IEA Bioenergy
Technology Collaboration Programme

Task 42
Biorefining in a Circular Economy

Final Task Report
Triennium 2019-2021

Task 42
Biorefining in a Circular Economy

Final Task Report
Triennium 2019-2021

Prepared by:
Bert Annevelink, Task Leader, WUR, The Netherlands;
Ed de Jong, Assistant Task Leader, Avantium, The Netherlands;
Michael Mandl, Assistant Task Leader, tbw Research GesmbH, Austria

Operating Agent:
Kees Kwant, NL Enterprise Agency, The Netherlands

Participating countries:
Australia, Austria, Denmark, Germany, Ireland, Italy, The Netherlands and Sweden

Website:
https://task42.ieabioenergy.com/

Published by IEA Bioenergy

INTRODUCTION

Biorefining, the sustainable processing of biomass into a spectrum of marketable biobased products and bioenergy/biofuels, is an innovative and efficient approach to use available biomass resources for the synergistic co-production of power, heat and biofuels alongside food and feed ingredients, pharmaceuticals, chemicals, materials, minerals and short-cyclic CO2 (Figure 1).

The **Circular Economy** is defined as an economy that is restorative and regenerative by design, and which aims to keep products, components and materials at their highest utility and value at all times, distinguishing between technical and biological-cycles [Ellen MacArthur Foundation, 2015]. The Circular Economy mainly focuses on the efficient use of finite resources and ensures that these resources are being re-used as long as possible. **Biorefining is one of the key enabling strategies of the Circular Economy**, closing loops of raw biomass materials (re-use of forestry, agro, process and post-consumer residues), minerals, water and carbon. Therefore, biorefining is the optimal strategy for large-scale sustainable use of biomass in the BioEconomy. It will result in cost-competitive co-production of food/feed ingredients, biobased products and bioenergy combined with optimal socio-economic and environmental impacts (efficient use of resources, reduced GHG emissions, etc.).

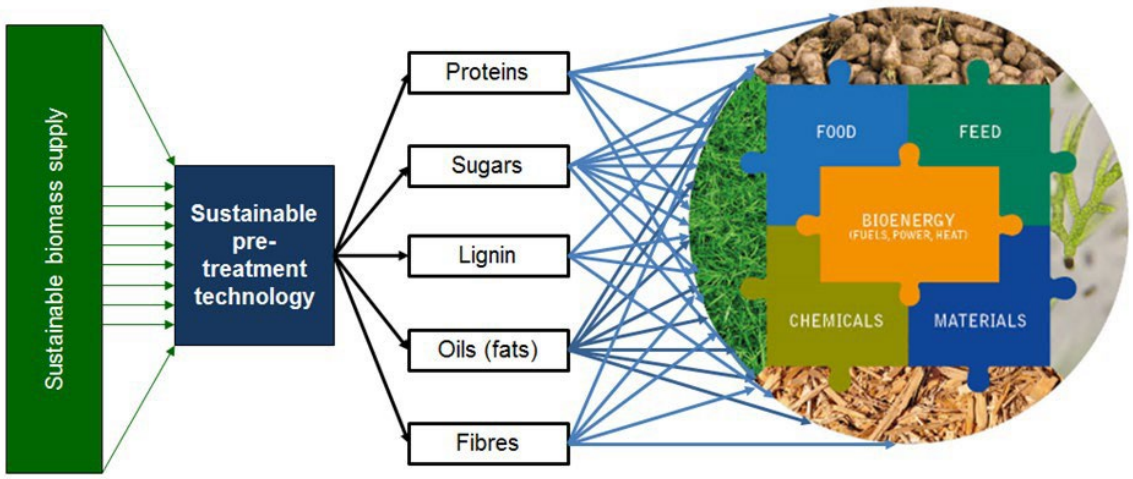

Figure 1. Bioenergy and biorefining being the lubricating oil of the Bio(based)Economy as part of the overall Circular Economy [IEA Bioenergy Task42].

BACKGROUND

Biorefining is not a fully new approach. Thousands of years ago the production of vegetable oils, beer and wine already required pre-treatment, separation and conversion steps; whereas paper production started around 100 AD. Today conventional industrial biorefineries are still mainly found in the food and paper sectors.

Within recently constructed biorefineries, **bioenergy/biofuel based facilities** are more common. In these biorefineries, heat, power and biofuels are the main products, and both agro and process residues are used to produce additional biobased products. In **product based biorefineries**, higher-value food and feed ingredients, pharmaceuticals, chemicals, fibrous materials (e.g. pulp, paper) and/or fertilisers are the main products. They use low-quality agro and process residues for the production of bioenergy and less commonly, biofuels. Product based biorefineries are mainly found in the food, feed and dairy, and pulp and paper industries today.

Assessing the number of biorefinery facilities currently in operation globally is challenging. However, over 100 commercial, demo and pilot facilities have already been identified in the IEA Task42 participating countries. Furthermore, in 2017 over 220 facilities have been identified Europe-wide by Nova Institut (GER), and the European Biobased Industries Consortium.

It is expected that within the next 10-20 years the use of biomass for non-food and feed applications will shift from an energy to a more product-based approach. However, also in the longer term part of the biomass resources is still expected to be used for the production of advanced biofuels for transport (heavy duty road transport, aviation and shipping) and bioenergy (HT-heat, RES-hybrids).

In the short-term (up to 2025) advanced biorefineries may be introduced in a variety of market sectors, mainly by means of upgrading of existing infrastructures, reducing both initial investment costs and the time-to-market. **Bioenergy will play both an initiating and central role for the market deployment of these advanced biorefineries by**:

- certified sustainable biocommodities that are now being developed and mobilised for energy applications will also be available as raw materials for the biorefinery facilities ensuring sustainable biomass supply;
- industrial bio-transportation fuel production facilities and digestion facilities can be further upgraded to integrated biorefineries co-producing fuels and added-value biobased products to optimise their overall sustainability, i.e. increase their financial market competitiveness;
- low-quality value chain residues, i.e. residues that cannot be reused for added-value applications in an economically attractive way, like forestry residues, agro-residues, process residues and post-consumer residues, will be used for bioenergy production.

A portfolio of new biorefining concepts - i.e. whole crop biorefineries, lignocellulosic feedstock biorefineries, oleo-chemical biorefineries, green biorefineries, thermochemical biorefineries, micro and macro algae (marine) biorefineries and next generation hydrocarbon biorefineries - is currently being developed. These concepts are expected to be implemented into the market in the medium-term (2025-2030). However, the current economic conditions (low oil price, credit crisis, recessions in part of the world) might cause severe delays in their market deployment.

A very important non-technical barrier for the market deployment of product-based biorefineries is the availability of sufficient amounts of sustainable biomass resources. Product-based biorefineries potentially **can accelerate their market deployment by using of both the certification expertise and logistical infrastructures that are currently being developed and set-up for the use of sustainable biobased commodities for energy purposes**.

