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A synthesis of five regional transition case studies

Project: "Regional transitions in existing bioenergy markets 2.0”

IEA Bioenergy: Task 40

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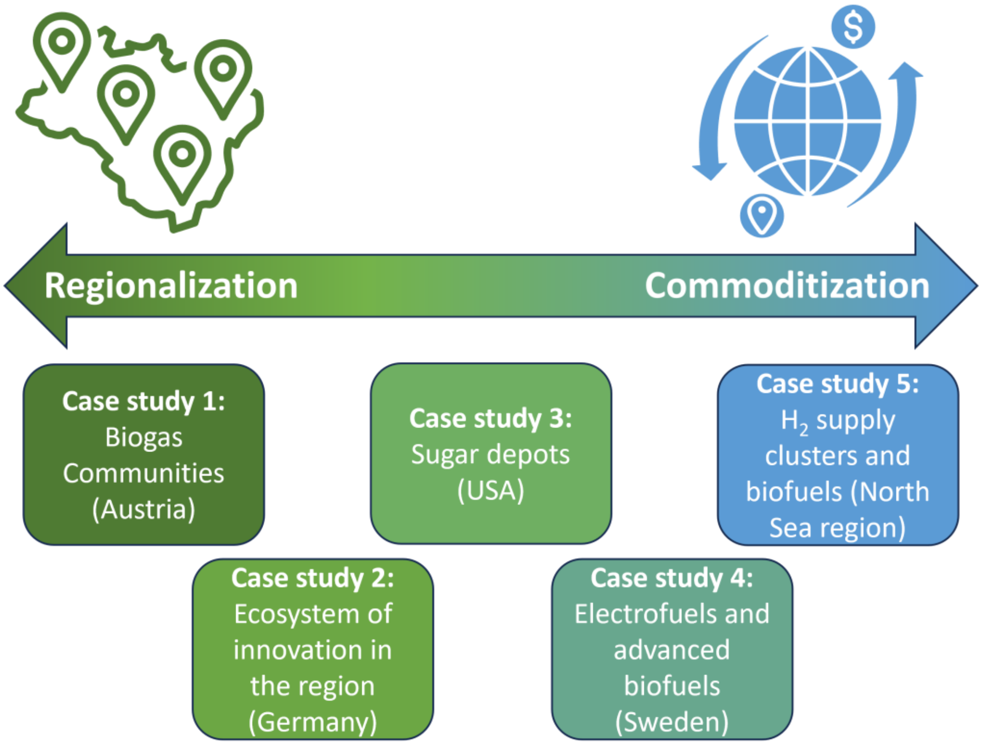

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Summary

One defining mega-trend of the energy transition involves replacing centralized fossil-fuel systems with decentralized renewable energy supply. This is mainly driven by the large deployment of wind and photovoltaics. Another mega-trend is the substitution of fossil-based materials and chemicals in a vast number of industry sectors. In this context, the bioenergy sector follows a dualistic path, marked by a tension between opposing strategic visions. Short, regional supply chains offer a path to decentralized systems, while commoditization aims to link diverse biomass sources to global markets. The "Regional Transitions 2.0" project demonstrates that regionalization and commoditization are mutually inclusive strategies for the energy transition. IEA Bioenergy Task 40 supports the deployment of viable, efficient, and profitable biobased value chains, regardless of their supply chain length. Both commoditization and regionalization of bioenergy supply chains are encouraged where they offer clear sustainability advantages.

The Regional Transitions 2.0 project has evaluated five case studies in Austria, Germany, Sweden, the USA, and the North Sea region (Figure 1), spanning the spectrum of regionalization and commodification strategies. These case studies demonstrate that each strategy presents unique opportunities and risks, and that, in all cases, the regional context is crucial to the sustainability of biobased supply chains.

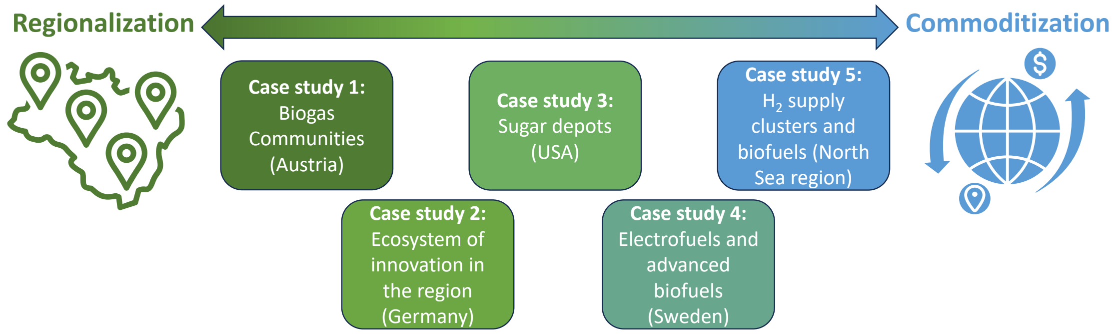

Figure 1 Classification of case studies by regionalization and commoditization strategies.

Biogas communities in Austria showcase a highly regionalized approach, using collective management to convert local waste into energy. **The BioZ project** in Germany leverages regional strengths, such as agriculture and the chemical industry, to create a competitive advantage and foster a bio-based economy. The **Sugar Depots** in the USA add value to the region by creating a standardized, commoditized product for broader markets. Meanwhile, a Swedish study on bioelectrofuels and electrofuels evaluates the viability of both centralized and decentralized production models, finding that co-location with existing industries (such as district heating) is vital to economic viability. Lastly, the North Sea region case study represents a highly commoditized value chain, with ports acting as hubs for global trade in biomass and green hydrogen.

All case studies confirm that regional integration and collaboration are key to economic and sustainable viability. Regionalization offers benefits such as reduced emissions and local economic development, but it can risk isolation from broader markets. Conversely, commoditization provides access to global markets and economies of scale but can lead to economic inequality and a loss of regional identity. The best strategy often involves a hybrid approach of regionalization and commoditization, creating a network of interconnected supply chains that leverage local strengths while remaining integrated into the global market.

