Regional transitions in existing bioenergy markets

Synthesis report of IEA Bioenergy Task 40 Regional Transitions project 1.0

IEA Bioenergy: Task 40

August 2023

Regional transitions in existing bioenergy markets

Synthesis report of IEA Bioenergy Task 40 Regional Transitions project 1.0

Ric Hoefnagels, Uwe Fritsche, Martin Graffenberger, Damon Hartley, Christiane Hennig,
Romy Kupfer, Chenlin Li, Alexandra Pfeiffer, Christopher Schmid, Fabian Schipfer

IEA Bioenergy: Task 40

August 2023

ISBN: 979-12-80907-32-5

Published by IEA Bioenergy

Summary

Introduction

Bioenergy is an essential component of the transition towards a climate-neutral energy sector by 2050 to meet global climate targets. However, rather than a single homogenous sector, bioenergy is a complex and diverse network of regional, national, and international value chains part of the larger bioeconomy. A better understanding is needed of how the bioenergy sector will develop in the context of the energy transition and development of the circular (bio)economy. In the **Regional Transitions** project, experts from IEA Bioenergy Task 40 have explored strategies to develop sustainable biobased value chains in a regional dynamic market context. The focus was on feedstock supply chains, which is a cornerstone for the deployment of sustainable and reliable biobased value chains and organized in three activities as summarized below.

Regional transitions – trends in the European Union and a case study for Germany

In Activity 1, Utrecht University and DBFZ assessed current and future bioenergy markets in the European Union and a specific case study for Germany. Model-based scenario projections largely support policies that aim toward high(er) value applications, including flexible power generation, high-temperature heat, aviation and shipping, and biobased materials and chemicals. One aspect that remains underexplored is how regional biobased value chains can be developed that, on the one hand, effectively mobilize low-value underutilized biomass sources while, on the other hand, meet the needs of high-value end-users. These include also new centralized demand markets such as power stations with BECCS (bioenergy with carbon capture and storage), high temperature heat in industry and advanced biofuels. The case study for Germany revealed that regulations and measures regarding the development of biobased value chains are still highly fragmented and limited to specific products or sectors. A more holistic, cross-sectoral regulation framework will be required to move towards a circular biobased economy. An analysis of scenario projections for Germany showed that biomass is expected to be shifted towards sectors or applications that are indispensable or irreplaceable and where no renewable alternatives are applicable or available. This means that biomass will fill the "gaps" applying to both material and energy use. These include biobased materials and chemicals as well as specific energy services like flexible power provision, process heat generation or fuel provision for specific transport applications. The actual development depends on multiple and interdependent factors that are not sufficiently covered in available studies. More detailed knowledge about current biomass use and the future development of bioenergy as part of the larger bioeconomy is needed to facilitate the transition at the national level.

Strategies to increase the mobilization and deployment of local (endemic) low value heterogenous solid biomass resources

In Activity 2, Vienna University of Technology and DBFZ assessed possible mobilization strategies for local, low-value and heterogenous biomass sources. To this purpose, knowledge of IEA Bioenergy Task 40 on international bioenergy trade, on the current provision of bioenergy, and cluster mobilization measures was used to develop strategies for the future feedstock provision of the circular bioeconomy. Topics were clustered in three categories, namely: legislative framework, technological innovation and market creation. By means of these assessment levels, the report tackles a cognitive bias of Bioeconomy supply chain discussions, which currently focus on the challenges rather than the opportunities of transitioning primary economic sectors.

In contrast to fossil fuels sourced from concentrated points, followed by large-scale and centralized refining and distribution, biomass mobilization encompasses vast regional areas, a large array of inter- and transdisciplinary knowledge involved, and a multitude of stakeholders woven into the fabric of decentralized, adaptable, and intricate supply networks. The report explores a small selection of opportunities which will be central to future studies.

