IEA Bioenergy

Technology Collaboration Programme

BioSyn Bioeconomy Synergies (BioSyn) Initiative 2022-2024

Synergies for bioenergy supply chains in bioeconomy networks

IEA Bioenergy: Task 40

December 2024

Bioeconomy Synergies (BioSyn) Initiative 2022-2024

Synergies for bioenergy supply chains in bioeconomy networks

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Summary

The **BioSyn (Bioeconomy Synergies) Initiative (2022–2024)**, led by the Austrian delegation under IEA Bioenergy Task 40, aimed to expand the linear value chain perspective into a broader network-based view for bioenergy and bioeconomy systems. By addressing synergies among ecosystems, bioenergy supply chains, bio-based materials, and nutrient services, the initiative developed a framework to enhance the interoperability between IEA Bioenergy TCP Tasks for informing on more coherent, efficient, and resilient international developments in renewable energy, bioenergy, and the bioeconomy.

In addition to this report, we published an extensive slide deck and a scientific paper in a peer-reviewed journal collecting and structuring the illustrated results of the BioSyn initiative. Besides, there is a presentation recording of the key insights at the BBEST / IEA Bioenergy End of Triennium conference in Sao Paolo, Brasil, available.

Recording of the final presentation: https://youtu.be/PHL7IG7icyE?si=fzA29FPz7scZ41mP

Key contributions and results

1. Integration dynamics and frameworks
    - Defined system integration as a process connecting elements (e.g., technologies, infrastructures, or actors) to form a cohesive network.
    - Identified three core integration dynamics: enabling resource exchange, improving resource flow efficiency, and enhancing resilience through diversification and flexibility.
2. Workshops and collaboration
    - Hosted workshops on flexible bioeconomy networks and bioenergy supply chain risks, involving multiple IEA Bioenergy tasks and Horizon Europe collaborations.
    - Highlighted risks and resilience strategies for supply chains, including cascade failures and natural and anthropogenic risks, providing tools for system-wide planning.
3. Scientific publications and case studies
    - Developed case studies demonstrating innovative biorefinery technologies, such as continuous oscillatory flow bioreactors and sequential biomass pretreatment methods.
    - Published findings in peer-reviewed journals, emphasizing the importance of circular bioeconomy practices and system integration in addressing climate and societal challenges.
4. Evaluation Frameworks
    - Proposed a biomimicry-inspired evaluation framework adapted from ecological models to assess bioeconomy network synthesis synergies.
    - Categorized contributions of bioeconomy systems into material, regulating, and non-material benefits, similar to the contributions of natural ecosystems.

Strategic importance

The **BioSyn Initiative**’s outcomes contribute significantly to the IEA Bioenergy TCP agenda by:

- Advancing knowledge on integrating bioenergy value chains into broader bioeconomy networks.
- Enhancing resilience and supply security through system integration.

- Providing a foundation for collaboration on biobased value chains and bioeconomy networks between IEA Bioenergy Tasks and beyond the IEA Bioenergy TCP.

Recommendations and outlook

1. Bioeconomy network planning:
    - Promote the use of integration impact assessments as a distinct discipline.
    - Develop comprehensive evaluation methods to account for economic, ecological, and societal benefits and trade-offs in bioeconomy networks.
2. International collaboration:
    - Facilitate cross-sector and cross-country cooperation to leverage synergies in areas like hydrogen, flexible biogas systems, and multifunctional land use.
3. Research and innovation:
    - Support interdisciplinary expertise and new strategies to address complex challenges in system integration and network resilience.

The BioSyn Initiative lays the groundwork for robust, efficient, and sustainable bioeconomy systems that align with global sustainability goals, reinforcing IEA Bioenergy TCP's role in advancing renewable energy and circular bioeconomy practices.

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1. Introduction

1.1 GOALS OF THE TASK 40 BIOSYN (BIOECONOMY SYNERGIES) INITIATIVE

The contribution of the Austrian delegation in the Task 40 Triennium 2022-20224 was a broad initiative within the IEA Bioenergy TCP network. The aim was to expand the linear value chain perspective of the Task by incorporating a network-based view to better identify synergies between ecosystem, bioenergy, bio-based materials, and nutrient services. Unlike linear value chains, which focus on delivering a specific service, a biogenic carbon network connects various types of services, enabling circular and cascading uses. But how can we represent this physical and societal networking activity, measure its benefits and risks, and better integrate it into the planning of future, interconnected bioeconomy sectors? These and related questions were addressed through the initiative, internal workshops, and scientific publications.

1.2 STRATEGIC RELEVANCE FOR THE TASK 40 AGENDA

Over 20 years Task 40 coins the discussion of how bioenergy technologies and deployment are embedded in value chains (Figure 1) spanning forestry, agriculture, and aquaculture activities, pre-treatment, densification, and commodification steps, to the conversion into electricity, heat, and transport fuel, for covering diverse societal needs including residential heating, transportation and others.

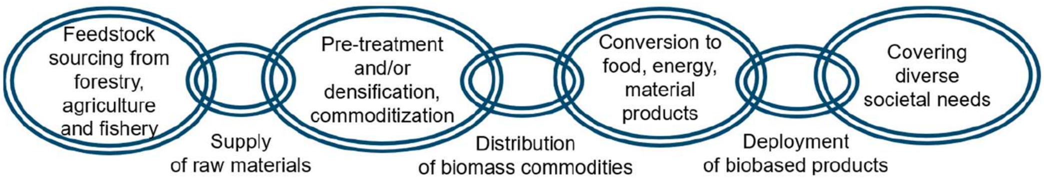

Figure 1: Illustrative bioenergy value chain. Source: own illustration

Numerous reports have been published and are freely accessible on the Task 40 homepage on the topics addressing the different supply chain steps sourcing, distribution, and deployment (Table 1).