Towards 2050, the portfolio of product-based biorefinery concepts could expand further. Lignocellulosic feedstock, herbaceous (green), oleo-chemical and marine (microalgae and seaweeds) biorefineries may enter the market. However, **expansion will require further technology development** as product-based biorefinery facilities are generally less technically mature than bioenergy/biofuel alternatives. In addition, current policy support is more favourable towards bioenergy and biofuels than the production of biobased products. As such, facilitating the market development of product-based biorefineries is likely to **require more widespread policy frameworks to support biobased products, or minimally a level playing field.**

However, since such materials are generally higher-value products than bioenergy and biofuels, expanding markets for biobased products will be a key factor in product-driven refinery expansion. **Initiatives to support industry development** include: a Biorefineries Roadmap in Germany in 2012, a Strategic Biomass Vision 2030 in the Netherlands, and ongoing funding for innovative biorefinery projects from the US Department of Energy (DOE). Deployment in Europe should be boosted by the Bio-Based Industries Joint Undertaking, a partnership between the European Union and the private sector to invest USD 4.1 billion in innovative technologies and biorefineries to produce biobased products from biomass wastes and residues. In addition, the European Commission's Circular Economy package includes biomass and biobased products as a priority sector and outlines the promotion of support to innovation in the BioEconomy.

REPORT ON THE TASK'S OBJECTIVES

WP1. Provide quantitative, scientifically sound, and understandable data on the technical, economic and environmental added value of biorefining to co-produce bioenergy and bio- products in a sustainable way

The activities in WP1 were performed within the framework of the Collaborative Inter Task Project (CITP) Technical, Economic and Environmental (TEE) Assessment of Integrated Biorefineries. WP1 had four tasks:

T1.1) Selection of biorefineries for TEE-assessment
The biorefineries that could be assessed were gross-listed by Task42 in close cooperation with other more technology specific Tasks. Selection and prioritisation – using qualitative evaluation criteria – of a short-list of biorefinery pathways to be TEE-assessed was done by an online survey and voting pool. An on-line questionnaire was sent-out in February 2020 to the coordinators of all other Tasks with the question to distribute it within their Tasks, and to fill it in if applicable. The NTLs were asked to distribute the link to the survey in their network and it was placed on the Task42 website. Some 63 stakeholders started the fill-in of the questionnaire but only 21 of them finalised it completely (33%). People dropped out at the characterization part and when a contact person was asked. However, four solid contacts came out, for data sharing necessary for a factsheet development. Almost nobody wanted to provide cost data. Environmental data response was a bit higher.

T1.2) TEE-assessment of selected biorefineries using Task42's Biorefinery Assessment Platform (BAP)
In this triennium the TEE-assessment methodology (open-access, transparent and based on a public database) – that was developed by the Austrian National Task42 Team – was used for the assessment of 10 biorefinery pathways. To be able to perform these TEE-assessments sufficient technical, economic and environmental data had to be available. The provision of (the right) data remains a key success factor for the success of the TEE-assessments. The TEE-assessment methodology presents a framework that can be used to explore potential impacts from the large- scale implementation of selected biorefineries. The methodology was described in a Task42 report (Lindorfer et al., 2019) and in an article in the IEA Bioenergy Annual report (Lindorfer et al., 2021). The TEE assessment was started in 2020 based on the selection In T1.1. For that purpose Task 33 (gasification) made a subtask on TEE where the cooperation with Task42 was defined. New TEE assessments started in 2021 and for that purpose several new pathways for assessment were selected. Two rough datasets were supplied by Task37 (biogas) where further data mining was still necessary. Also some reserve options were available from European projects.

T1.3. Preparation of Biorefinery Fact Sheets for dissemination purposes
The Task42 TEE-assessment methodology was used in this triennium to prepare about 10 additional factsheets providing open access on used primary data. The factsheet format was further optimised and extended with other relevant info. Four new factsheets were published in 2019 by IEA Bioenergy Task42. More details can be found in the updated report 'Technical, Economic and Environmental Assessment of Biorefinery Concepts – Developing a practical approach for characterisation'. About four (draft) factsheets have been generated in 2021 in cooperation with Task33 (EF gasification integrated with Kraft mills). So it is expected that about 5-6 additional factsheets in total will be published in the beginning of 2022, adding up to a total of 9-10 in this Triennium.

T1.4. Creating IEA Bioenergy broad support for using Task42's BAP for TEE-assessment integrated biorefineries
Task42 cooperated with the more technology specific IEA Bioenergy Tasks, and IEA IETS Annex XI, on biorefinery selection and data-input. The goal was to create IEA Bioenergy broad support of using the Task42 TEE-assessment methodology for assessment of integrated biorefineries. We identified how the TEE-assessment methodology and Biorefinery Fact Sheets link to the tools/methodologies used in these other Tasks and IEA IETS Annex XI, and how they can synergistically support each other.

WP2. Monitor the biorefineries deployment and market potential, incl. non-technical deployment barriers, in the Circular Economy

The Tasks in the work package are all defined to accelerate the successful market deployment of integrated biorefineries. The activities will be performed in cooperation and collaboration with the new IEA Bioenergy Task on deployment of biobased value chains that will start in the new triennium.

T2.1. Barriers and Incentives for the Market Diffusion
New product development and diversification into new markets and product areas, provide new business opportunities for stakeholders along the value chain, but also mean higher complexity and risk in business undertakings. The diversification into new markets and product areas calls for an early identification of specific barriers and incentives for a successful market diffusion of newly developed biobased products. This activity was started in 2020. The methodology used is a multi-perspective & multi-stakeholder approach called Importance-Performance-Gap-Analysis that is based on a recently published paper. An Importance Performance Assessment (IPA) survey was held in 2021 with over 300 invitations, over 70 replies (performance vs. gaps). This includes 39 experts on LCF biorefineries, 25 experts on Green Biorefineries and 6 experts algae biorefineries. The activity has identified and analysed specific barriers to and incentives for a implementation/ commercialisation of biorefineries. The results were presented at the IEA Bioenergy End Of Triennium Conference in December 2021 (Hilz et al., 2021). A slide-deck and short summary report was made available at the beginning of April 2022 (Hilz et al., 2022) and finally scientific publication is being prepared.

T2.2. Prepare Biorefinery Country Reports (slide decks)
Biorefinery country reports were delivered that contain information on: national (circular) bio(based) economy strategy, BR-related (national) policy goals & instruments, biomass use for energy and non-energetic applications, BR mapping at the national level, commercial BR facilities, BR demo-plants, BR pilot-plants, major BR-based R&D projects, national & regional BR initiatives, major national stakeholders, BR-related publications, etc. Almost all of the countries delivered these reports. Only the Irish country report still needed to being finalized in the beginning of 2022.

T2.3. Publish a Global Biorefinery Status Report (GBRSR)
The focus of the Global Biorefinery Status Report (GBRSR) is on IEA Bioenergy Task42 member countries. However, also other important countries/continents will be described in a qualitative way. The report is an integrated summary of the recent IEA42 deliverables (e.g. the status as mentioned in the country reports, an analysis of the information in the Task42 data base, the barriers and incentives for market diffusion, etc.). Several meetings were held with the database activity in order to obtain the correct biorefinery data for the analysis. The NTLs have been supplying information on the specific situation in their countries, e.g. key-biorefinery examples, country summaries and they are in the process of describing success stories. Much input was found in the report of the Biorefinery Outlook project (Platt et al., 2021). The first results were shown at the IEA Bioenergy End Of Triennium Conference in December 2021 (Annevelink et al., 2021). The final report is scheduled at the end of April 2022.

