alternative approach would be to add external hydrogen to obtain the right H_2/CO ratio, thereby avoiding the WGS reaction and even converting the CO_2 in the syngas back to CO. This would maximize the valorisation of biogenic carbon in the process. In the example, the output of Fischer-Tropsch fuels would double compared to the original case, through the input of 550 GWh per year of renewable electricity (leading to 11 ktons of hydrogen). The oxygen from the electrolyser can also be used in the gasification process.

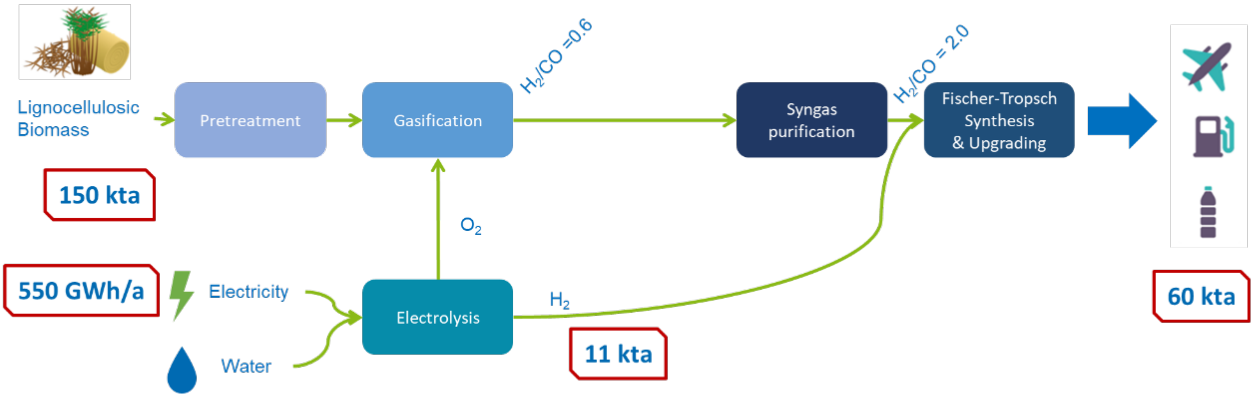


Figure 20: e-BTL way to maximize the use of biogenic carbon. Source: IFP EN

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Luc Pelkmans, the Technical Coordinator of IEA Bioenergy, prepared the text with input from the different speakers. ETA Florence arranged the final design and production.

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