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1. Introduction

1.1 BACKGROUND

The global energy transition towards carbon neutrality is complex and uncertain, but key trends are emerging. These include the increasing cost-effectiveness of solar and PV electricity, the electrification of road transport, and the future potential of a "green" hydrogen economy alongside a circular carbon economy. There is also a shift from centralized fossil-fuel-based energy supply to decentralized, distributed renewable energy systems. Recent conflicts and climate change-driven events have heightened the urgency of this transition, sparking interest in regionalizing energy for improved security of supply.

Bioenergy, part of the larger bioeconomy, plays a significant role in this transition, with both regional and global supply chains contributing to sustainable energy. While international bioenergy trade has been crucial for the development of the bioenergy sector and the deployment of renewable energy (Junginger et al. 2019), it also faces criticism for potentially hindering the move towards decentralized, renewable energy and for possibly lacking ecological sustainability (McGovern and Klenke 2016). IEA Bioenergy Task 40 supports the deployment of viable, efficient, and profitable biobased value chains, especially bioenergy, as part of a sustainable energy system and circular economy. Both commoditization and regionalization of bioenergy supply chains are encouraged where they offer clear sustainability advantages.

1.2 REGIONAL TRANSITIONS 2.0

The future size and viability of the bioenergy sector, as part of biobased value chains, depend on its adaptability to the dynamic context of the energy transition and on its role in securing a reliable and sustainable energy system. In the **Regional Transitions 1.0** project, IEA Bioenergy Task 40 explored possible strategies to develop sustainable feedstock supply chains in a regional dynamic market context to deliver biomass for different end-use markets (Hoefnagels et al. 2023, Schipfer et al. 2022). **The Regional Transitions 2.0 project aims to demonstrate that regionalization and commoditization strategies are mutually inclusive to the energy transition.** Their common denominator is that the regional context is important for the sustainability performance of bioenergy supply chains.

1.3 CASE STUDIES

In five case studies, experts from IEA Bioenergy Task 40 explored the strengths and weaknesses of both regionalization and commoditization strategies for selected bio-based supply chains. The case studies range from short, local supply chains in Austria to long, commoditized supply chains within the North Sea region:

1. The case study on ***Biomass communities in Austria*** (Schipfer 2026) explored the concept of collectively producing, managing, and consuming their own generated energy, primarily from renewable sources for biogas. European definitions of "energy communities" are often narrow and focused on electricity. For other renewable energy sources, including biogas, it is still relatively new. This case study explores the feasibility and potential for integrating regionally produced biomethane into the local energy system in Austria. It aims to define a common terminology to help different stakeholders, from economists to biogas plant operators, discuss the opportunities and risks of this emerging concept.
2. The case study on the *Innovation Alliance BioZ in Central Germany* (Fürst et al. 2026) focused on using regionalization and available local infrastructure to drive a sustainable, bio-based economy. The project leverages the area's agricultural, food, and chemical industries to reduce its dependence on fossil resources by using regional biogenic materials and by-products. The project has created an innovation platform that brings together regional stakeholders, including local businesses and research institutions. Collaboration is fostered through "dialogue groups" that concentrate on specific areas: functional proteins, lipids, fine chemicals, and biopolymers. These groups help develop joint research projects. The initiative is accompanied by two key studies. A "Life cycle assessment and sustainability assessment" helps regional companies adopt sustainable production methods. An "Innovation Ecosystem Case Study" analyzes the project's impact on the

region's innovation, economy, and quality of life. This helps identify the strategies needed for a successful transition to a bio-based economy.

3. The case study on *Sugar depots in the United States* (see annex) explored a model for converting biomass into a commodity by producing fermentable sugars from lignocellulosic biomass at strategically located depots. This regionalization approach is key because it centralizes processing of inconsistent biomass feedstocks, which are often dispersed and bulky. By transforming these raw materials into a standardized product, the model enhances efficiency, reduces logistical costs, and improves overall economic viability.
4. The case study on *Bioelectro- and electrofuels production in Sweden* (Pettersson and Axelsson 2025) investigated the best locations for producing novel renewable fuels in a Swedish context, examining different supply chain setups and how the distribution of electricity and hydrogen affects costs. Electrofuels are made by converting captured carbon dioxide with hydrogen. Decentralized production at multiple sites appears to be the most cost-effective option. Hybrid fuels (bioelectrofuels) can increase carbon efficiency by adding renewable hydrogen. The lowest production cost is achieved when the facility is located near a district heating system, allowing the use of excess heat. The study shows that both bioelectrofuels and electrofuels are primarily driven by hydrogen-related costs, but are also heavily influenced by the ability to utilize excess heat or co-produced oxygen. This makes it more economical to produce these fuels in locations where this integration with existing industries is possible.
5. The case study on *Hydrogen supply and biofuel production in the North Sea region* (Hoefnagels et al. 2026) explored possible synergies between hydrogen supply infrastructure and advanced biofuel production. The study shows that most advanced biofuel pathways need substantial amounts of hydrogen. If hydrogen were supplied from renewable sources, it could yield synergistic benefits by increasing the carbon efficiency of biofuel production while reducing costs and improving the energy efficiency of electrofuel supply. The North Sea region could play a large role in this development, but the existing and planned hydrogen infrastructure and biofuel production are misaligned.

1.4 SYNTHESIS

All case studies were evaluated using a similar structure based on the following topics:

- Supply chain strategy: regionalization vs commoditization strategies;
- Regional impacts and contribution to development/community building;
- Region-specific factors determining the economic and ecological viability;
- Embedment in the region and market;
- Opportunities and threats from the interplay with commoditized markets.

The synthesis was derived from individual case study reports, with Google Gemini utilized to summarize key findings. The results are presented in Section 2. More detailed information is available in the annex for the Sugar Depots case study and in the individual case study reports.