Adoption of bioenergy by existing agriculture and forestry biomass feedstock suppliers in the United States

In Activity 3, Idaho National Lab (INL) evaluated the adoption of herbaceous and woody biomass supply by existing biomass feedstock suppliers including agriculture and forestry. A detailed Agent Based model (ABM) was used including, amongst others, spatial explicit land data and farmer's characteristics. ABM models are useful in determining the conditions under which grower participation is higher and enables identification of levers that result in adoption at faster and higher rates. The study included case studies for two types of biomass in the USA. A case study for agricultural biomass in Colorado, Nebraska, and Kansas and a case study for woody biomass in Georgia. Results for the herbaceous case indicate that farmers' credibility has the highest impact on the adoption of crop residue harvest and crop cultivation. Media influence has a low impact on crop residue harvest, but has a substantial impact on energy crop grower adoption caused by high risks, access to information and best practice examples of other farmers which are less applicable to crop residue harvests. Results for the woody biomass case are found to be very different from the herbaceous case studies. The availability of forest residue is linked and therefore highly dependent on the production of primary products. Alternative forest management approaches could increase forest residue availability, but the incentives to drive this behavior are yet unclear.

Index

1. Introduction

1.1 BACKGROUND

Bioenergy is deemed essential to the transition towards a climate-neutral energy sector by 2050 to meet the Paris climate goal to keep long-term global temperature rise to well below 2ºC (WB2) (Thrän et al. 2020). Policies targeted at reducing GHG emissions and improving energy security of supply have led to strong growth in bioenergy, commoditizing of biomass and international trade in the past two decades (Junginger et al. 2019). However, current policies are not enough to meet the Paris agreement so that further changes in the energy system are needed (IEA 2021; IPCC 2023; IRENA 2023), and in that, the role and position of biomass in the energy system will need to change as well.

Transformation efforts of bioenergy systems cover the entire value chain, from feedstock supply to conversion up to final markets, as depicted in Figure 1. On the supply side, efforts are, amongst others, focused on the promotion of low-value, underutilized biomass sources as part of a future circular bioeconomy. On the demand side, there is a drive to shift towards high-value applications including high temperature heat, aviation and shipping, and the production of biobased materials and chemicals that have limited alternatives to decarbonize. The deployment of wind and solar electricity will reduce the need for traditional baseload electricity, but will increase the need for flexible, dispatchable power options, that bioenergy can deliver. Markets for baseload power might also return when combined with carbon capture and utilization (BECCU) or storage (BECCS) the latter driven by the need of negative emission technologies.

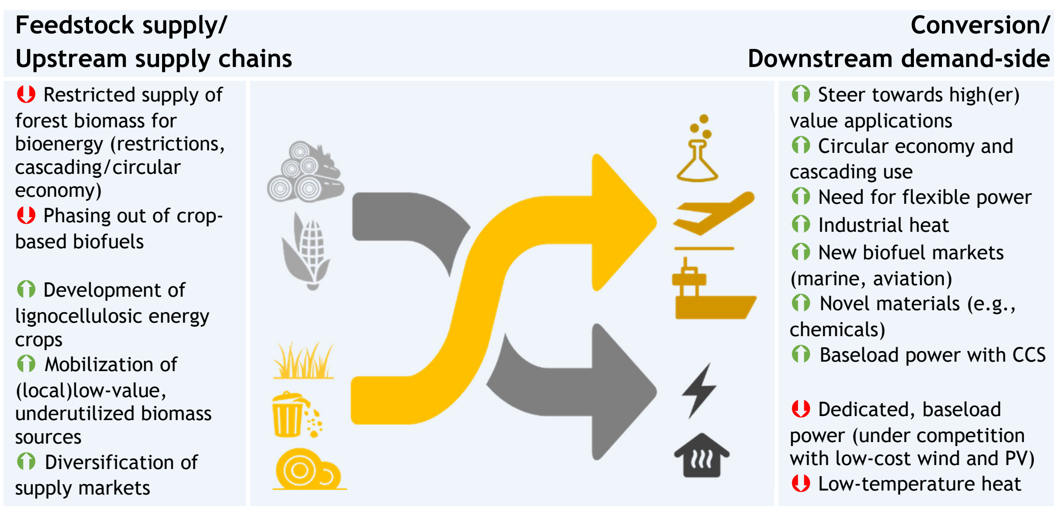

Figure 1 Possible transformations of bioenergy systems. Based on the tentative field of application of biofuels in SER (2020), and EU bioeconomy drivers in a successful circular EU bioeconomy implementation in Fritsche et al. (2020, 2021).