Table 1: Task 40 topics addressed in report publications listed chronologically by the year of a first report published on the topic.
Source: https://task40.ieabioenergy.com/iea-publications/task-40-library/#

Sourcing topics (first report)	Distribution topics (first report)	Deployment topics (first report)
	International bioenergy trade (2010)	Sustainability certification (2010)
	Wood pellets markets (2011)	Science-policy interface (2013)
	Liquid biofuel markets (2012)	Large industrial bioenergy (2013)
Forest biomass mobilisation (2016)	Wood chips, biojetfuels, torrefaction (2012)	Cascading use of biomass, global bioeconomy, small-scale heating (2016)
Socio-economic impacts (2017)	Advanced biofuels, biomethane markets (2014)	Biocarbon capture and storage (2020)
Biomass waste streams & trade (2019)	Biorefineries, future use of pellets (2019)	Industrial process heat (2021)
Local, low-value, biomass (2022)	Hydrogen, renewable gases (2022)	Bioeconomy synergies (2022)
	Regional biobased value chains (2023)	BECCUS value chains (2023)

Table 1 paints a picture of a continuous evolution in the fields of biomass and biogenic energy carrier supply, conversion, and utilization:

Sourcing topics:
Initially, the focus was on analyzing international bioenergy trade (2010) and markets for wood pellets (2011) and liquid biofuels (2012). This reflected the prevailing practice of sourcing biomass primarily through a few large suppliers to be used in global supply chains for large-scale energy applications. In recent years, however, the focus has shifted significantly. Topics such as the mobilization of forest residues (2016), biomass from waste streams (2019), and the use of local, low-grade biomass (2022) have taken centre stage. This supports a diversified and regionalized sourcing approach.

Conversion topics:
In the early stages, the emphasis was on technologies and markets for wood chips, biofuels, and torrefaction (2012). The focus has since moved towards advanced biofuels, biogas, and renewable gases like hydrogen (2022). Alongside this, biorefineries and future biomass utilization potentials are being explored. This transition highlights the shift from medium-sized, globalized supply chains to flexible and versatile networks that strengthen both regional and international connections.

Deployment topics:
Early efforts concentrated on sustainability certifications (2010) and large-scale industrial applications of biomass (2013). Today, the focus reflects a much broader perspective. Key topics now include the cascading use of biomass (2016), carbon capture and storage (2020), industrial process heat (2021), and the integration of synergies within the bioeconomy (2022). Instead of being limited to large-scale applications, biomass is increasingly used for small- and medium-scale purposes, providing services in energy supply, carbon sequestration, and the circular economy.

The thematic evolution of Task 40 introduced new focal areas which are centred around identifying and highlighting the multi-faceted benefits for various stakeholders throughout the value chains. Table 2 provides selected examples which we used as a seed for the BioSyn initiative (starting 2019) with the aim to contribute to the agenda of Task 40 and of the IEA Bioenergy TCP as a whole in the upcoming triennia.

Table 2: Shifting the Task40 discussion towards the multiple benefits of bioenergy value chains

Sourcing benefits	**Distribution benefits**	**Deployment benefits**
• Stakeholder diversification • Multi-level value creation and decision making • Green jobs • Biosphere link > Taking care of a changing environment	• Networks of networks -> ability to shift resources between different networks • Flexibility and reconfigurability to react to risks and uncertainties in sourcing and demand	• From cost-efficient services to sufficient and equitable services • Resilience and reliability, safety and security • For conscious waste management and much more

The BioSyn initiative tackled the challenge of synthesizing the new focal areas and related topics into a common framework. This report summarizes the underlying methods and definitions required to advance the supply chain perspective into a bioeconomy network perspective (section 2), the results and publications during the Triennium 2022-2024 (section 3), and derives conclusions and recommendations (section 4) for the Task 40, the IEA Bioenergy TCP and the Research, Technology, and Innovation policies of the IEA TCPs members.

2 Methods and definitions

The primary objective of the IEA Bioenergy TCP is to foster and enhance the exchange of knowledge and expertise among professionals on current topics. This enables the anticipation of significant technical, societal, and ecological developments across countries and disciplines. It also facilitates the sharing of experiences and insights of policies and practices from different member states. While the tangible impacts of this exchange are not easily measurable, participants often report a more robust, long-term orientation in their research and work fields. Additionally, as demonstrated by the BioSyn initiative, the exchange frequently yields immediate, concrete outputs, such as scientific publications, reports, workshops, webinars, new collaborations, and joint projects.

The **purpose of the BioSyn Initiative** was to identify and formalize the numerous synergy effects between bioenergy supply chains and other networks related to the mobilization, provision, and (re-)utilization of bioeconomy products and services, offering them a shared framework.