T2.4. Global mapping scheme and database on Biorefineries
In this triennium, the available Task42 info on biorefinery market deployment has been schematically organised in a Mapping Scheme and Database that was made available through the Task42 website by the end of 2021. In this triennium, Task42 also tried to initiate a cooperation with other stakeholders (e.g. JRC) working on databases and mapping systems to join forces.

<u>Database</u> - At the beginning of 2020 it was assessed if it possible to merge the Task42 database with the IEA Bioenergy data-base managed by Bioenergy2020+? This turns out to be difficult because of another set-up (not dealing with bio-based products but mainly with bioenergy). The same is the case with the JRC Seville database on the bioeconomy. Task42 had a meeting with JRC Seville and JRC Ispra to discuss a possible cooperation with their database (aimed at Europe) and dashboard website. We can probably work together on data collection but not on merging the databases. However, this still has to be approved by the DG-R&D. The Biorefinery Outlook project (lead by E4Tech) has made a recent update based on the JRC database, and Task42 is in contact to see if these data can also be added to the Task42 database after the finalization of that project (in February 2021). So in the end it was decided that Task42 will look carefully at those databases and extract cases/data wherever possible. Task42 will also provide those databases with biorefinery data if applicable. The Task42 biorefinery database has been

continuously updated during 2020 and 2021. Some 915 BRs are included at the moment. Harmonizing the data has been an ongoing activity. Harmonizing the data has been an ongoing activity. The new classification of the Biorefinery Outlook project was incorporated. All biorefinery data were taken from public sources, that have been cited properly. The biorefinery records of the Task42 countries were checked by the NTLs.

Global mapping scheme - A WebGIS application was developed, which enables industry and policy to get a visual overview of the distribution of biorefineries in the world. The functionality of this GIS interface was updated according to remarks of the NTLs. The Biorefinery Plant Portal and database (https://task42.ieabioenergy.com/databases/) were officially published in December 2021 and announced at the IEA Bioenergy End Of Triennium Conference in December 2021 (see Figure 2).

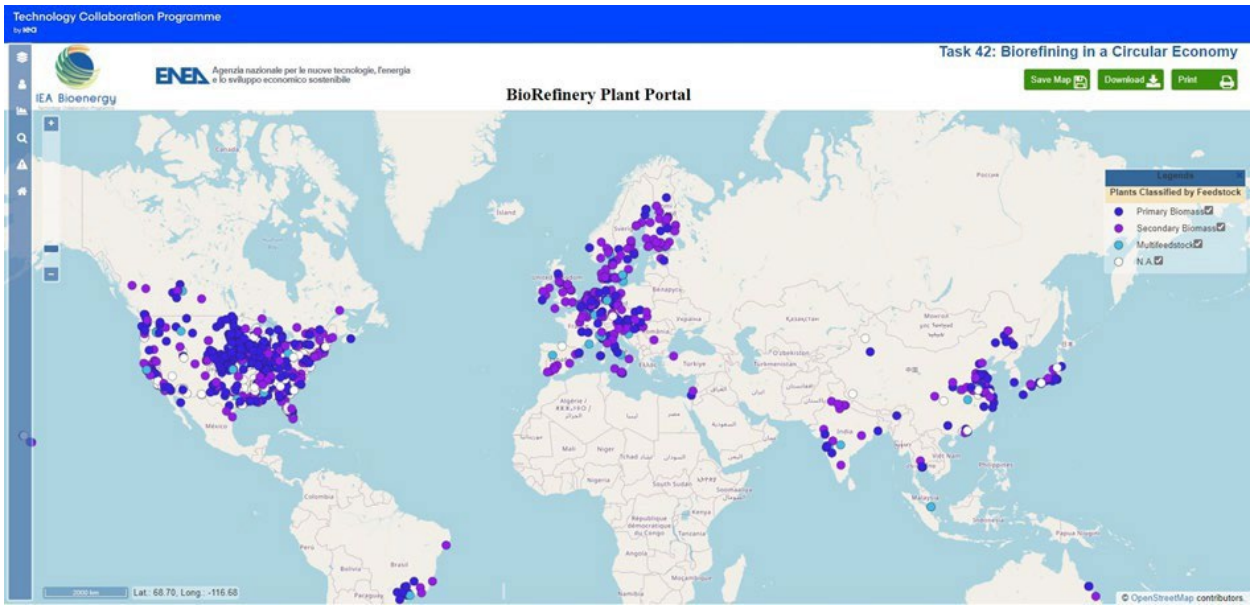

Figure 2. Final version of the Task42 Biorefinery Plant Portal.

T2.5. Reports on markets for biobased products to get insight in deployment strategies
The report 'Bio-Based Chemicals: A 2020 Update' (de Jong et al., 2020) was finalized during this Triennium and presented during two Webinars on the 20th of February and the 10th of March 2020. In this triennium also two lignin-based reports were delivered:

- Alternative sustainable carbon sources as substitutes for metallurgical coal (Sahajwalla et al., 2019);
- Sustainable Lignin Valorisation – Technical lignin, processes and market development (Mastrolitti et al., 2021).

The report 'Alternative sustainable carbon sources as substitutes for metallurgical coal' has been written in cooperation with the Australian NTL. It was presented during a Webinar on the 20th of April 2020. The report 'Sustainable Lignin Valorisation – Technical lignin, processes and market development' was published together with the EU COST initiative LignoCOST coordinated by Richard Gosselink of Wageningen Food & Biobased Research (WFBR, The Netherlands). The work was also carried out together with the University of Athens from the LignoCOST project. This report was presented at the IEA Bioenergy Webinar 'Sustainable Lignin Valorisation' on the 4th of November 2020.

Task 2.6. Monitor international developments biobased products standardisation/ certification
In the 2016-2018 triennium Task42 monitored the international developments in biobased products standardisation and certification. This activity was continued in the 2019-2021 triennium. However, this was not done as a single Task activity, but more as an activity linked to the new Task on Climate and Sustainability Effects. Focus was more on the quality of products on the application side, rather than on the raw material biomass supply side. The activity was addressed at each progress meeting to give updates. E.g., an overview was given of CEN issues regarding bio-based products, algae-based products, plant biostimulants, soil improvers, solid biofuels, and biolubricants. Also hydrogen developments were

described which might be useful related to the planned hydrogen inter-task in the next Triennium. However, no specific report was delivered during this Triennium.

WP3. Dissemination & Communication

To involve more relevant stakeholders in Task42, and to increase its platform role (central international scientifically based platform for information exchange) Task42's existence was actively communicated to the outside world. This was done by means of operating an up-to-date Task42 website, lecturing at international conferences (e.g., IEA42 session at the NWBC2020 conference, IETS Workshop Future Scenarios and Strategic Decision-Making for Industry Transformation: Powered by System Engineering), organizing Webinars (on the TEE- methodology, the chemicals report, the two lignin reports) and organising a dedicated session at the IEA Bioenergy End Of Triennium conference.

Almost no face-to-face meetings with stakeholders could be organized given the Covid-19 restrictions. This again hindered our dissemination and communication, both internationally and nationally in the member countries. Therefore, our approach in 2021 was to have regular news items on the website. Only an Austrian national meeting was held were the Austrian NTL presented Task42 results.