REGIONAL TRANSITIONS

Despite a clear direction of transition pathways towards more efficient use of biomass resources and steering towards high-value applications, it is yet unclear which biobased value chains should be transformed and scaled-up to contribute to sustainable energy system for multiple reasons. First, rather than a single homogenous sector, bioenergy is a complex and diverse network of regional, national and international value chains as part of the larger bioeconomy. Secondly, the potential of different bioenergy options varies among countries, and at regional levels within countries as a result of local context conditions. This necessitates the alignment of biomass strategies and policies to specific regional or local conditions and circumstances within countries to get the transition going. IEA Bioenergy has published many studies on the overarching role of bioenergy in a (WB2) world (Thrän et al. 2020), and individual sectors or systems including industrial heat and BECCU and BECCS (Olsson et al 2021, 2022).

To make decisions and develop strategies on biomass resources, the logistical challenges, and experience from biomass mobilization strategies of developed markets and existing infrastructure, regional considerations embedded in the larger context of national, international and global energy transition. This report provides a synthesis of the three research activities of the IEA Bioenergy Task 40 Regional Transitions project.

To this purpose, it combines insights from studies with different geographic scopes, spatial resolution and level of detail to develop strategies for the development of secure and sustainable biomass supply chains. These include:

- Chapter 2: Current and future bioenergy markets, insights from model-based scenario projections in the European Union and a detailed case study for Germany;
- Chapter 3: Strategies to increase the mobilization and deployment of local (endemic) low value heterogenous solid biomass resources focusing on the legislative framework, market structures, and technological innovation;
- Chapter 4: Adoption of bioenergy by existing forest and agriculture biomass feedstock suppliers with case studies in the United States (Colorado, Nebraska, Kansas and Georgia).

2 Regional transitions - trends in the European Union and a case study for Germany

In Activity 1, Utrecht University and DBFZ assessed current and future bioenergy markets in the European Union and a specific case study for Germany. The case study for Germany is published in a separate report (Schmid and Hennig 2022).

Highlights

Model-based scenario projections largely support policies that **aim toward high(er) value applications, including flexible power generation, high-temperature heat, aviation and shipping, and biobased materials and chemicals.** One aspect that remains underexplored is how regional biobased value chains can be developed that, on the one hand, effectively mobilize low-value underutilized biomass sources while, on the other hand, meet the needs of high-value end-users. These include also new centralized demand markets such as power stations with BECCS, high temperature heat in industry and advanced biofuels.

The case study for Germany revealed that **regulations and measures regarding the development of biobased value chains are still highly fragmented** and limited to specific products or sectors. A more holistic, cross-sectoral regulation framework will be required to move towards a circular biobased economy.

An analysis of scenario projections for Germany showed that **biomass is expected to be shifted towards sectors or applications that are indispensable or irreplaceable and where no renewable alternatives are applicable or available**. This means that biomass will fill the "gaps" applying to both material and energy use. These include biobased materials and chemicals as well as specific energy services such as flexible power provision, process heat generation or fuel provision for specific transport applications.

The **actual development depends on multiple and interdependent factors that are not sufficiently covered in available studies**. More detailed knowledge about current biomass uses and the future development of bioenergy as part of the larger bioeconomy is needed to facilitate the transition at the national and regional level.

2.1 REGIONAL CONSIDERATIONS: THE EUROPEAN UNION (EU)

2.1.1 Current and future use of bioenergy in the EU

Bioenergy has experienced significant growth in the EU prior to 2020. As a result of advancements in wind power and photovoltaic electricity production, effective energy efficiency measures and policy uncertainties regarding bioenergy, a stagnating trend can be observed in bioenergy deployment. According to the EU Climate Target Plan and EU Reference scenario projections, bioenergy deployment will only start to recover from the stagnation trend after 2030. Nonetheless, post-2030, significant growth in biomass demand is projected driven by the demand in sectors with limited alternatives to bioenergy. These include a significant increase in bioenergy for thermal power stations with the deployment of BECCS, high temperature industrial processes, and advanced biofuels, especially in marine and aviation sectors (EC 2021).