So, what is a bioeconomy network essentially? Figure 2 provides an illustrative overview of the BioSyn Initiative's themes, presented in the style of a bioeconomy value network. This network integrates raw materials from forestry, agriculture, and aquaculture, processing them into commodities for applications such as food production, construction materials, electricity, space and process heating, chemicals, pharmaceuticals, carbon capture, and more. The network also incorporates other renewable energy sources like wind, solar, and hydropower, necessitating the interconnection of various infrastructures such as power grids, gas networks, pipelines, CO_2 and hydrogen networks, roads, railways, shipping, water supply, as well as digital, societal, and socio-political networks. Additionally, ecosystem services, landscape maintenance, community aspects, nature experiences, and biodiversity play a vital role, many of which often fall outside the scope of marketable goods or human-made networks.

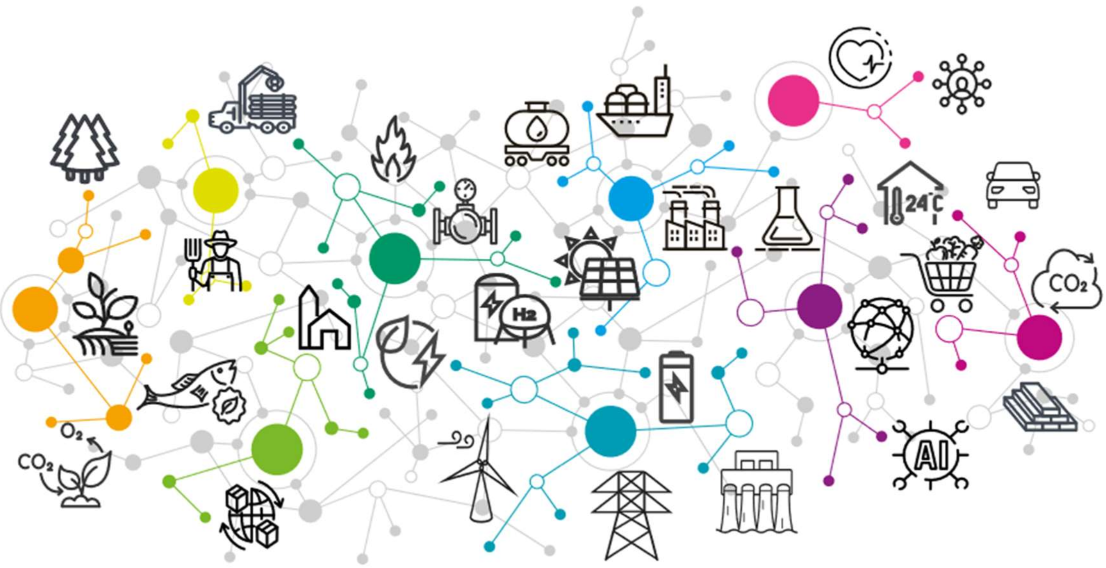

Figure 2: Illustrative representation of selected aspects of the Bioeconomy network. Source: own illustration

2.1 SYNERGIES AND SYSTEM INTEGRATION

Synergies between different supply chains primarily arise from the interconnection of the diverse economic sectors, technologies, and systems illustrated in Figure 2. Some of these systems are actively linked by us, raising the general question: why do we pursue these connections, and what benefits do we expect? We refer to this activity as "system integration" and propose a straightforward definition for the term:

Definition: Integration is the process of combining at least two elements to form a whole.

Note 1: Elements can be actors, infrastructures, technological components, or processes. These elements we refer to as tangible. More broadly defined, cultures, individual attitudes and behaviours, or markets can be intangible elements which can be subject to integration as well.

Note 2: Integrated tangible elements (a) enable resource exchange, (b) enhance its efficiency, and/or (c) secure it against external influences increasing its reliability and the resilience of the individual elements. Thus, the whole is greater than the sum of its parts.

Note 3: Synergies, co-benefits, and trade-offs, as well as conflicts and risks arising from integration, are rarely systematically described, let alone quantitatively assessed or estimated.

Note 4: In energy research, integration aspects such as system integration, sector coupling, multi-sector coupling, hybrid energy systems, and energy communities play a role. In process and chemical engineering, concepts such as process intensification, process integration, and heat network synthesis are closely related to this definition. Similarly, biology and ecosystem research explore related concepts, such as the effects of biodiversity loss on tightly integrated food webs.

Note 2 in our definition sheds light on potential synergies in a more integrated circular bioeconomy. Within the BioSyn Initiative and through several publications and workshops, we have sought to clarify the various integration dynamics to provide them with a shared framework.

1. First integration dynamic: Enabling resource exchanges that would not be possible without integration. Results related to this dynamic include a scientific publication on mobilization strategies for low-grade, heterogeneous biomass (Section 3.3) and a inter-task workshop on supply chain networks (Section 3.4).

2. Second integration dynamic: Increasing resource flow efficiency through direct exchange between integrated elements, processes, or systems. Results for this dynamic were mainly compiled and discussed in the context of process and chemical engineering in biorefineries (Section 3.2).

3. Third integration dynamic: Enhancing resilience for integrated elements, processes, or systems through diversification and flexibility of resource flows. Results related to this dynamic emerge particularly from the inter-task workshop on supply chain networks (Section 3.4) and a dedicated Task 40 workshop on supply chain risks (Section 3.5).

The leadership of the BioSyn Initiative by TU Wien's Institute for Process Engineering, Environmental Technology, and Technical Biosciences (ICEBE), in collaboration with biorefinery experts from AEE Intec with a close link to the IEA IETS (Industrial Energy-Related Technologies and Systems) TCP, enabled an interdisciplinary approach. This approach bridged systemic bioeconomy considerations (Section 3.1) with process engineering perspectives for biorefineries (Section 3.2). The following sections present the partial results and their sources, with further information provided for each.