2 Main findings of the Regional Transitions 2.0 project

2.1 REGIONALISATION VS COMMODITIZATION STRATEGIES

The **commoditization** of biomass is promoted as a way to connect regionally available, diverse biomass with global markets. It could lower costs, provide supply security, and make large-scale biorefineries feasible, ultimately contributing to climate change mitigation and the transition to a circular economy (Elbersen et al. 2022). Standardization of bio-based products makes them more accessible and affordable, but it also entails trade-offs. It could, for example, come at the expense of unique regional characteristics, such as biomass processed by specialized firms into niche products, and local economic diversity created by small and medium-sized enterprises (SMEs) embedded in the region (Fürst et al. 2026). Furthermore, the following risks to commodization were identified by McGovern and Klenke (2016):

- **Increased Emissions:** long, international supply chains can potentially generate more emissions and have a greater environmental impact compared to short, regional supply chains.
- **Economic Inequality:** Local biomass producers might be reduced to material or resource suppliers, with most profits being captured by global value chains elsewhere.
- **Re-centralization:** A shift toward global supply chains could favor large utilities for cost-effectiveness, leading to the re-centralization of energy supply.
- **Lack of anchorage:** Supply chains that rely on subsidies and lack a strong regional foundation (anchorage) are more susceptible to market instability, disruptions, or policy changes.

Regionalization, in the context of the energy transition, often refers to the shift from conventional, centralized electricity generation to local, small-scale energy sources, such as wind and PV, which could improve the resilience and sustainability of the energy system (EY 2022). Also, for biomass, promoting local use is considered an option to achieve environmental and socioeconomic benefits (McGovern and Klenke, 2018; Mola-Yudego et al., 2024). Although the physical length (distance) and scale of the supply chain play a role, the environmental performance of bio-based value chains is generally dominated by upstream biomass production and midstream conversion processes rather than by supply chain length (Tsalidis et al. 2017; Hilst et al. 2019). Furthermore, regional bioenergy and other bio-based supply chains are often fragmented segments of larger, more complex energy or material systems that extend beyond the regional scale and remain tied to global commodity markets, such as (green) chemicals and fuels. A too-narrow regional focus may therefore also incentivize inefficient, low-value end-uses, potentially becoming excluded from higher economic and sustainability benefits available through national or international markets.

Neither commoditization nor regionalization offers a total solution. Rather than abandoning long-distance (international) transport and trade, we therefore propose regionalization strategies that create a competitive advantage in the global market by establishing a network of interconnected, yet largely self-sufficient, supply chains built upon a region's unique characteristics, strengths, and resources (Fürst et al. 2026). It thus prioritizes the unique regional context, including local biomass resources, infrastructure, and socioeconomic factors for each part of the value chain (Schipfer et al. 2022). Figures 1 illustrates a classification of the different case studies between regionalization and commodization strategies. The ranking of the different case studies is based on both upstream feedstock supply and downstream markets, as discussed in more detail below Figure 1.

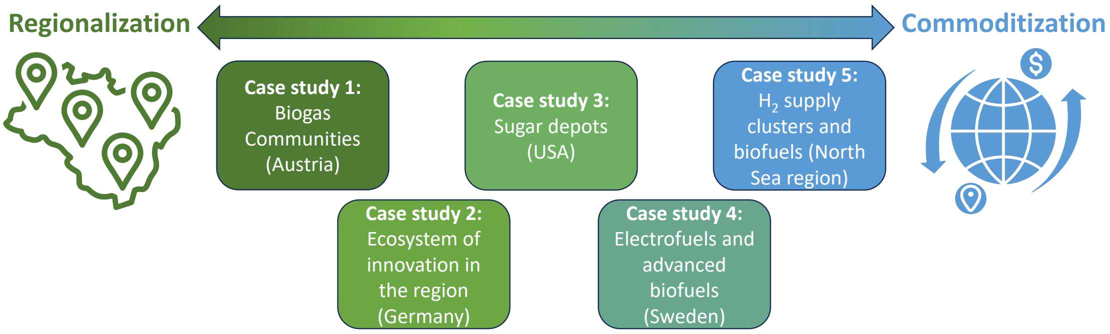

Figure 1 Classification of case studies by regionalization and commoditization strategies.

Biogas Communities (Schipfer, 2026) is classified as the most regionalized case study included. It strengthens regions by prioritizing autonomy (local control and collaboration) over complete self-sufficiency, allowing them to remain part of larger markets. The **BioZ project** (Fürst et al. 2026) in Germany leverages unique regional strengths, including agriculture and a strong chemical industry, to create a competitive advantage rather than standardizing products. The regional **Sugar Depots in the US** (see Annex) overcome biomass transport challenges by acting as hubs to standardize feedstock, improving efficiency, and serving as innovation centers. They provide a cost-effective, scalable, and regionalized supply chain that offers logistical benefits and access to commoditized markets while capturing economic benefits in the region. Sugar depots could therefore reduce the risks of economic inequality and increased emissions associated with commoditized value chains.

The production of **bioelectrofuels and electrofuels in Sweden** (Pettersson and Axelsson 2025**)** evaluates both centralized and decentralized models. This analysis considers different plant locations: near biomass sources, near users, or integrated with district heating. It also compares hydrogen distribution via pipelines or the electricity grid. For methanol production, decentralized units convert CO_2 at multiple sites, while centralized production transports CO_2 from various plants to a single large (centralized) facility. Finally, **the North Sea** region (Hoefnagels et al. 2026) exemplifies commoditized value chains, with ports acting as hubs for imported biomass, fuels, and hydrogen. While this case study region benefits from existing infrastructure, it faces challenges from global competition, highlighting the need for combined access to green hydrogen, biomass, and downstream markets as a key strength.

2.2 ECONOMIC VIABILITY

The case studies show that integration and collaboration in the supply chain are key for a transformation towards well-functioning, economically viable bio-based value chains:

- The Biogas case study (Schipfer 2026) demonstrates that low-value biomass sources, such as organic waste, could be converted into valuable products such as electricity, heat, and fertilizers, creating synergies between industries and providing new revenue streams. But it requires diverse participation and shared governance to reduce financial risk and dependence on a single entity.
- The **"chemical triangle"** in Central Germany in the BioZ case study (Fürst et al. 2026) provides a strong competitive advantage, as it established industrial infrastructure and large corporations, alongside innovative SMEs, offering a robust network for integrating bio-based processes. This integration allows SMEs to enhance their competitive edge and meet new market demands for sustainability.
- Finally, the **Sugar Depots** model (see Annex) focuses on a distributed production network to minimize transportation costs by locating depots near feedstock sources. These smaller, decentralized depots act as hubs that supply larger downstream conversion facilities, enabling them to achieve **economies of scale**. This model not only reduces logistical challenges but also stabilizes local biomass markets.