Integrated assessment models (IAMs) are useful to analyze the role of bioenergy in the broader context of energy, economy and land use systems, but with major limitations concerning system, sectoral and geographic details (Thrän et al 2020). The difference in model structure between different IAMs leads to large variations in model outcomes regarding the role of bioenergy. A comparison of 12 different IAMs for bioenergy demand in the EU shows a large range in outcomes (yellow area in Figure 2 Left). A more detailed analysis shows however that bioenergy could contribute on average 19% (range 7 – 34%) of EU primary energy consumption by 2050 (Mandley et al 2020).

Most IAM model projections indicate that the EU will remain a net importing region of bioenergy due to the availability of lower-cost feedstock supplies. These models estimated that imports will account for approximately 35% of the EU's primary bioenergy demand, with a wide range of projections ranging from 13% to 76%. This is significantly higher than the figures projected by the EU Energy Roadmap 2050 (7.5%). This possible overestimation of imports could result from the lack of regional details in IAMs with respect to transport infrastructure (Matzenberger et al 2015, Mandley et al 2020).

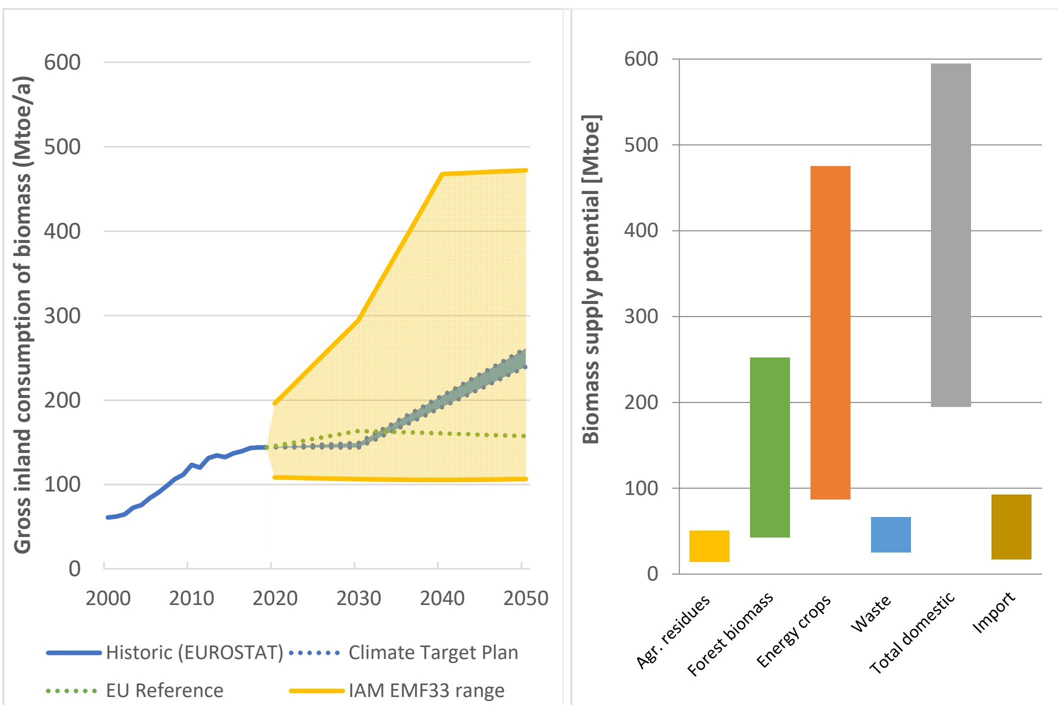

Figure 2 Left: Historic and future gross inland consumption of biomass for bioenergy in the EU27+UK, 2000 - 2050. Projections of PRIMES (EU SWD/2021/621 final, EC 2021) and EMF33 participating IAMs (Mandley et al 2020). Right: Ranges in EU27+UK Biomass supply potential in 2050, in EU biomass resource assessments (2006 - 2017) (Hoefnagels et al 2018).