3 Results

3.1 THE CIRCULAR BIOECONOMY AS A SYSTEM INTEGRATOR

Schipfer, F., Burli, P., Fritsche, U., Hennig, C., Stricker, F., Wirth, M., Proskurina, S., Serna-Loaiza, S., 2024. The circular bioeconomy: a driver for system integration. Energ Sustain Soc 14, 34. https://doi.org/10.1186/s13705-024-00461-4

In 2024, we published the lead paper summarizing the central findings of the Task 40 contribution in a special issue of the Springer Journal *Energy, Sustainability and Society* (guest editors: Fabian Schipfer and Svetlana Proskurina). This publication serves as a cornerstone for understanding the integration of systemic approaches into the circular bioeconomy.

The modeling of human and earth systems, traditionally focused on the interplay between energy systems and the atmosphere, is undergoing a paradigm shift. The Intergovernmental Panel on Climate Change (IPCC) mandate for comprehensive, cross-sectoral climate action highlights the need to overcome the limitations of narrowly defined sectoral approaches. Our study explores the circular bioeconomy and emphasizes the complex interconnections between agriculture, forestry, aquaculture, technological advancements, and ecological recycling. Together, these sectors play a vital role in addressing the food, material, and energy demands of a growing global population. We pose a central question: how can these diverse sectors be integrated into a new era of holistic, systemic thinking and planning?

At the heart of our discussion is an innovative graphical representation that incorporates statistical data on food, materials, energy flows, and circular economy practices. This representation forms the basis for an inventory of technological advancements and climate mitigation measures that could fundamentally reshape the economic metabolism system in the coming decades. In the context of three dominant megatrends—population dynamics, economic development, and the climate crisis—we analyze the potential impacts of these measures, categorized into four key areas: substitution, efficiency, sufficiency, and reliability.

Currently, substitution and efficiency measures dominate system modeling. Incorporating new bio-based processes and circular economy aspects may only require expanding system boundaries. In contrast, paradigm shifts in system design are expected to focus on sufficiency and reliability measures. Effectively evaluating sufficiency measures will demand significant progress in inter- and transdisciplinary collaboration, especially given their non-technological nature. Additionally, modeling the reliability and resilience of transformation pathways represents a promising new research direction, underscoring the importance of an integrated "network of networks."

Existing and emerging practices in the circular bioeconomy serve as exemplary cases of system integration. These practices enable the linking of complex biomass supply chain networks with other networks, including resource-independent renewable energy, hydrogen, CO_2, water, as well as biotic, abiotic, and intangible resources. Strengthening these connections will empower policymakers to maximize synergies across systems, sectors, and objectives while minimizing trade-offs.

3.2 BIOREFINERIES AS SYSTEM INTEGRATORS

Process engineering approach and case studies in Task 40

While the lead publication (Section 3.1) focused on systemic aspects, this time, and for the first time, a process engineering approach was also adopted. By looking into various case studies in the area of biorefining, a better understanding how bioeconomy networks behave could be achieved. The case study approach was primarily enabled by the collaboration between the TU Wien Institute for Process Engineering, Environmental Technology, and Technical Biosciences (Fabian Schipfer, Sebastian Serna-Loaiza, Michael Harasek – TU Wien ICEBE) and the Institute for Sustainable Technologies (Judith Buchmaier, Bettina Muster-Slawitsch – AEE INTEC), which is also active in the IEA IETS Task11 on industrial biorefineries. The results, presented during a joint workshop on November 7, 2023, are based on the cited publications.

Industrial biorefinery efficiency

Meitz S., Muster-Slawitsch B., Lindorfer J. 2023. IN GERMAN. IEA Industrielle Energietechnologien und Systeme (IETS) Task 11: Industrielle Bioraffinerien. Arbeitsperiode 2020 – 2022 Endbericht. https://nachhaltigwirtschaften.at/resources/iea_pdf/schriftenreihe-2023-75-iea-iets-task-11.pdf

In the framework of IEA IETS Task11, innovative methodologies for assessing energy and resource efficiency in industrial biorefineries were developed. These methodologies, based on real case studies (e.g., lignocellulose biorefineries and biogas systems), cover the entire value chain - from raw material supply and process optimization to final products and by-products. A central focus was on integrating emerging technologies, minimizing energy intensity, and maximizing resource utilization.

Key Performance Indicators (KPIs) such as greenhouse gas savings, cumulative energy demand, resource efficiency, and by-product utilization were used to evaluate the interconnections of energy and material flows holistically. This expanded understanding of efficiency and highlights the role of industrial biorefineries as core components of the bioeconomy, addressing economic, ecological, and social objectives.

The developed KPIs provide a systematic foundation for optimizing existing technologies and advancing toward net-zero and negative-emission biorefineries. They support renewable energy integration, resource circularity, and the strengthening of local value chains, contributing to the sustainable economic viability of future biorefineries.

Innovative process design: Continuous Oscillatory Flow Bioreactor (COFB)

Buchmaier, J., Krampl, S., Eibinger, M., Kaira, G.S., Nidetzky, B., Muster -Slawitsch, B., 2024. Continuous oscillatory flow as process intensification strategy in protein extraction from brewer’s spent grain. Chemical Engineering and Processing - Process Intensification 200, 109772. https://doi.org/10.1016/j.cep.2024.109772

A continuous oscillatory flow bioreactor (COFB) was developed and tested for extracting proteins from brewer's spent grain (BSG) without pre-treatment. The process demonstrated efficient direct protein extraction and subsequent anaerobic digestion of the residual solids for biogas production. This dual-purpose approach significantly improves material and energy efficiency, showcasing how circular bioeconomy principles can be implemented through innovative technologies.