Website

The dedicated Task42 website (Figure 3) was built in the previous Triennium. It is located at http://task42.ieabioenergy.com. The Task42 website layout was updated in 2021. In 2021 there was an increase of about 24% for sessions and 54% for page views compared to the 6 Month period March until August 2020.

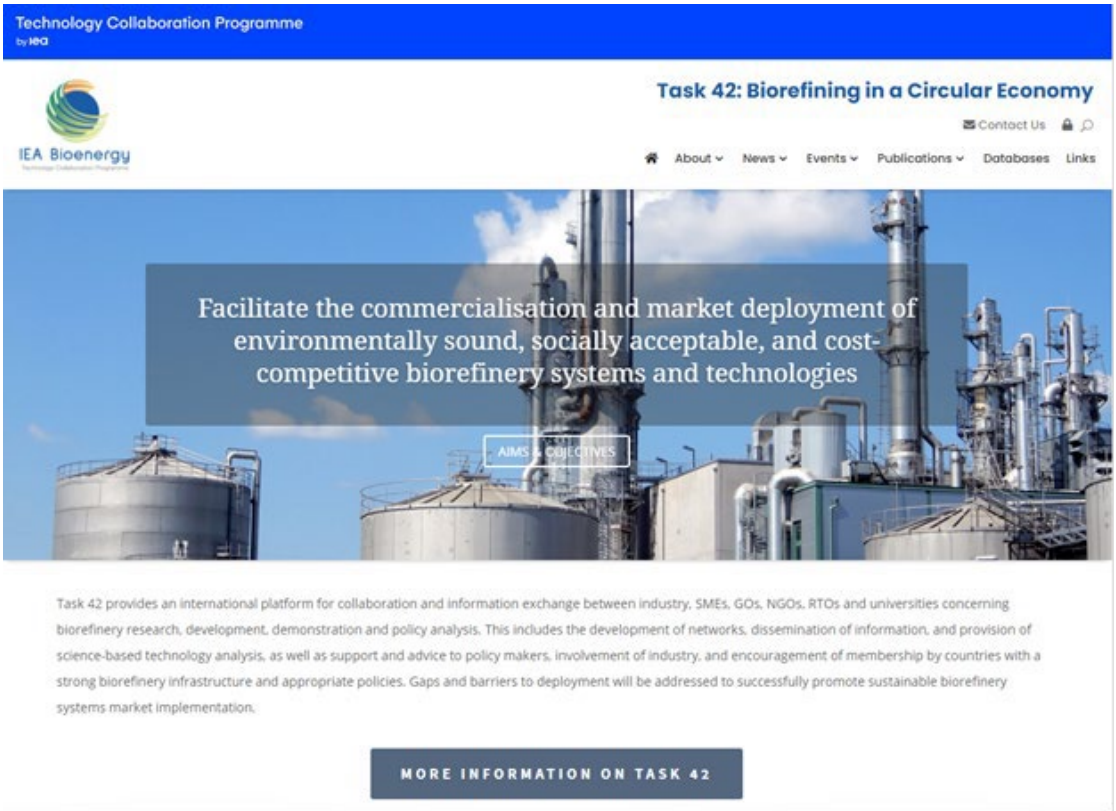

Figure 3. Home page of the Task42 website.

SUCCESS STORY

Task42 has produced and actively distributed several technical reports (TEE-assessment methodology, biobased chemicals update, sustainable lignin valorization; Figure 4) showing the importance of the biorefining approach for the sustainable (co)production of food and feed ingredients, chemicals, materials, transport fuels, and energy as foundation of a Circular Economy. An accepted open source TEE-assessment methodology was further developed, and applied which delivered 10 new Biorefinery Factsheets. Several technical and non-technical barriers that prevent large-scale deployment of biorefineries into the market sector have been identified. The status of biorefineries in the member countries and the rest of the world has been described. A new Biorefinery Atlas Portal has been developed and launched. All these activities of Task42 in this triennium have provided scientifically sound information to relevant stakeholder groups (industry, SMEs, policy makers). The results also showed that bioenergy/biofuels – both in energy/fuel-based and product-based biorefineries – will remain to play an important role to meet the market demands in various sectors of the Circular Economy.

Figure 4. Reports produced by Tak42 (2019-2021)

CONCLUSIONS AND RECOMMENDATIONS

CONCLUSIONS

Technical, ecological and economic (TEE) assessment of biorefinery concepts

Biorefinery concepts are an important building block for establishing a vital bioeconomy. This is because biorefinery concepts address some of the most important aspects of the bioeconomy strategy. The cascade-use of biomass for the production of biobased materials and energy in closed loop process designs is the core principle that is addressed by the biorefinery pathways. These pathways were investigated via a technical, economic and environmental assessment (TEE) tool, as documented in the report 'Technical, Economic and Environmental Assessment of Biorefinery Concepts ('Lindorfer et al., 2019).

The four case studies depicted showed the potential environmental benefits of biobased products from biorefinery processes. However, at the moment the economic feasibility of those products is still partly questionable as their fossil counterparts are available on the market at much lower cost. Furthermore, today´s biorefinery processes still show significant optimisation potential while the production processes of fossil-based products are technically mature and optimised. Technical developments in the biorefinery sector continue to generate new knowledge and as they are commercialised and deployed these are likely to lead to further improvements via economies of scale. As a result, it is expected that the production cost for biorefinery products will decline in the (near) future and that the products will become more competitive over time. Until this is achieved, biorefinery pathways will continue to rely on targeted policy measures and public support programs to drive the development. The wide implementation of biorefinery technologies requires, that a large number of possible products meet the quality and price requirements of the market. In addition, it is necessary to identify and optimise the site-adapted biorefinery technologies and recycling paths from the multitude of potentially available raw materials and conversion paths.

However, it is questionable if there will be a "one-fits-all" solution comparable to fossil based refineries. The biorefinery concepts have to consider regional situations and take into account available raw material mixes and the resulting platforms that are based upon the biorefinery products. Furthermore, research and development should address these aspects in order to develop a regionally adapted decentralized biorefinery solution. Technical research on biorefinery concepts has to be accompanied with systemic and structural research in order to design biorefinery pathways of the right scale, right raw material mix, right platforms, etc. for their specific site location. The IEA Task 42 provides the basis for doing so as it classifies biorefinery concepts and gives an overview of available concepts and their environmental performance and economic feasibility based on available generic data in an "open access" approach concerning assessment methodology and primary data origin to enable a strong knowledge-based community within the biorefinery sector.

Barriers and Incentives for the Market Diffusion

Analysing the relation of importance and performance of different factors of commercialization can serve as a guide to policy development and investment strategies. The measurement of importance and performance and the calculated Importance-Performance gap revealed the current perception in the research environment related to the prevalence of specific impact areas affecting the commercialisation process of biorefineries. Because all factors generally were assigned as rather important, factors assigned relatively low importance and high performance should not be wrongly interpreted as exclusion criterium for further developments.