For commoditized value chains, co-location and industrial integration can provide a strategic anchor, significantly enhancing economic viability, as demonstrated in electrofuel and biofuel production:

- The Swedish case study (Pettersson and Axelsson 2025) shows that the economics of electrofuels are dominated by the **cost of electricity** for hydrogen production. A key trade-off exists between lower electricity prices in northern Sweden and greater opportunities to utilize excess heat in the more populated southern regions.
- Furthermore, integration options, such as the ability to use excess heat, can offset higher production costs. For electrofuels (without biomass), the potential to monetize the oxygen by-product is a crucial economic factor, as a lack of oxygen demand can significantly impact profitability. Co-locating production with other industries, a district heating network, or an oxygen consumer is a decisive factor for economic viability.
- The North Sea region case study (Hoefnagels et al. 2026) also shows that, next to biomass supply, access to either green hydrogen or electricity could become an important factor for advanced biofuel production.

2.3 ECOLOGICAL IMPACTS

All case studies emphasize the potential of GHG mitigation by providing renewable alternatives for fossil-based electricity, heat, chemicals and materials, and liquid transport fuels. Local sourcing of biomass indeed minimizes the carbon footprint associated with transportation and some of the ecological benefits are also linked to regionalization. For example, the local generation of electricity and heat from combined heat and power (CHP) systems in the Biogas Case study (Schipfer 2026) reduces reliance on centralized, fossil-fuel-based energy production. Furthermore, the BioZ case study demonstrates that integrating bio-based materials into the chemical industry helps reduce the environmental footprint of a historically fossil-fuel-dependent sector within the same region. This shift leverages existing industrial infrastructure to enable more sustainable practices (Fürst et al. 2026).

The Biogas, BioZ (Schipfer 2026, Fürst et al. 2026) and Sugar depot case studies (see Annex) also highlight ecological benefits related to land use and management practices. The creation of fertilizers from digestate in the Biogas case study closes nutrient loops, benefiting soil health. **BioZ** promotes and provides sales markets for drought-resistant, protein-rich crops in Central Germany that have not been utilized so far. This supports the creation of new value chains, thereby contributing to climate-resilient agriculture. Furthermore, sustainable agricultural practices like crop rotation and the cultivation of perennial energy crops for fermentable sugar production could improve soil health, increase biodiversity, and reduce erosion.

However, the environmental impact of the entire pathway is largely determined by energy use during conversion, which could be enabled by long-haul transport of biomass. As an example, access to renewable electricity for hydrogen production is critical for achieving a low-carbon footprint of electrofuels and bioelectrofuels (Pettersson and Axelsson 2025, Hoefnagels et al. 2026). The ecological benefits are further enhanced when excess heat and oxygen by-products are used to replace energy or products that would otherwise have a higher carbon footprint (e.g., district heating from biomass or oxygen from electricity-intensive air separation units) (Pettersson and Axelsson 2025).

Finally, adverse ecological impacts related to the cultivation of agricultural biomass, the harvesting of forest residues, and the significant water consumption required for electrolysis were also mentioned as relevant regional impacts.

2.4 REGIONAL DEVELOPMENT/COMMUNITY BUILDING

Community building is one of the drivers of regionalization strategies; it is not exclusive to regional supply chains and is a critical strategy for differentiation and value creation in commoditized markets, such as biobased chemicals (Fürst et al. 2026). Furthermore, all case studies drive local economic development by creating jobs and providing direct local benefits and value creation.

Successful community building requires early, accessible, and continuous engagement with local residents and stakeholders. This ensures that community concerns, such as safety, noise, and traffic, are addressed proactively, which can prevent opposition and project delays. The proposed energy communities provide a strategic framework also for bioenergy systems to accelerate the energy transition and bolster regional circular bioeconomies (Schipfer 2026). By adopting a regional focus and involving local stakeholders in planning and operations, these initiatives foster ownership and collective responsibility, effectively mitigating public opposition.

By leveraging northern Sweden's electricity surpluses and forest biomass resources, the deployment of bio-electrofuels could help to revitalize sparsely populated areas through localized production. This strengthens the competitiveness of internationally traded transport fuels, but also drives regional development by integrating new fuel production facilities directly into rural economies. For the deployment of these fuels in port terminals, developing the needed energy architecture, including vast infrastructure for hydrogen pipelines, CO_2 transport networks, and facilities for sustainable bioenergy supply chains, could potentially create new high-value jobs and revitalize port-adjacent economies.

2.5 MARKET OPPORTUNITIES

The case studies highlight several opportunities that arise from considering the regional characteristics of the included supply chains.

2.5.1 Integrated, regional value chains

Both BioZ and Biogas communities demonstrate the value of being embedded in a local context. This involves integrating with regional agriculture for feedstock, local energy users for output (e.g., electricity, heat), and municipalities for institutional support. This approach fosters economic resilience by creating self-sufficient, local supply chains that are less dependent on global markets.

BioZ also highlights opportunities from diversification and resilience by using a variety of regional biomass to create a diverse range of products, from biopolymers and specialty chemicals to protein-based foods. This strategy spreads risks and ensures the initiative can adapt to changing market demands. Similarly, biogas communities integrate multiple stakeholders—like farmers and local businesses—to create a robust, shared system for energy and resource management.

2.5.2 High-value, specialized markets

Although specialization could reduce market potential, serving niche industries also creates opportunities for high-value end-uses. The Sugar depots case study is a prime example. While biomass can be used for many things, high-purity fermentable sugars are a suitable feedstock for niche markets like pharmaceuticals, nutraceuticals, etc.. These sectors demand consistency and purity, which a dedicated feedstock can provide better than a varied, regional supply. Similarly, BioZ demonstrates that bringing all stakeholders together could connect local farmers with high-value end-markets within the same region to produce high-value products from local biomass sources.

Both BioZ and the Sugar depots also offer a significant opportunity in providing building blocks or intermediates for bio-based materials. Fermentable sugars can, for example, be used to produce bio-based polymers for the automotive, construction, and packaging sectors.