The integration of COFB exemplifies combined efficiency evaluation principles, creating sustainable cycles that combine economic, ecological, and social benefits. Protein hydrolysates as high-value ingredients open additional markets, while the biogas potential enhances energy self-sufficiency in breweries and reduces their carbon footprint.

Sequential pretreatment for biomass valorization

Serna-Loaiza, S., Adamcyk, J., Beisl, S., Miltner, M., Friedl, A., 2022. Sequential Pretreatment of Wheat Straw: Liquid Hot Water Followed by Organosolv for the Production of Hemicellulosic Sugars, Lignin, and a Cellulose-Enriched Pulp. Waste Biomass Valor 13, 4771–4784. https://doi.org/10.1007/s12649-022-01824-8

TU Wien’s sequential pretreatment method, combining liquid hot water and Organosolv processes, was studied for wheat straw valorization. This method enables the extraction of hemicellulosic sugars and lignin while leaving a cellulose-rich fraction suitable for paper production. The study demonstrated that these materials could achieve comparable quality to conventional pulp, highlighting their potential as a substitute for pure cellulose.

This comprehensive utilization of lignocellulosic materials addresses sustainability challenges in biorefineries, supporting the development of processes that maximize raw material use.

System integration and circular bioeconomy

The combined evaluation of energy and resource efficiency offers a foundation for addressing critical questions in sustainable biorefinery design, such as:

- What product portfolios are most promising and for whom?
- What is the value of producing multiple (1+n) products from diverse raw materials?

By analyzing the "branching capacity" of biorefineries - their ability to integrate flexible and diverse value chains - new approaches to quantifying system integration benefits can be explored. This includes assessing system risks such as supply chain complexity while identifying strategies that maximize economic, social, and ecological synergies.

With a systemic perspective, promising R&D strategies can be developed, considering market potential, regional conditions, and the evaluation of risks and opportunities in human and earth systems. These approaches foster flexibility and resilience in biorefineries, strengthening their role in the bioeconomy.

3.3 MOBILISATION STRATEGIES FOR LOW-VALUE, HETEROGENOUS BIOMASS

Schipfer, F., Pfeiffer, A., Hoefnagels, R., 2022. Strategies for the Mobilization and Deployment of Local Low-Value, Heterogeneous Biomass Resources for a Circular Bioeconomy. Energies 15, 433. https://doi.org/10.3390/en15020433

With its bioeconomy strategy, Europe aims to strengthen and expand bio-based sectors. Achieving this goal requires unlocking investments and markets for bio-based value chains while promoting local bioeconomies. Central to these efforts is adherence to ecological and social sustainability goals. However, current biomass supply structures are not equipped to handle the diversity of biomass residues and their respective supply chains.

This raises a central research question: what strategies are suitable for mobilizing and utilizing local, low-value, and heterogeneous biomass resources? Our work builds on the results and expertise of members of the IEA Bioenergy Task 40, which focused on international bioenergy trade in the previous triennia and current measures for biomass supply, mobilization and deployment in the current work undertaken. Three evaluation levels are considered: the legal framework, technological innovations, and market creation. The challenges and opportunities identified within these levels point to a common denominator: the systemic importance of strengthening the potentially last remaining primary economic sectors—forestry, agriculture, and aquaculture—has not been adequately quantified.

As the significance of other primary economic sectors, such as fossil fuel extraction and mining, continues to decline, the time has come to evaluate and actively promote the value of the supply side in a circular bioeconomy. This value includes supporting structurally disadvantaged regions by creating meaningful jobs and activities, as well as enhancing the resource-democratic significance of rural areas.

3.4 WORKSHOP ON FLEXIBLE BIOECONOMY NETWORKS

Organised by Fabian Schipfer and Biljana Kulisic and edited by Bas Heukels. A workshop between IEA Bioenergy TCP Tasks 40, 42, 43, 44 & 45 and the Horizon Europe Branches project. https://www.ieabioenergy.com/wp-content/uploads/2022/12/BioSyn_Workshop_report_Nov2022_v2.pdf

On November 2, 2022, the BioSyn working group, initiated under IEA Bioenergy Task 40, hosted a collaborative workshop with Tasks 40, 42, 43, 44, and 45, along with the Horizon 2020 project BRANCHES. The workshop aimed to identify synergies in regional biomass value networks, focusing on mobilizing heterogeneous, low-value biomass for diverse bioeconomy applications. Special attention was given to the potential of small and medium-sized enterprises (SMEs) to drive regional development while aligning with sustainability goals.

The discussions highlighted the advantages of flexible value networks, including the efficient use of waste and by-products and the integration of post-harvest management systems as alternative infrastructures for biohubs. A case study from wine production was used to analyze the economic and ecological potentials unlocked through the mobilization of by-products. Transitioning from linear supply chains to integrated networks was characterized as "System integration," emphasizing the additional societal and economic benefits it can generate.