Independent of the biorefinery concepts analysed, this investigation suggests that there is a need for policies to transform the market environment which then levers the different economic aspects. The competitive advantage of oil refineries due to decades of promotion, efficiency increase, scaling, market formation etc. builds on market distortion because the environmental damage associated to this oil refinery technology is not paid for by the polluter. Unless the market environment is not equalized by e.g. representing the external costs related to environmental damage of using fossil resources and emitting CO_2, no matter which biorefinery concept will find itself struggling with this commercialization

barrier. However, recent uncertainties in the oil and gas market in the beginning of 2022 could create opportunities.

Deployment status based on Global mapping scheme and database on Biorefineries

The analysis of the deployment status made a combined use of the IEA Bioenergy Task 42 database and the Biorefinery Outlook database. So the total number of operational biorefineries (1,312 records) in the analysis originate from two databases. More than 40 biorefineries were found in the **countries** China, Finland, France, Germany, The Netherlands, Sweden and the United States. Between 10 and 40 biorefineries were found in Australia, Austria, Belgium, Brazil, Canada, Denmark, India, Italy, Japan, Spain and the United Kingdom. All other countries had less than 10 biorefineries. The main **feedstock** type is primary biomass. However, secondary biomass is also an important feedstock for biorefineries. The main primary biomass feedstocks are starch crops and oil crops. Sugar crops, lignocellulosic biomass from crop lands/grass lands and lignocellulosic biomass from forestry are also important primary biomass feedstocks. The main secondary biomass feedstock is other organic residues followed by residues from agriculture and residues from forestry. Unfortunately, the large number of blanks (602 in total) have been excluded from the results on **process** type. Biochemical conversion is mostly used in biorefineries and within that category fermentation sticks out. Chemical conversion is second in line with catalytic conversion, esterification and hydrogenation as specific technologies. Finally mechanical and thermo-chemical conversion is often used with extraction, separation, gasification and pyrolysis as specific technologies. The main biorefinery **product** group is still energy and especially the fuels type. Chemicals, although produced in a much smaller number of biorefineries, are also an important product group, with building blocks as the largest type, followed by pharmaceuticals and neutraceuticals. Materials is the smallest product group that still matters, with polymers and fibres as the main types.

Bio-based chemicals: a 2020 update

The biobased chemicals and materials industry has reached a tipping point, with several processes ready for scale-up in the upcoming years (de Jong et al., 2020). Several strong forces including mitigating global warming, realising a truly circular economy, consumer preference, corporate commitment, and government mandates and support, are driving development in this area. However, relatively low oil prices, the absence of a carbon-tax in many places, trade wars, as well as lack of consistency in policy and legislation, slows down the deployment. The data in the report (de Jong et al., 2020) show that a shift in the deployment strategy is occurring. Many companies are refocusing on high profits, low volume specialty areas. Areas which are generating special traction are Food and Nutrition, Flavours/Fragrances, Cosmetics/Personal Care, Pharmaceutical, Fine chemicals as well as chemicals needing more Research and Development: lubricants, surfactants, coatings, solvents, high-tech materials (e.g. biomedical, engineering plastics). In addition, also some platform biochemical, with competitive or even better performance than the incumbent molecules, are expected to grow substantially over the next five years. The “drop-in” molecules aiming for a direct replacement of their fossil-based counterparts have a hard time because costs need to be the roughly the same as its fossil equivalent with only a very small green premium acceptable by the market. Although, the growth of the sector is less pronounced than anticipated a decade ago the described development will still generate a strong boost for the cost effective production of biofuels within a biorefinery context.

Alternative sustainable carbon sources as substitutes for metallurgical coal

Each year over 1 billion tonnes of metallurgical coal (coking coal) is utilised to produce most of the 1.7 billion tonnes of steel produced worldwide (Sahajwalla et al., 2019). Renewable alternatives need to be developed so that current fossil derived coking coal can be substituted by renewables at reasonable cost. This would be a significant step forward in addressing the underlying cause of climate change. The results from tests of the lignin showed that the impurities contained can be advantageous or at least tolerated by steel manufacturers. It was found that the lignin was also a suitable substitute at a range of temperatures with typical sponge iron product being produced. Not only would the use of lignin derived from lignocellulosic sources reduce the need for fossil coke, it could significantly enhance the economics of lignocellulosic bioethanol production. Metallurgical coal typically trades at a premium to that of

thermal coal. In replacing the relatively low value option of burning lignin in the lignocellulosic bioethanol refinery, the effective value of the lignin could be doubled if sold as a metallurgical coal replacement (ignoring any potential carbon credits). In total, lignocellulosic biorefinery revenues could be lifted by between 5.8% and 11.2% depending upon whether higher or lower met coal price assumptions are utilised.

Sustainable Lignin Valorisation – Technical lignin, processes and market development

Lignin-derived chemicals such as phenols for the production of adhesives and resins have rapidly increased in the last 5–10 years (Mastrolitti et al., 2021). Additional applications close to the market include asphalts and additives for concretes (i.e., polyurethanes). The major part of the developed applications uses lignin as a macromolecular stream. Kraft lignin and lignosulfonates are the most abundant technical lignins already tested for several applications. In the short term, the production of lignin-derived SAFs could have a chance to be rapidly integrated in existing oil refinery infrastructures to produce drop-in fuels, especially for the aviation and marine sectors.
The volume of Kraft and lignosulfonates could decrease in the future due to the reduction in printed paper and the increasing trend in the use of recycled paper. In contrast, technologies for biorefineries are expected to reach higher TRLs and to be more widely available in the market. This could increase the volume of technical lignins through biorefinery applications. In addition to phenols, fine chemicals from lignin with huge potential include aldehydes and BTX. The use of innovative and light materials with improved mechanical and technical properties will progressively involve wide sectors in the future. In this regard, lignin-derived carbon fibres could have an important market share. In the long term, the main application could be the progressive replacement of steel with carbon fibre. At the same time, lignin could be used as a coke replacement in the iron and steel industry.

RECOMMENDATIONS

Technical, ecological and economic (TEE) assessment of biorefinery concepts

Future research will need to include further TEE-assessments of different types of biorefinery by Task 42 in close cooperation with other Tasks and stakeholders. The discussion and evaluation of preliminary biorefinery data collected on various biorefinery set-ups needs to be done by exchange with experts. This will enable to integrate academic and industrial experts and stakeholders in order to further define and select biorefineries for the detailed assessment and the consequent compilation of a comprehensive fact sheets.

Sustainable Lignin Valorisation – Technical lignin, processes and market development

Research in the short term must include a higher exploitation of the most abundant technical lignins, namely kraft and lignosulphonates, mainly for the production of macromolecules (i.e. adhesives, resins, carbon fibers). Research in the medium to long term must include:

- the development of novel value added applications (i.e. nanoparticles, smart materials);
- the development of novel biorefinery layouts yielding high purity lignins and to prove their scalability;
- integrated techno-economic and environmental assessments.

Finally, a deep knowledge of the lignin structure is a key element to tailor the lignin chemistry and to achieve streams with standardized properties.