2.1.2 A multi-model approach for improved energy system and trade representation

Some of the limitations of IAMs regarding the oversimplified representation of regional specificities, including those associated with international bioenergy trade, could be addressed by applying a multi-model framework. Mandley et al (2022) combined the IAM IMAGE with the energy system model PRIMES and the dedicated EU bioenergy system model RESolve-Biomass to analyze the role of bioenergy in the EU27+UK in a below 2°C scenario up to 2050. The results show a significant increase in imports of bioenergy from 0.6 EJ/y (14.3 Mtoe/y) today to 8.5 EJ/y (203 Mtoe/y) by 2050, and therefore higher than domestic supply at 6.3 EJ/y (150 Mtoe/y) by 2050.

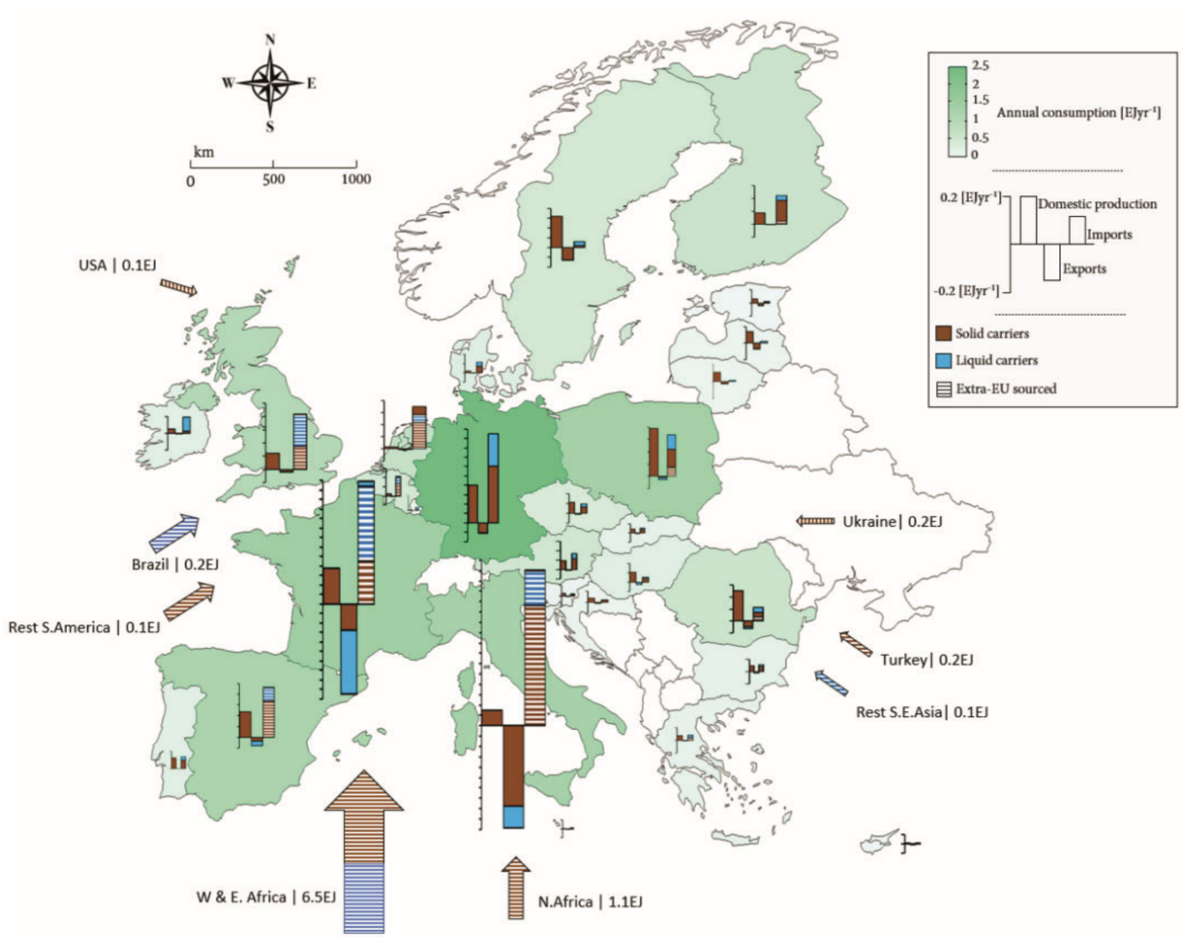

Figure 3 Future projections of gross inland consumption of biomass for bioenergy in the EU27+UK, distribution and trade dynamics by 2050 (in EJ/y). Extra-EU imports are only shown to EU27 and UK hub nations and might be traded between member states. Mandley et al. (2022)

2.1.3 Final thoughts

The improved energy system and biomass trade representation at the country level provide important insight in the future role of bioenergy in the European Union and the interplay between international and domestic biomass sources. On the demand side, these scenario projections confirm the shift of biomass towards higher value end-use applications including biobased chemicals, advanced biofuels used in aviation and the deployment of BECCS (Figure 1). Out of total biomass consumption, 55% is projected to be used for power generation with CCS in 2050.

On the supply side, these scenario projections indicate a larger reliance on imported, commoditized biomass sources. This will require major investments in infrastructure of which its feasibility requires dedicated transport modelling with a detailed, regional (and geographic explicit) representation of transport infrastructure (Mandley et al. 2022). Both the transport infrastructures (the fixed components of the transport system), and energy infrastructure (the energy delivery system), play a decisive role in shaping the energy transition, but are not considered in sufficient detail in these modeling studies.

Finally, investment decisions should be compared with alternative strategies to increase the mobilization and deployment of local (endemic) biomass resources, which are still underexplored and could possibly reduce the reliance on imported biomass. In the next section 2.2, Germany, which is projected to remain the leading country in bioenergy consumption in the EU, will be discussed in more detail, while Section 3 addresses strategies to increase the mobilization and deployment of local (endemic) low value heterogenous solid biomass resources.