Opportunities in system integration

System integration within regional bioeconomy value networks offers numerous opportunities, as demonstrated by the collaboration between IEA Bioenergy Tasks and the BRANCHES project. Key insights include:

- Flexible value chains (Task 40): Moving from linear supply chains and waste management systems to flexible value networks underscores the importance of existing infrastructures to promote efficient and sustainable material flows.
- Biohubs (Task 43): Biohubs enhance the mobilization and diversification of biomass, yielding not only economic benefits but also social and ecological gains at the regional level.
- Technology integration (Task 42): Combining biorefining and green hydrogen with renewable energy sources such as photovoltaics and wind power opens new pathways for sustainably producing carbon-based chemicals.
- Energy systems flexibility (Task 44): Bioenergy can act as a key element in enhancing energy system flexibility, particularly in regions with a high share of renewable energy, highlighting the importance of energy storage and overarching system integration.
- Broader sustainability goals (Task 45): Climate action should extend beyond CO_2 reduction to address broader sustainability objectives (SDGs) and cross-sectoral approaches.

These insights demonstrate the diverse potential of system integration to enhance economic resilience, ecological sustainability, and social benefits. They also stress the urgency of creating market and policy frameworks that recognize and reward the added value of complex bioeconomic networks.

Key areas for collaboration

The workshop identified critical collaboration opportunities, grouped into five thematic areas:

1. Pertinent case studies: Sharing and analyzing examples of system integration in practice.
2. Regional perspectives and SME involvement: Promoting regional development through SME participation.
3. Development of Key Performance Indicators (KPIs): Measuring the benefits of system integration.
4. Quantitative modeling: Applying models to assess impacts and optimize strategies.
5. Designing market and policy frameworks: Supporting bioeconomic networks through informed policies.

Outcomes and next steps

Participants found the workshop to be productive and encouraging and stressed, that future steps should include:

- Developing KPIs to measure the benefits of system integration.
- Applying these indicators in case studies and models.
- Designing frameworks that recognize the added value of flexible bioeconomy network synthesis.

This workshop primarily strengthened collaboration between the Tasks and laid the foundation for further projects in the current and upcoming triennia. It marked a significant step forward in aligning regional bioeconomic efforts with broader sustainability and system integration goals.

3.5 WORKSHOP ON BIOENERGY SUPPLY CHAIN RISKS AND UNCERTAINTIES

This workshop was developed for IEA Bioenergy Task 40 and implemented during a physical Task meeting in Utrecht, Netherlands, in September 2023.

The work presented in sections 3.1–3.4 aimed to assess the benefits and risks of more integrated bioeconomy sectors and biorefinery processes or to identify and formulate relevant indicators. A recurring theme was the lack of attention given to criteria related to supply security and resilience. To address this gap within Task 40, a dedicated workshop format was designed to leverage the expertise of its members.

Workshop focus and central questions

The central questions of this workshop were:

1. What uncertainties and risks arise along bioenergy value chains?
2. Can their resilience be improved by connecting individual chains into networks, thereby increasing the degree of system integration?

To structure the discussion, risk sources, types of uncertainties, and their impact on various value chain/network components—such as biomass supply, pre-treatment and conversion technologies, end-users, and infrastructures (including transport and storage)—were categorized.

Identified risk sources and categories

The workshop identified two types of risk sources:

- Natural risk sources: Including the atmosphere (e.g. storms, heatwaves), biosphere (e.g. invasive species), hydro/cryosphere (e.g. heavy rainfall and melting permafrost), geosphere (e.g. earthquakes).
- Anthropogenic risk sources: Including the technosphere (e.g. accidents), sociosphere (e.g. strikes), cybersphere (e.g. cyberattacks), econosphere (e.g. price fluctuations and crisis)

Three types of uncertainties were considered:

- Uncertain trends: Often considered in strategic planning.
- Variabilities: Relevant for flexible operations.
- Extreme events: Focused in traditional risk and disaster management.

These categories were visually represented, and Task 40 experts worked in groups to discuss selected value chains regarding their risks.

Key findings

1. Current risk assessments: While risk considerations are critical for project development and financing, they often focus too heavily on bioenergy plants themselves, neglecting the broader risks in supply chains. Initial risk assessment protocols for agricultural residues, energy crops, and woody biomass, developed in 2021 by Task 40 member Idaho National Laboratory (INL), should be expanded for holistic evaluations. (See more here - https://bioenergylibrary.inl.gov/BSCR/Home.aspx).
2. System integration as a resilience measure: Connecting supply chains into bioeconomy networks is a resilience and adaptation strategy. Modern conversion technologies can process diverse biomass fractions (e.g., from various agricultural and forestry sources) and residues of varying qualities to produce multiple products (e.g., electricity, heat, biomethane, fertilizers). This "portfolio diversification" enhances resilience.
3. Holistic risk planning: Joint consideration of uncertain trends, variabilities, and extreme events in bioeconomy network planning is essential. Diversified input-output portfolios, broad system boundaries for different resource flows, and flexible conversion technologies not only buffer the impacts of extreme events but also efficiently address fluctuations, such as those caused by intermittent renewable energy sources like photovoltaics and wind. For example, biomass gasification technologies can be used initially for building heat supply and later shifted to biomethane production as heating demand decreases.
4. New risks of integrated systems: Integrated systems and bioeconomy networks introduce unique risks that must be accounted for in planning. Cascade failures—where negative impacts in one system or supply chain spread to others—are a particular concern.

Workshop outcomes

The workshop provided valuable insights into resilience and risk management for bioeconomy networks. It highlighted the importance of considering supply chain risks, system integration benefits, and new risks introduced by networked systems. The results will inform future research and development within Task 40 and support ongoing efforts to design resilient and sustainable bioeconomy systems.