ATTACHMENTS

LIST OF PARTICIPATING COUNTRIES AND NATIONAL TEAM LEADERS

Participating countries: Australia, Austria, Denmark, Germany, Ireland, Italy, The Netherlands and Sweden

National Team Leaders: Geoff Bell (AUS), Michael Mandl (AUT), Solange I. Mussatto (DK), Heinz Stichnothe (GER), J.J. Leahy (IRL), Isabella De Bari (IT), Bert Annevelink (NL) and Johanna Mossberg (SVE)

TASK LEADERSHIP AND OPERATING AGENT

Task Leader: Bert Annevelink, Wageningen Food & Biobased Research, The Netherlands.
Assistant Task Leaders: Ed de Jong, Avantium, The Netherlands & Michael Mandl, tbw Research GesmbH, Austria.

Operating Agent: Kees Kwant, NL Enterprise Agency, Ministry of Economic Affairs, The Netherlands

STATE-OF-THE ART REPORT

No state-of-the-art report was published at the beginning of the Triennium. How the Task42 Global Biorefinery Status Report will be published by the end of March 2022.

PUBLICATIONS (INCLUDING TECHNOLOGY PROGRESS REPORTS)

Annevelink, E., 2021. Technical, Economic and Environmental Assessment (TEE) of biorefinery concepts. PowerPoint presentation at online IETS Workshop Future Scenarios and Strategic Decision-Making for Industry Transformation: Powered by System Engineering, 6 May 2021.

Annevelink, E., L. Garcia & V. Motola, 2021. The status of biorefineries in a circular economy. PowerPoint presentation at IEA Bioenergy End Of Triennium Workshop, Session Industrial symbiosis and biorefineries in a circular economy, 6 December 2021.

Annevelink, E., 2019. An introduction to the IEA Bioenergy Task 42 Biorefining in a Circular Economy. Power Point presentation at Italian IEA42 workshop on 'New industrial models in the bioeconomic era: the biorefineries'.

Bari, I. de, 2021. Sustainable Lignin Valorization. PowerPoint presentation at IEA Bioenergy Webinar on Sustainable Lignin Valorization - Technical lignin, processes and market development, 4 November 2021.

Bell, G., 2021. Country Report Australia; Status May 2021 . IEA Bioenergy, Task42 Power Point.

Bell, G., 2020. Alternative and sustainable carbon sources as substitutes for metallurgical coal. Power Point presentation at NWBC2020 online conference.

Giuliano, A., 2021. Simulation tools for lignin valorisation. Power Point presentation at IEA Bioenergy Webinar on Sustainable Lignin Valorisation - Technical lignin, processes and market development, 4 November 2021.

Hilz, X., T. Stern & F. Hesser, 2022. Barriers and incentives for the market diffusion of biorefineries in a circular economy. Slide deck final report of Triennium 2019-2021/WP2/T2.1.

Hilz, X., T. Stern & F. Hesser, 2021. Barriers and incentives for the market diffusion of biorefineries in a circular economy. PowerPoint presentation at IEA Bioenergy End Of Triennium Workshop, Session Industrial symbiosis and biorefineries in a circular economy, 6 December 2021.

Jong, E. de, H. Stichnothe, G. Bell & H. Jørgensen, 2020. Bio-Based Chemicals: A 2020 Update. IEA Bioenergy, Task42, 2020:01, 78 pp.

Jong, E. de, H. Stichnothe, G. Bell & H. Jørgensen, 2020. Biobased Chemicals: Current status and future outlooks. Power Point presentation at NWBC2020 online conference.

Jong, E., 2019. Biobased Chemicals - Current status & Potential. Power Point presentation at Italian IEA42 workshop on 'New industrial models in the bioeconomic era: the biorefineries'.

Lindorfer, J., K. Fazeni-Fraisl & E. Annevelink, 2021. Technical, ecological and economic assessment of biorefinery cases. In: Bennett, P. & P. Buckley (eds.), IEA Bioenergy annual report 2020, 2021:02, 7-22.

Lindorfer, J., M. Mandl & F. Hesser, 2020 TEE assessment of integrated biorefineries. Power Point presentation at NWBC2020 online conference.

Lindorfer, J., M. Lettner, F. Hesser, K. Fazeni, D. Rosenfeld, E. Annevelink & M. Mandl, 2019. Technical, Economic and Environmental Assessment of Biorefinery Concepts. IEA Bioenergy, Task42, 2019:01, 55 pp.

Mandl, M., J. Lindorfer & F. Hesser, 2021. Country Report Austria; Status March 2021. IEA Bioenergy, Task42 Power Point.

Mandl, M., J. Lindorfer & F. Hessert, 2019. Technical, Economic and Environmental Assessment of Biorefineries - Developing a practical approach for characterisation. Power Point presentation at Italian IEA42 workshop on 'New industrial models in the bioeconomic era: the biorefineries'.

Mastrolitti, S., E. Borsella, A. Giuliano, M.T. Petrone, I. De Bari, R. Gosselink, G. van Erven, E. Annevelink, K.S. Triantafyllidis & H. Stichnothe, 2021. Sustainable Lignin Valorisation – Technical lignin, processes and market development. IEA Bioenergy, Task42 report, 2021:01, 192 pp.

Mossberg, J., 2020. Biorefineries in the Nordic context. Power Point presentation at NWBC2020 online conference.

Mussatto, S.I., 2021. Country Report – Denmark. IEA Bioenergy, Task42 Power Point. Petrone, M.T & I. De Bari, 2021. Country Report Italy. IEA Bioenergy, Task42 Power Point.

Platt, R., A. Bauen, P. Reumerman, R. van Ree, C. Geier, I. Vural Gursel, L. Garcia, M. Behrens, P. von Bothmer, J. Howes, Y. Panchaksharam, K. Vikla, V. Sartorius & E. Annevelink, 2021. EU Biorefinery Outlook to 2030 for deployment. Studies on support to R&I policy in the area of bio-based products and services, LOT3. Expert report written by E4tech, WUR, BTG, FNR & ICONS, 394 pp.

Sahajwalla, V., S. Maroufi, G. Bell, P. Bell & I. De Bari, 2019. Alternative sustainable carbon sources as substitutes for metallurgical coal. IEA Bioenergy, Task42, 2019:02, 28 pp.

Stichnothe, H., 2021. Country report: Germany 2021; Bioenergy and bio-based products. IEA Bioenergy, Task42 Power Point.

Stichnothe, H., 2019. Role of future energy mixes on the environmental performance on biobased products from agricultural residues. Power Point presentation at Italian IEA42 workshop on 'New industrial models in the bioeconomic era: the biorefineries'.

TASK MEETINGS AND PARTICIPATION IN MAJOR EVENTS

28th Task Progress Meeting on Skype for business, 11 March 2019

This was the kickoff meeting where all tasks discussed the working plan for the following months.

29th Task Progress Meeting, Wageningen, The Netherlands, 20-21 May 2019

This meeting was the first physical meeting in the new Triennium. All tasks within the Work Packages were discussed and actions were initiated. Another topic was an update of the biorefinery situation in the participating countries.

30th Task Progress Meeting on Skype for business, 8 October 2019

This meeting was to monitor the progress of the various tasks within the Work Packages and to prepare the meeting in Rome.