2.5.3 Promotion schemes

EU policies, including the **Renewable Energy Directive (RED III)** and regulations like **ReFuelEU Aviation** create a guaranteed, stable market. By setting specific quotas for Renewable Fuels of Non-Biological Origin (RFNBOs), these policies de-risk investment in technologies that would otherwise be too expensive to be competitive.

By centralizing processing and integrating regional resources, biomass sugar depots can modernize existing biofuel supply chains developed under existing promotion schemes. More importantly, this infrastructure provides the essential foundation for scaling emerging markets such as Sustainable Aviation Fuel (SAF) and biobased chemicals.

2.6 MARKET THREATS

2.6.1 (Feedstock) supply chain

Biomass supply volatility and scarcity were highlighted as important threats:

- The availability and cost of biomass feedstocks, such as those for the Sugar depots, are vulnerable to factors like weather, agricultural yields, and competition for land use. This volatility can affect the operational stability and profitability of production facilities.
- Limited and declining cultivation areas pose a significant challenge. This can lead to greater reliance on imported biomass, eroding regional benefits and potentially increasing impacts.
- Finally, the conversion of biomass into end products involves complex, capital-intensive processes. Technological failures, inefficiencies, or delays in scaling up production can hinder economic feasibility.

2.6.2 Limits to regionalization

Recognizing the benefits of international collaboration and standardization is highlighted by two important threats:

- A narrow focus on regionalization by either pure efficiency or complete (regional) self-sufficiency can lead to suboptimal outcomes. Overemphasis on efficiency may exclude interregional actors, while overemphasis on autarky may isolate regions from beneficial international cooperation.
- Smaller companies often struggle to provide transparent sustainability information or go through costly certification processes, unlike larger, centralized corporations with dedicated departments

for such tasks. This can lead to a risk of greenwashing or choosing less reputable certifications. Complex sustainability requirements could therefore limit access to (commoditized) markets. The BioZ project demonstrates how LCA expertise and verification can be made available to smaller companies in the value chain.

2.6.3 Policy environment

Regulatory and Policy Changes: Government policies, subsidies, and mandates play a critical role. Changes, such as the reduction or removal of subsidies or the introduction of new regulations, can significantly impact market demand and the financial stability of projects.

Misaligned Incentives: existing frameworks, such as the EU RED III, which credits fuels where they are consumed rather than produced, may make it less attractive for member states to produce these fuels for export without specific cooperation agreements.

Restrictive Regulatory Frameworks: Stricter regulations and lengthy approval procedures, particularly in the EU and Germany, act as a significant barrier to entry for innovative bio-based products and processes from smaller companies. This can hinder their commercialization and ability to compete.

2.6.4 Markets

Undervaluation of Resilience and Security: Global market mechanisms often prioritize short-term cost efficiency, thereby disadvantaging regional production systems, such as biogas communities, that offer critical long-term benefits in terms of stability and sovereignty. This undervaluation can limit the viability of decentralized, regional models that are connected to global markets.

Competition from Global, Commoditized Markets: Regional bio-based products, like those from BioZ, face significant challenges competing on price and scale against established players who benefit from economies of scale. This can marginalize local efforts and impede the growth of regional SMEs.

Market Volatility and Dependency: Exposure to global commodity markets can introduce price volatility and supply chain disruptions, especially for communities lacking hedging mechanisms or long-term contracts.

Market Acceptance and Consumer Perception: Public perception and consumer preferences can be fickle and influenced by price, performance, and perceived environmental benefits. If bio-based products are seen as inferior or too costly, market acceptance may be limited. Production in the region could reduce this risk and improve consumer perception, for example, by offering traceability and transparency.

High Production Costs: Innovative fuels like electrofuels and bioelectrofuels are significantly more expensive to produce than conventional biofuels. Without specific incentives, their market development remains slow and uncertain, leading to the cancellation of large-scale projects.

Lack of Public and Private Investment: Securing investment is a major challenge for the implementation of innovations. This is exacerbated by limited private investment, stringent regulations, and lengthy authorization processes that can hinder the mobilization of essential resources for new projects and companies.

3 Conclusions

Commoditization of biomass has been promoted as a solution to connect regionally available and diverse biomass sources to global markets. This strategy could lower costs, provide supply security, and make large-scale biorefineries feasible, contributing to climate change mitigation and the transition to a circular economy. It is, however, also criticized for reducing regionally unique characteristics, re-centralization, increased vulnerability, and supply chain emissions from long-distance transportation.

The Regional Transitions 2.0 project has evaluated five different case studies on both regionalization and commodization strategies in Austria, Germany, Sweden, the US, and the North Sea region. These case studies demonstrate that regionalization and commoditization strategies are mutually inclusive to the energy and material transition and that a successful supply chain strategy mostly requires elements of both. Their common denominator is that the regional context is important for the sustainability performance of biobased value chains.

Supported by these case studies, the Regional Transitions 2.0 project challenges the assumption that supply chain length is the primary determinant of sustainability. Rather than abandoning international trade, the project redefined regionalization as a form of strategic autonomy and competitive advantage. Regions strengthen their own capacities while remaining deeply interconnected through shared infrastructures, resource flows, and people. This creates regional competitive advantage without isolation and offers an often under-discussed alternative to the false dichotomy between regionalization and commoditized globalization: autonomous regions that are resilient on their own, yet able to cooperate, exchange, and support one another within a global market. By prioritizing specific regional contexts, such as local biomass and existing infrastructure, sustainability is built directly into the value chain, creating a resilient network of self-sufficient yet cooperative global partners.

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Annex: Sugar depots in the United States

THE ROLE OF SUGAR DEPOTS IN ENABLING REGIONALIZED SUPPLY WITH COMMODITIZED INTERMEDIATES FOR COMMERCIAL-SCALE BIOREFINERIES IN THE US

A1. Case study description

This case study delves into the viability of biomass commoditization through the production of fermentable sugars at strategically located biomass depots. As the global demand for sustainable and renewable feedstock sources intensifies, leveraging biomass as a key feedstock has emerged as a promising solution. This study investigates how centralizing the conversion of diverse biomass feedstocks into standardized sugar intermediates at regional depots can enhance economic efficiency, logistical feasibility, and environmental sustainability. By examining various operational aspects, the study aims to provide a holistic understanding of the potential benefits and challenges associated with this approach.