3.6 BIOECONOMY SYNERGIES EVALUATION FRAMEWORK

Developing a unified framework for evaluating integration dynamics offers the opportunity to highlight the often complex benefits of advanced bioeconomy sectors and biorefinery processes to policymakers and economic stakeholders. A well-structured framework simplifies the challenge of articulating the added value of activities such as biomethane production from forestry by-products or small, decentralized biorefineries managed cooperatively by winemakers for innovative residue utilization.

One of the **key outcomes of the BioSyn Initiative** is the proposal to adapt existing ecological evaluation frameworks to assess the synergies in the bioeconomy. The Intergovernmental Science-Policy Platform on Biodiversity and Ecosystem Services (IPBES) defines and categorizes the contributions of nature to human well-being. While this framework pertains to biosphere services, its similarities to the potential outputs of integrated technological elements, processes, and systems are striking. This resemblance led to the conclusion that advanced bioeconomy sectors and biorefinery processes could serve to mimic and enhance the contributions of nature to human well-being. This systemic biomimicry approach, while abstract at first glance, provides clear insights and actionable recommendations.

Contributions of nature to human well-being (as defined by IPBES[1])

Nature's contributions to human well-being are categorized into three broad types:

1. Regulating contributions: Includes habitat creation, pollination, air quality regulation, climate control through greenhouse gas sequestration, soil protection, natural hazard mitigation, and pest/disease control.
2. Material contributions: Encompasses the provision of bio-based fuels, food and feed, materials, and genetic resources for industrial, medical, or aesthetic uses.
3. Non-material contributions: Encompasses inspiration, learning, and technological innovations derived from nature, as well as physical and psychological benefits like recreation and healing, fostering identity, social cohesion, and long-term societal resilience.

Contributions of the bioeconomy to human well-being (categorized by the BioSyn initiative)

Advanced bioeconomy approaches, particularly in biorefineries, have the potential to systematically imitate and amplify nature's contributions:

1. Regulating contributions: Enhanced through innovations like recycling processes, wastewater treatment, carbon capture, and hybrid approaches enabling dynamic bioeconomy system adjustments. These technologies mimic natural processes, increasing resilience to extreme conditions and exploiting synergies between biological and technological components.
2. Material contributions: Achieved by using residues to produce bioenergy and supplying proteins, fertilizers, and pharmaceuticals.
3. Non-material contributions: Realized through fostering regional networks, diversifying actors, and creating new identities and learning opportunities. Flexible and decentralized infrastructures complement and optimize existing ecosystem services.

Recommendations for bioeconomy network planners

Based on the BioSyn Initiative findings and the biomimicry approach, specific recommendations for IEA Bioenergy TCP members and bioeconomy planners are as follows:

1. Recognize integration opportunities: Bioeconomy sectors and activities, such as biorefineries, offer diverse integration possibilities. Their benefits often stem from complex interconnections that need to be clearly articulated.
2. Assess resource flows holistically: Planners should begin by creating an overview of integrated energy, material, and intangible resource flows, such as knowledge.
3. Evaluate system integration impacts: Planners should assess the outcomes of integration, including the creation of new resource flows, overall resource flow

[1] https://www.ipbes.net/glossary-tag/natures-contributions-people accessed 05.12.2024

efficiency improvements for multiple resources, non-material benefits such as stakeholder participation, and increased resilience of integrated elements, systems, and processes.

4. Expand system boundaries in socio-environmental-techno-economic evaluations: Traditional evaluations often have limited system boundaries, dividing resources into internal and external factors or excluding performance indicators for process reliability and resilience. Such frameworks frequently underestimate the potential of advanced bioeconomy activities.
5. Adopt nature as a model: Nature provides three categories of contributions to human well-being—regulating, material, and non-material—all of which are equally important despite their differences. These contributions arise from tightly interconnected ecosystems and offer a blueprint for anthropogenic system integration. Planners should aim to balance these contributions equally, even if they cannot be unified under a single performance indicator.

Conclusions

By adopting a biomimicry-inspired framework, bioeconomy planners can advance well-integrated, human-designed systems that prioritize resilience, sustainability, and innovation. This approach emphasizes the importance of treating material, and non-material contributions as equally significant pillars of a sustainable bioeconomy, enabling both technological and ecological systems to sustainably develop.

3.7 TARGET AUDIENCE AND IMPACT OF THE BIOSYN INITIATIVE

The IEA Bioenergy Task 40 BioSyn Initiative targeted at an exchange within the Technology Collaboration Programme (TCP) and within Task 40 itself. Results and derived insights are being disseminated to broader audiences through this final report and the communication channels of project partners, including websites, LinkedIn, conference presentations, and project collaborations.

The project outcomes have significant relevance and diverse applications at both national and international levels. The consideration of system integration aspects within IEA Bioenergy fosters the harmonization and advancement of standards, norms, and policy strategies.

- National impacts: These findings can strengthen national bioeconomy strategies by introducing new approaches to biomass utilization and integrating innovative technologies, such as biogenic carbon management systems and flexible bioeconomy systems.
- International collaboration: An international framework for system integration could serve as a platform for enhancing cooperation between countries, particularly in areas such as green technologies like hydrogen, flexible biogas systems, and multifunctional land use.