31st Task Progress Meeting, Rome, Italy, 19-20 November 2019

All tasks within the Work Packages were discussed and further actions were initiated. Again an update was given of the biorefinery situation in the participating countries. On the morning of the 20th the Mater-Biopolymer Plant in Patrica was visited where the team got a presentation and guided tour. Thanks to Novamont for hosting Task42! More information can be found at: http://www.novamont.com and http://www.materbi.com.

Italian IEA42 workshop on 'New industrial models in the bioeconomic era: the biorefineries', 21 November 2019

On the 21st of November 2019 a successful workshop was held in the ENEA Headquarters in Rome on 'New industrial models in the bioeconomic era: the biorefineries' (http://task42.ieabioenergy.com/news/italian-iea42-workshop-on-new-industrial-models-in-the-bioeconomic-era-the-biorefineries/). The program with the titles of the presentations can be found here. About 70 Italian stakeholders participated from industry, research institutions, technological clusters, and associations. The workshop was organized by IEA Bioenergy Task 42 'Biorefining in a Circular Economy' in cooperation with ENEA and supported by Novamont. The workshop aimed at sharing knowledge and having discussions at national level on the current status and future challenges of biorefineries within the bioeconomy. Session 1 included several presentations by international delegates of Task IEA42 (1) an overview of Task42 activities, (2) an update of the biobased chemicals report, (3) the role of future energy mixes on the environmental performance of biobased products and (4) the newly developed Technical, Environmental & Environmental assessment method (including biorefinery factsheets).

32nd Task Progress Meeting on Skype for business, 20 February 2020

Webinar on Biobased chemicals – a 2020 status update, 24 February 2020

This webinar was organised by Bioenergy Australia and presented by Ed de Jong & Geoff Bell. The recording is available at: https://www.bioenergyaustralia.org.au/events/61261/

Webinar on Biobased chemicals – a 2020 status update, 10 March 2020

This webinar was organised by IEA Bioenergy and presented by Ed de Jong & Bert Annevelink. The recording is available at: https://www.ieabioenergy.com/publications/iea-bioenergy- webinar-biobased-chemicals-a-2020-status-update/

Webinar on Lignin and other sustainable carbon sources as metallurgical coal substitutes, 30 April 2020

Bioenergy Australia organized this Webinar supported by IEA Bioenergy Task42. It was given by Samane Maroufi & Geoff Bell. The recording and presentation are available at the Task42 website: http://task42.ieabioenergy.com/news/australia-webinar/ and more information can be found at: https://www.bioenergyaustralia.org.au/events/64864/

33rd Task42 Progress Meeting on Skype for business, 7 May 2020

34th Task Progress Meeting on Skype for business, 25 June 2020

Special session organized by IEA Task42 during NWBC2020, 14 October 2020

The postponed NWBC2020 was held online instead of Stockholm. Four IEA Task42 presentations were given in a special session on Biorefineries in a circular economy:

- IEA Bioenergy Task42 – Biorefineries in the Nordic context – Johanna Mossberg
- Biobased Chemicals: Current status and future outlooks – Ed de Jong, Heinz Stichnothe & Henning Jorgensen
- Alternative and sustainable carbon sources as substitutes for metallurgical coal – Geoff Bell
- TEE assessment of integrated biorefineries – Johannes Lindorfer, Michael Mandl & Franziska Hesser

The recordings of these presentations will become available at Task42 website once they are released by the organization of NWBC2020.

35th Task Progress Meeting on MS Teams, 15-16 October 2020

36th Task Progress Meeting on MS Teams, 28 January 2021

37th Task Progress Meeting on MS Teams, 24 March 2021

IETS Workshop Future Scenarios and Strategic Decision-Making for Industry Transformation: Powered by System Engineering, 6 May 2021

A Task42 presentation was given by E. Annevelink on 'Technical, Economic and Environmental Assessment (TEE) of biorefinery concepts'

38th Task Progress Meeting on MS Teams, 9 June 2021

Life Cycle Assessment Seminar "Ökobilanzwerkstatt 2021" hosted from Vienna by Wood K plus and supported by IEA Bioenergy Task42, 22-24 September 2021

39th Task Progress Meeting on MS Teams, 19 October 2021

IEA Bioenergy Webinar on Sustainable Lignin Valorisation - Technical lignin, processes and market development, 4 November 2021

A Task42 presentation was given by I. de Bari on 'Sustainable Lignin Valorization'
A Task42 presentation was given by A. Giuliano on 'Simulation tools for lignin valorisation'

IEA Bioenergy End Of Triennium Workshop, Session Industrial symbiosis and biorefineries in a circular economy, 6 December 2021

A Task42 presentation was given by E. Annevelink, L. Garcia & V. Motola on 'The status of biorefineries in a circular economy'

A Task42 presentation was given by X. Hilz, T. Stern & F. Hesser on 'Barriers and incentives for the market diffusion of biorefineries in a circular economy'

DELIVERABLES

2019

- Report on Technical, Economic and Environmental Assessment of Biorefineries (http://task42.ieabioenergy.com/publications/tee-2019/)
- Updated country reports of Austria, Germany, Italy, and the Netherlands (http://task42.ieabioenergy.com/document-category/country-reports/)
- Report on Alternative sustainable carbon sources as substitutes for metallurgical coal (http://task42.ieabioenergy.com/publications/alternative-sustainable-carbon-sources/)
- Newsletter Number 4 has been published end of July 2019. The link to this newsletter is: (http://task42.ieabioenergy.com/document-category/newsletters/)
- Description of new Triennium plan & new team members on the website (http://task42.ieabioenergy.com/about/)
- Denmark now has a national webpage (in Danish) describing our activities in Task42 (and Task 39) with links to official task website (https://plen.ku.dk/forskning/plante--og- jordvidenskab/plant-nutrition/forskningsprojekter/iea-bioenergy/)
- Presentation at Italian WS of Bert Annevelink - An introduction to the IEA Bioenergy Task42 Biorefining In a Circular
- (http://task42.ieabioenergy.com/wp- content/uploads/2020/01/1-Annevelink-An-introduction-to-the-IEA-Bioenergy-Task-42- Biorefining-in-a-Circular.pdf)
- Presentation at Italian WS of Ed de Jong - Biobased Chemicals - Current status & Potential (http://task42.ieabioenergy.com/wp-content/uploads/2020/01/2-Ed-de-Jong-Biobased-Chemicals-Current-status-Potential.pdf)
- Presentation at Italian WS of Stichnothe - Role of future energy mixes on the environmental performance on biobased products from agricultural residues (http://task42.ieabioenergy.com/wp-content/uploads/2020/01/3-Stichnothe-Role-of- future-energy-mixes-on-the-environmental-performance-on-biobased-products-from- agricultural-residue.pdf)
- Presentation at Italian WS of Michael Mandl - Technical, Economic and Environmental Assessment of Biorefineries (http://task42.ieabioenergy.com/wp-content/uploads/2020/01/4-Mandl-Technical-Economic-and-Environmental-Assessment- of-Biorefineries.pdf)

2020

- Report on 'Bio-Based Chemicals: A 2020 Update' (http://task42.ieabioenergy.com/publications/bio-based-chemicals-a-2020-update/)