Variability in biomass feedstock, including differences in moisture content, composition, and quality, significantly impacts conversion efficiency and the overall economics of biomass depots (Hartley et al., 2020). Inconsistent feedstock characteristics can lead to suboptimal performance of pretreatment and hydrolysis processes, resulting in lower yields of fermentable sugars and increased operational costs. This variability necessitates additional processing steps or adjustments, driving up energy consumption and reducing overall efficiency. Furthermore, procurement of inconsistent biomass can lead to frequent equipment maintenance and downtime, further escalating costs. To mitigate these challenges, it's essential to implement stringent quality control measures, diversify feedstock sources, and continuously optimize processing technologies to handle variability effectively, thereby enhancing both conversion efficiency and economic viability.

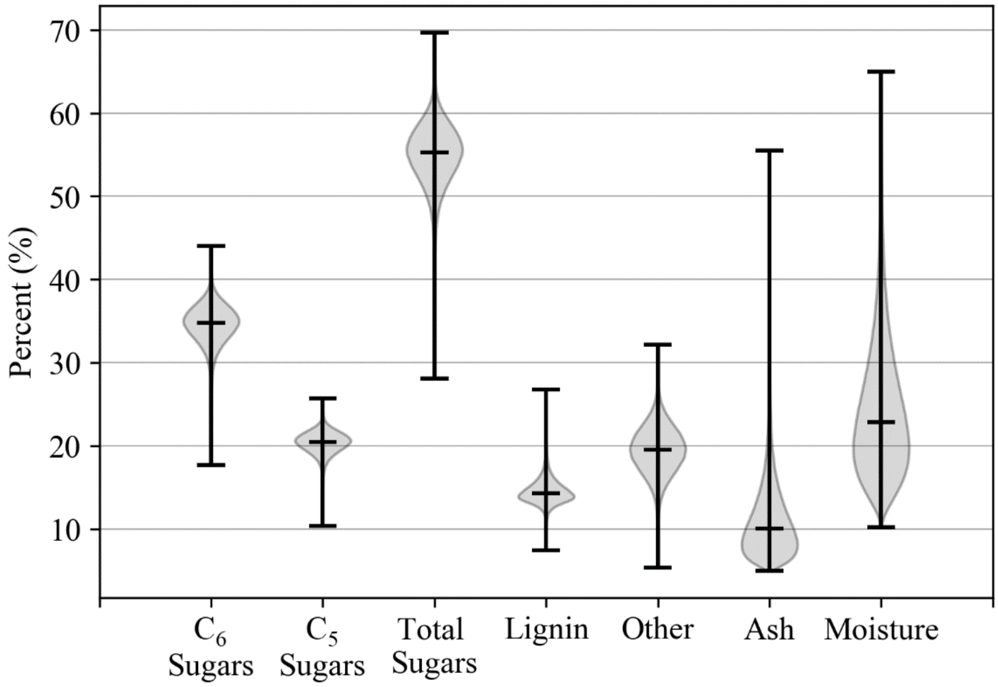

Figure A1 Violin plot of compositional components of corn stover taken from (Hartley et al., 2020)

Commoditization of biomass seeks to minimize the variability of the biomass by transforming the biomass into an intermediate good with a standard quality (Olsson et al., 2016). By processing the biomass down to the fermentable sugars, much of the variability is removed, with the sugars that remain having a known set of quality attributes and performance characteristics. When the material has known and predictable quality traits, then need for robustness in the conversion system is diminished leading to an improved ability to optimize processes and improve efficiency (Thompson et al., 2013). Beyond the standardization of quality, logistical considerations form a significant part of this study, particularly the role of biomass depots in optimizing supply chain efficiency. By centralizing biomass collection and initial processing steps, depots can reduce transportation costs and logistical challenges associated with dispersed biomass sources (Roni et al., 2019). The study explores how depots can serve as hubs for regional biomass markets, standardizing feedstock quality and ensuring a steady supply of raw materials. It also investigates the potential for depots to act as innovation centers, fostering research and development in biomass processing technologies and enhancing overall supply chain coordination.

Economic viability is another critical aspect addressed in this case study. This case study explores the operational benefits associated with implementing sugar depots including the impact on operational expenses, and potential revenue streams from sugar intermediates and other byproducts. The study also examines the broader economic impacts on local communities, including job creation and regional economic development. By comparing the depot-based approach with decentralized biomass processing models, the study aims to identify the most cost-effective and scalable solutions for biomass commoditization.

Finally, the environmental implications of biomass commoditization through sugar production at depots are thoroughly evaluated. This includes an exploration of how sugar depots can reduce lifecycle greenhouse gas emissions, energy consumption, and lead to reducing reliance on fossil fuels. The study considers how depots can contribute to sustainable biomass supply chains by promoting the use of renewable feedstocks and implementing environmentally friendly processing technologies. Overall, this case study provides a comprehensive examination of the feasibility and sustainability of using biomass depots to commoditize biomass into valuable sugar intermediates, offering valuable insights for stakeholders in the bioeconomy sector.

A2. Economic and ecological viability

Benefits to production economics

The economic benefits of commoditizing biomass through sugar production at distributed depots are multifaceted, impacting various aspects of the supply chain, market dynamics, and regional economies. By transforming raw biomass into fermentable sugars at strategically located depots, several cost efficiencies and economic opportunities arise, enhancing the overall viability of this approach.

Firstly, distributed depots minimizing the diseconomies of scale that is seen by feedstock supply systems (Thompson et al., 2013). Biomass is often bulky and has a low energy density, making its transportation from dispersed locations to processing facilities expensive. By situating depots closer to biomass sources, the initial transportation distance is minimized, reducing fuel costs and logistical complexities. Also, this can result in a stabilizing effect on local biomass markets, as the depots act as centralized points for aggregating and standardizing biomass, ensuring a consistent supply of high-quality feedstock (Roni et al., 2023). This reduces market volatility and provides biomass producers with a reliable revenue stream, encouraging more farmers and landowners to invest in biomass production. The standardized sugar intermediates produced at depots can also meet the quality requirements of various industrial applications, enhancing their marketability and value.