Alignment with IEA Bioenergy Tasks

The relevance of the project outcomes is underscored by IEA Bioenergy Tasks work programme proposals for the upcoming triennium, in which also activities are planned addressing different system integration dynamics. The proposals for the next three years focus among others on advancing the IEA Bioenergy agenda by addressing critical themes in bioenergy and bioeconomy integration. Key priorities include the development of hybrid bioenergy systems, the valorization of organic waste, and the production of renewable fuels, chemicals, and biochar to enhance grid stabilization and circular resource use. Emphasis will be placed on thermochemical liquefaction technologies, decentralized pyrolysis, and system-wide integration of electricity and heat sectors to optimize energy and material flows.

Additionally, the proposals highlight the evaluation of biogas system co-benefits, the exploration of synergies between biofuels and power-to-liquid technologies, and the resilience of bioeconomy value chains. Socioeconomic dimensions, such as the social life cycle analysis of biorefineries and the impacts of biomass supply on regional development, will also be studied. Multifunctional landscapes and biodiversity effects remain a focus, alongside pioneering initiatives like the strategic Inter-Task Synergies Green Hydrogen-Biobased Value Chains Project and BECCUS 2.0, which explore green hydrogen integration and biogenic carbon management.

Cross-task collaborations and inter-TCP coordination will be strengthened to harmonize standards, enhance system flexibility, and drive innovation in bioenergy systems. These initiatives aim to create a resilient, sustainable, and inclusive bioeconomy that aligns with global energy transitions and sustainability goals.

The comprehensive connections fostered by Task 40 and by the BioSyn Initiative ensure that the results of the Triennium 2022-2024 can drive changes not only at the national level through the development of standards and legislation but also by promoting international collaboration. This is essential for establishing bioeconomy networks that have sustainability, flexibility, resilience, and efficiency, at their core, contributing to global sustainability goals (SDGs) and ultimately enhancing human well-being. Insights from the BioSyn Initiative hold the opportunity to improve the interoperability between vocabularies, guiding concepts, and approaches of Tasks and TCPs, resulting, ultimately, in more coherent, efficient, and resilient international developments in renewable energy, bioenergy, and the bioeconomy.

4 Conclusions and recommendations

The Task 40 BioSyn Initiative, led by the Austrian delegation, along with inter-task projects on topics such as sequencing biogenic carbon and hydrogen-bioenergy interactions, fulfilled a crucial role in synthesizing the diverse activities across IEA Bioenergy TCP Tasks and other Technology Collaboration Programmes in the 2022-2024 Triennium. The insights gained and collaborations established provide a strategic foundation for the alignment and continuation of all IEA Bioenergy Tasks. The results of the Task 40 BioSyn Initiative have the potential to become a cornerstone for more coherent, efficient, and resilient international developments in renewable energy, bioenergy, and the bioeconomy.

Moving forward, Task 40 will increasingly focus on supply chain risks and the contribution of bioeconomy networks to enhancing supply security and societal resilience. Here the focus will be on the analysis of resilience of new biogenic carbon value chains within the bioeconomy. The flexibility and resilience of biogenic carbon value chains to changes in policy, market or availability of resources will be examined. The circularity of the biogenic carbon value chains is designed to integrate components from feedstock production to product end-of-life and assume that each necessary component will be available when needed. All systems face disruptions and must be adaptable to changing conditions that may negatively affect performance. The upcomimg Task40 activities will utilise developed value chain designs to examine threats and define mitigation strategies across the broad segments of the value chain contained within 1) feedstock production, 2) pre-processing and material merchandising, 3) production of consumer products, and 4) biogenic carbon storage and recycling. The findings will provide strategic guidance and decision support for the establishment and deployment of biogenic carbon value chains. Potential collaboration with Tasks 42, 43, 44 and 45 is sought continuing the successfully established collaboration within the IEA Bioenergy TCP also in the next triennium.

Recommendations for Research, Technology, and Innovation (RTI) policy

We recommend that the IEA Bioenergy TCP members' RTI policies place greater emphasis on integration aspects in research, technology development, and innovation. Recognizing bioeconomy RTI as a driver of system integration means expanding its value beyond improving the efficiency of individual resource flows. This paradigm shift should also bring the often-overlooked non-material societal outcomes into focus, particularly those arising from the participation of diverse stakeholders across value chains and in extensive bioeconomy networks.

Key priorities for RTI policy

1. Acknowledge regulatory impacts of the bioeconomy: The bioeconomy's contributions to ecological, economic, social, and technical reliability and stability must be recognized. Comprehensive evaluation and anticipation methods should be developed to better understand and leverage these balancing capacities.
2. Establish integration impact assessment as a distinct discipline: Policies should facilitate the establishment of "integration impact assessment" as an independent research and development field. This would include evaluating synergies, identifying trade-offs and conflicts between different targets, and mitigating integration risks.
3. Leverage system integration as a facilitator to reach common goals: The energy system and economy already exhibit a high degree of integration. Achieving climate and sustainability goals will require further mobilization of synergies and planned avoidance of conflicts and integration risks.
4. Invest in interdisciplinary expertise: Developing intelligent integration strategies and assessing their impacts will require a new cadre of interdisciplinary "integrators." Existing investments in bioeconomy expertise can form a strong foundation, as bioeconomy planning inherently involves integration themes, as demonstrated in this report.

Final outlook

By fostering synergy effects and mitigating integration risks, IEA Bioenergy TCP members can position themselves at the forefront of sustainable development. These strategies will play a crucial role in achieving national climate targets while contributing to global sustainable development goals (SDGs). Through well-designed integration approaches and enhanced interdisciplinary collaboration, the bioeconomy can be supported to become more resilient and flexible.

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