2.2 A CASE STUDY FOR GERMANY

2.2.1 Introduction

The use of biomass has greatly evolved from its traditional applications such as food, feed, construction material, and primary energy for heating and cooking, to modern applications such as flexible energy provision, transport fuels, process heat, chemicals, biobased polymers and modern composite materials. Especially in Germany, the role of biomass has transformed since the 19th century from being mainly used as timber and firewood to a versatile material with high utility in different sectors. Since the early 1990s, state support systems and subsidies in Germany have promoted the use of biomass for energy purposes, leading to a significant increase in energy-related biomass use in the electricity, heat and transport sector. The nation was among the first to introduce “bioenergy villages” and refrained from supporting biomass use for co-firing in coal plants. Alongside biomass, other renewable energies such as wind and solar power also experienced rapid growth in Germany. As the share of renewable energy sources increases, integration into the energy system is a challenge due to various technical, infrastructural, spatial aspects and social acceptance issues. Germany's situation exemplifies the challenges faced by European countries during the energy transition, including supply of growing renewable energy demand, phasing out coal-fired and nuclear power plants, and facing site competition and local acceptance problems for wind and photovoltaic plants. Furthermore, biomass utilization itself has challenges related to its sustainable provision, climate change impacts, competing uses, efficiency, and its role within the energy system. Studying current biomass utilization and potential transition directions is crucial to define measures for achieving desired targets. This case study explores the current state and potential transition of biomass utilization in Germany as an example for regional transitions.

Germany's approach to transitioning biomass utilization is outlined in numerous strategies, laws, and regulations that are tied to the European legal framework and international agreements. The central policy for this transition is the National Bioeconomy Strategy (2020), which lays out measures for establishing a biobased economy, tapping into its potential for sustainability and climate goals. Additional strategies, such as the National Energy and Climate Plan (2020) and the Climate Action Plan 2050, further frame biomass utilization and its long-term transition.