- Report on Technical, Economic and Environmental Assessment of Biorefineries (http://task42.ieabioenergy.com/wp-content/uploads/2020/02/TEE_assessment_report_final_rev17022020.pdf)
- Four new factsheets of Biorefinery Concepts (https://task42.ieabioenergy.com/document-category/factsheets/)
- Country report of Sweden (http://task42.ieabioenergy.com/publications/sweden-country- report-2020/)
- Report on Alternative sustainable carbon sources as substitutes for metallurgical coal (http://task42.ieabioenergy.com/publications/alternative-sustainable-carbon-sources/)
- Presentation at the NWBC2020 online conference: IEA Bioenergy Task42 – Biorefineries in the Nordic context – Johanna Mossberg

- Presentation at the NWBC2020 online conference: Biobased Chemicals: Current status and future outlooks – Ed de Jong, Heinz Stichnothe & Henning Jorgensen
- Presentation at the NWBC2020 online conference: Alternative and sustainable carbon sources as substitutes for metallurgical coal – Geoff Bell
- Presentation at the NWBC2020 online conference: TEE assessment of integrated biorefineries – Johannes Lindorfer, Michael Mandl & Franziska Hesser
- Bioenergy Australia Webinar on Biobased chemicals – a 2020 status update (https://www.bioenergyaustralia.org.au/events/61261/)
- IEA Bioenergy Webinar on Biobased chemicals – a 2020 status update (https://www.ieabioenergy.com/publications/iea-bioenergy-webinar-biobased-chemicals- a-2020-status-update/)
- Bioenergy Australia Webinar on Lignin and other sustainable carbon sources as metallurgical coal substitutes (http://task42.ieabioenergy.com/news/australia-webinar/)

2021:

- Country report of Austria available at: https://task42.ieabioenergy.com/publications/austria-country-report-2021/
- Country report of Italy available at: https://task42.ieabioenergy.com/publications/italy-country-report-2021/
- Country report of Australia available at: https://task42.ieabioenergy.com/publications/australia-country-report-2021/
- Country report of Denmark available at: https://task42.ieabioenergy.com/publications/denmark-country-report-status-july-2021/
- Country report of Germany available at: https://task42.ieabioenergy.com/publications/germany-country-report-2021/
- Presentation by E. Annevelink on 'Technical, Economic and Environmental Assessment (TEE) of biorefinery concepts' available at: https://task42.ieabioenergy.com/wp-content/uploads/sites/10/2021/04/IETS-workshop-6-May-IEA-Bioenergy-Task-42-TEE- methodology-Annevelink-210506.pdf
- Presentation by I. de Bari on 'Sustainable Lignin Valorization' available at: https://www.ieabioenergy.com/wp-content/uploads/2021/11/Lignin-Webinar-De-Bari.pdf
- Presentation by A. Giuliano on 'Simulation tools for lignin valorisation' available at: https://www.ieabioenergy.com/wp-content/uploads/2021/11/Lignin-Webinar- Giuliano.pdf
- Presentation by E. Annevelink, L. Garcia & V. Motola on 'The status of biorefineries in a circular economy' available at: https://www.ieabioenergyconference2021.org/wp-content/uploads/2021/12/10-02_ANNEVELINK.pdf
- Presentation was given by X. Hilz, T. Stern & F. Hesser on 'Barriers and incentives for the market diffusion of biorefineries in a circular economy' available at: https://www.ieabioenergyconference2021.org/wp-content/uploads/2021/12/10- 03_HESSER.pdf
- Report 'Sustainable Lignin Valorisation – Technical lignin, processes and market development' available at: https://task42.ieabioenergy.com/publications/sustainable- lignin-valorization/
- Webinar on 'Sustainable Lignin Valorisation – Technical lignin, processes and market development' available at: https://www.ieabioenergy.com/blog/publications/iea- bioenergy-webinar-sustainable-lignin-valorisation/
- Support of Life Cycle Assessment Seminar "Ökobilanzwerkstatt 2021". More information available at: https://task42.ieabioenergy.com/news/life-cycle-assessment- seminar-okobilanzwerkstatt-2021-hosted-from-vienna-by-wood-k-plus-and-supported- by-iea-bioenergy-task-42/
- GIS portal and database available at: https://task42.ieabioenergy.com/databases/

VARIATIONS FROM ORIGINAL PROPOSAL

No major variations occurred from the original proposal.

CO-ORDINATION WITH OTHER TASKS WITHIN IEA BIOENERGY

The coordination with the other IEA Bioenergy Tasks was mainly within the activities of WP1 and the Collaborative Inter Task Project (CITP) TEE Technical, Economic and Environmental (TEE) assessment of integrated biorefineries to collect data for case studies (Task 33, Task 34, Task 36, Task 37 and Task 39). Task 33 (gasification) made a subtask on TEE where the cooperation with Task42 has been defined. For the organization of the end-of-triennium conference there was cooperation with Task 36.

CO-ORDINATION WITH OTHER BODIES OUTSIDE OF IEA BIOENERGY

- A joint survey was performed with JRC and BBI JU in 2019.
- A presentation was be given by Michael Mandl at the deep carbonisation workshop from 9th – 11th of October 2019 in Vienna. This is organised by the IETS TCP (the Technology Collaboration Programme on Industrial Energy-Related Technologies and Systems under the auspices of the International Energy Agency).
- Initial talks have been held in 2020 with JRC Seville and Ispra on cooperation regarding the JRC database on the bioeconomy (also containing biorefineries) and the IEA Task42 database. The cooperation depends on the approval of the EC. Another meeting was held in 2021. However, no final decisions have been taken yet.
- The EC was asked for permission to use the results of the BR Outlook project, that is led by E4Tech. The results of the BR Outlook project became available in a final report that was published at https://op.europa.eu/en/publication-detail/-/publication/7223cd2e-bf5b- 11eb-a925-01aa75ed71a1. These results include data that are valuable for the Task42 database, but also for the global biorefinery status report. The IEA current and former Task42 leaders have been participating in that project (as researchers of Wageningen Research) and also FNR and BTG were involved as project partners.
- The work on the lignin report is being carried out together with the University of Athens from the LignoCOST project.
- IETS Annex XI on Biorefineries is focusing on the system analysis of biorefineries, while Task42 is also looking broader at characterization of biorefineries (technologies, products, overview of existing biorefineries, global status of BRs etc.). However Task42 is also working on a TEE tool for analysing biorefineries so this is where we could complement each other by broadening the common tool box. An activity within IETS Annex XI that has recently been started is 'Decision Support Systems (DSS) and Ex-ante Research'. A cooperation possibility for Task42 is participating in that activity.

INDUSTRY PARTICIPATION

First of all, the assistant Task Leader Ed de Jong of the Dutch company Avantium continuously brings the industry perspective to the Task. The 31st progress meeting in Rome was coupled to workshop on 'New industrial models in the bioeconomic era: the biorefineries', 21 November 2019. This workshop was especially aimed at Italian industry. However, due to the covid pandemic it was not possible to organize any further events where industry could be invited. The alternative approach has been to present our Task42 results at four webinars dedicated to Task42 reports, the end-of-triennium conference and several other on-line events (see list in section 'Task meetings and participation in major event' above).

IEA Bioenergy

Technology Collaboration Programme

Further Information

IEA Bioenergy Website
www.ieabioenergy.com

Contact us:
www.ieabioenergy.com/contact-us/