The concentrated sugar intermediates at the depot reduces the volume and weight of material that needs to be transported to downstream processing facilities, leading to additional savings in transportation costs. Additionally, the more easily transported intermediate enables conversion processes to centralize their processes to take advantage of efficiency gains that come from increased scale (Thompson et al., 2013). In addition, efficiency is further enhanced through the ability to improve process optimization due to the reduced variability in the feedstock. These improvements enhance the economic competitiveness of biomass-derived products. The cost reductions realized through the commoditization of the biomass into a sugar product, enables these products to compete more effectively with their petroleum-based counterparts in the market. Additionally, the ability to produce a diverse range of products from a common sugar intermediate broadens market opportunities and reduces dependency on a single product line, further enhancing economic resilience (Biddy et al., 2016).

Biomass depots can also help improve production economics through serving as a catalyst and proving ground for process improvement and technical innovation. Due to the scale of the depots, they provide ideal opportunities for collaboration with academic institutions, government agencies or other industrial partners to examine and validate research and development. Compared to large conversion facilities, the relatively small capital investments enable technological agility which can lower the barriers of exploring new technologies and process designs, enabling near continuous innovation leading to more efficient and cost-effective processing technologies, benefiting the entire biomass supply chain.

The total economic benefits of commoditizing biomass through sugar production at distributed depots are substantial. From cost efficiencies and job creation to market stabilization and technological innovation, this approach offers a comprehensive strategy for enhancing the economic viability of biomass as a key resource in the bioeconomy. By leveraging the advantages of centralized processing and regional integration, biomass depots can play a pivotal role in transforming the biomass supply chain and unlocking new economic opportunities.

Environmental Benefits

The sustainability benefits of biomass depots can be profound, with one the most significant benefits being the promotion of renewable energy sources. By promoting the use of renewable biomass feedstocks and reducing reliance on fossil fuels, this approach can contribute to long-term energy security and environmental sustainability compared to long supply chains of unprocessed biomass. The transition to a bio-based economy can also support national and regional policies aimed at reducing greenhouse gas emissions and mitigating climate change. By converting diverse biomass feedstocks into fermentable sugars at depots, the reliance on fossil fuels is reduced, leading to lower greenhouse gas emissions. This shift helps mitigate climate change and supports national and international goals for carbon reduction.

On a more local level, using locally sourced biomass reduces the carbon footprint associated with long-distance transportation of raw materials, further enhancing the environmental sustainability of the supply chain. Biomass depots also encourage sustainable agricultural practices, which have long-term positive effects on the environment. By providing a stable market for agricultural residues and energy crops, depots incentivize farmers to adopt practices such as crop rotation, residue management, and the cultivation of perennial energy crops. These practices can improve soil health, increase biodiversity, and reduce soil erosion, leading to more resilient agricultural ecosystems. Furthermore, the diversification of crops can enhance farm productivity and reduce the risk of crop failure, contributing to the overall sustainability of the agricultural sector.

A3. Regional development/community building

Community engagement and collaboration are integral to the success of a sugar depot supply chain. By involving local stakeholders in planning and decision-making processes, depots can ensure that their operations align with the needs and priorities of the community. This can include engaging with local governments, farmers' associations, and community groups to address concerns, gather input, and build trust. Such collaborative efforts can enhance community support for the depot, fostering a sense of ownership and pride in the regional bioeconomy.

For the communities that support the development of sugar depots and their associated supply chains, the economic benefits for the community can be substantial. The development of the biobased industries will enhance regional development and community building by creating new economic opportunities, fostering local investments, and promoting sustainable practices. One of the primary benefits is job creation. Establishing and operating biomass depots necessitates a diverse workforce, encompassing roles in biomass collection, processing, quality control, logistics, and administrative functions (Crandall et al., 2017; Romero et al., 2023). These jobs can provide stable employment for local residents, particularly in rural and agricultural communities where such opportunities may be scarce. Consequently, this can lead to increased household incomes and improved standards of living.

A direct impact of the establishment of the depot infrastructure will be an increased investment in supporting industries and infrastructure. As depots become operational, there is a need for improved transportation networks, storage facilities, and processing equipment. This infrastructure development can stimulate further economic activities and attract additional businesses, such as equipment suppliers, maintenance services, and ancillary industries that support the biomass supply chain. Additionally, the increased financial wellbeing within the communities and region further help to strengthen the communities through the multiplier effect, where increased economic activity leads to further investments and growth in the region (Domański & Gwosdz, 2010). Additional indirect effects that can result from the increased economic activity would be the expansion of public services. Increased tax revenues from depot operations and related economic activities can support local governments in funding public services, such as education, healthcare, and infrastructure improvements. Enhanced community well-being, driven by economic stability and environmental sustainability, can lead to a more resilient and cohesive community, better equipped to face future challenges.

In summary, the implementation of a sugar depot supply chain presents numerous regional development and community-building opportunities. Through job creation, local investments, innovation, sustainable practices, community collaboration, and enhanced public services, sugar depots can act as catalysts for economic growth and social progress. By integrating these depots into the regional landscape, communities can reap the benefits of a robust and sustainable bioeconomy, fostering long-term prosperity and resilience.

A4. Markets: opportunities and threats

Market Opportunities for Sugar Depots

The establishment of sugar depots creates a myriad of market opportunities by providing a versatile and standardized intermediate product—fermentable sugars—that can serve as a feedstock for a wide array of industries (Werpy & Petersen, 2004). Biofuels and biochemicals are at the forefront of market opportunities provided to the sugar depot concept (Biddy et al., 2016). Fermentable sugars derived from biomass can be converted into bioethanol, biodiesel, and other advanced biofuels. Fermentable sugars, can also be the building blocks for various biochemicals, including bioplastics, organic acids, and specialty chemicals. These biochemicals can replace petroleum-based counterparts in numerous applications, ranging from packaging materials to pharmaceuticals (Biddy et al., 2016). As global demand for renewable energy sources increases, sugar depots can position themselves as key suppliers to biofuel producers, helping to meet regulatory mandates and sustainability goals aimed at reducing carbon emissions. Additionally, the growing consumer and regulatory push towards sustainable and biodegradable products enhances the market potential for biochemicals derived from renewable sugars. Sugar depots can thus cater to a diverse range of industries seeking sustainable raw materials.

Beyond fuels and chemicals there are other smaller volume but relatively higher value markets where biomass sugars could find opportunity. The pharmaceutical and nutraceutical industries represent a potentially lucrative market for fermentable sugars (Espro et al., 2021; Karnaouri et al., 2021). These industries utilize sugars in the production of antibiotics, vitamins, and other health-related products. The trend towards using renewable and sustainable inputs in pharmaceutical manufacturing creates opportunities for sugar depots to become key suppliers. By providing consistent and high-purity sugars, depots can support the production of essential medicines and health supplements, contributing to public health and wellness.

The cosmetics and personal care industry is another area where sugar depots can find market opportunities (Ruales-Salcedo et al., 2022). Fermentable sugars are used in the formulation of various cosmetics and personal care products, such as exfoliants, moisturizers, and hair care treatments. The industry's shift towards natural and sustainable ingredients offers sugar depots the chance to supply raw materials that align with these market trends. Collaborations with cosmetic companies looking to enhance their green credentials can lead to new business ventures and product innovations.

Furthermore, the emergence of the bio-based materials sector presents additional market opportunities. Fermentable sugars can be used to produce materials such as bio-based polymers, which are increasingly being used in automotive, construction, and packaging industries. As these sectors seek to reduce their environmental impact and adopt more sustainable materials, sugar depots can become vital suppliers of the necessary feedstocks. This diversification into bio-based materials represents a significant growth area, driven by both regulatory pressures and market demand for sustainable alternatives.

Sugar depots have the potential to unlock a wide array of market opportunities across multiple industries, from biofuels and biochemicals to food, pharmaceuticals, and bio-based materials. By providing a versatile, renewable feedstock, sugar depots can meet the growing demand for sustainable products, fostering innovation and economic growth. As global markets continue to prioritize sustainability, the role of sugar depots in supplying high-quality, sustainable sugars will become increasingly vital, creating new business opportunities and driving the transition to a bio-based economy.

Market Threats for Sugar Depots

While sugar depots present numerous market opportunities, they also face several market threats that need to be carefully managed to ensure long-term viability. One of the primary threats is the volatility in biomass supply and pricing (Hess et al., 2009; Hess et al., 2007). The availability and cost of biomass feedstocks can be influenced by various factors such as weather conditions, agricultural yields, and competition for land use (Kumar & Sokhansanj, 2007). These factors can lead to fluctuations in feedstock supply and pricing, which can affect the operational stability and profitability of sugar depots. Ensuring a consistent and affordable supply of biomass is crucial for the sustained operation of depots.

Another significant threat is the competition from other renewable energy and biochemical sources. The bioeconomy is rapidly evolving, with advancements in alternative feedstocks and technologies such as algae, synthetic biology, and waste-to-energy processes (Osman et al., 2021). These alternatives may offer cost advantages, higher efficiencies, or less environmental impact, potentially outcompeting biomass-derived sugars. Sugar depots must continuously innovate and improve their processes to remain competitive in an increasingly diverse and dynamic market.

Regulatory and policy changes also pose a threat to sugar depots. Government policies and subsidies play a critical role in the economic viability of renewable energy and bio-based products (Sen & Ganguly, 2017). Changes in policy, such as the reduction or removal of subsidies, changes in renewable energy mandates, or the introduction of new regulations, can significantly impact the market demand and financial stability of sugar depots. Staying informed about policy trends and actively engaging in policy advocacy are essential strategies to mitigate this threat.

Market acceptance and consumer perception present another challenge. While there is growing demand for sustainable and renewable products, consumer preferences can be fickle and influenced by various factors, such as price, performance, and perceived environmental benefits (Zhuang et al., 2021). If biomass-derived sugars and their end products are perceived as inferior or too costly compared to alternatives, market acceptance may be limited. Effective marketing, education, and ensuring product quality and competitiveness are essential to gaining and maintaining consumer trust and market share.

Technological barriers and operational risks are also significant threats. The conversion of biomass to fermentable sugars involves complex and often capital-intensive processes. Technological failures, inefficiencies, or delays in scaling up production can hinder the economic feasibility of sugar depots (Asghar et al., 2022). Furthermore, advancements in processing technologies are necessary to improve yields and reduce costs continually. Investing in research and development, along with adopting best practices and technologies, is crucial to overcoming these barriers and mitigating operational risks.

In conclusion, while sugar depots offer substantial market opportunities, they must navigate several threats to ensure long-term success. These include biomass supply volatility, competition from alternative technologies, regulatory changes, market acceptance challenges, technological and operational risks, and environmental sustainability concerns. By proactively addressing these threats through innovation, strategic planning, sustainable practices, and stakeholder engagement, sugar depots can enhance their resilience and continue to play a vital role in the bioeconomy.

A5. Conclusion

As the global demand for sustainable and renewable energy sources continues to rise, the centralization of biomass conversion into standardized sugar intermediates at regional depots presents a promising solution. This approach can significantly enhance economic efficiency, logistical feasibility, and environmental sustainability by addressing various operational aspects such as feedstock variability, quality control, and supply chain optimization.

However, there are several challenges that need to be addressed to realize the full potential of this strategy. While the commoditized sugar provides a mitigation to the variability that is experienced in the feedstock for the downstream conversion processes, the variability in biomass must still be managed during the sugar production process. At the depots, the variability of the feedstocks will still negatively affect conversion efficiency and increase operational costs. Additionally, the economic viability of sugar depots depends on mitigating risks associated with biomass supply volatility, competition from alternative technologies, and regulatory changes. By diversifying feedstock sources, and staying abreast of policy trends, sugar depots can enhance their resilience and operational stability.

Ultimately, the establishment of sugar depots offers substantial economic and environmental benefits, including regional job creation, market stabilization, reduced greenhouse gas emissions, and the promotion of sustainable agricultural practices. By serving as hubs for innovation and fostering regional economic development, sugar depots can play a pivotal role in advancing the bioeconomy. Through strategic planning, stakeholder engagement, and continuous improvement, sugar depots can navigate the existing threats and capitalize on the myriad opportunities to drive the transition towards a sustainable, bio-based economy.

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