2.2.2 Method

The overall objectives for biomass utilization in Germany are economic, environmental, and social sustainability, with a focus on climate change mitigation, sustainable biomass provision, resource efficiency, and economic value creation. The transition vision for biomass utilization in Germany includes its use as a central and renewable resource for material utilization sectors and its efficient use in optimized cascades and in a circular economy to increase economic value creation. When used in cascades energy-related utilization comes at the end of the utilization chain when no profitable material use is possible.

Implementation of these strategies is supported by laws, regulations, and measures such as the Renewable Energy Act, Building Energy Act, German Fuel Emissions Trading Act, Greenhouse Gas Emissions Trading Act, and the Federal Emission Control Act, among others. Despite this comprehensive legal framework, a cross-sectoral regulation for biomass use is still lacking, particularly in the context of a bio- and circular economy. Future efforts may focus on creating a holistic regulation and support system for biomass resources, especially biogenic waste and residual materials, addressing the nature of a circular economy. This will enable a more efficient use of these resources.

2.2.3 Status quo

The utilization of biomass in Germany can be divided into four main sectors: feed, energy, material, and food, with feed usage taking the most significant role in terms of quantity. Energy and material use follow next, while food production uses about four times less biomass than feed production. Both woody and agricultural biomass are used in material and energy-related applications.

In terms of agricultural biomass utilization, cereals, sugar, and vegetable oils and fats are most crucial. Woody biomass mostly originates from forestry, with raw wood being the dominant material. Nearly 30% of raw wood is used for energy purposes, mostly in the form of logs for decentral direct heating. Looking at energy-related biomass utilization, the majority of bioenergy comes from forest and agricultural biomass in Germany. Most bioenergy within the German energy system is used in the heat sector, followed by electricity generation and transportation. Material biomass utilization in Germany is mostly based on woody biomass and, to a lesser extent, agricultural biomass. Woody biomass is used mainly in timber, pulp, and sawmill industries. Agricultural biomass, such as crop-based materials, are also used for material purposes, with the majority being utilized in the chemical industry.

Overall, the German biomass supply is characterized predominantly by domestically produced agricultural and woody biomass. Solid biomass represents the largest share within bioenergy carriers.

2.2.4 Future outlook

Expectations for future biomass utilization in Germany depend on a variety of factors including GHG goals, available biomass types and potentials, governance on biomass resources, bioenergy technologies, material use concepts, and renewable alternatives. Studies suggest a wide range of potential for domestic bioenergy, though the methodologies for determining these potentials are variable and lead to different results.

Scenario studies indicate that biomass utilization for food and feed could significantly decline by 2050 due to changes in private consumption patterns. Sales of 2nd generation biofuels for transport are expected to increase by 2050, while 1st generation biofuels may likely decline. Use of wood could remain at the current level, or increase, depending on the importance of the biobased economy in the future. While fossil fuels remain an important resource for the chemical industry, there is an increasing interest in the use of biogenic carbon for chemical products.

In the heat and power sector, bioenergy is expected to shift from base-load generation towards a more flexible energy provision. Here especially biogas and biomethane installations will play an important role. Solid biomass is seen as an important transitional technology in decentralized heat supply, especially for poorly insulated buildings. Drivers and trends for the near-term outlook of German biomass utilization include demographic and economic development, consumption behaviors, and available biomass supply. Biomass is expected to fill the gaps in sectors where renewable alternatives are not applicable or available, such as biobased materials and chemicals, flexible power provision, process heat generation, and fuel provision for specific transport applications.

3 Strategies to increase the mobilization and deployment of local (endemic) low value heterogenous solid biomass resources

In Activity 2 of the Regional Transitions project, Vienna University of Technology and DBFZ assessed possible mobilization strategies for local, low-value and heterogenous biomass sources. The full study is published in an academic journal [Schipfer et al. 2022].

Highlights

Local, low-value and heterogenous biomass feedstock types, including forestry and agricultural residues and biogenic wastes, are identified as the backbone of tomorrow's circular bioeconomy.

Knowledge of IEA Bioenergy Task 40 on international bioenergy trade, on the current provision of bioenergy, and cluster mobilization measures was synthesized to develop strategies for the future feedstock provision of the circular bioeconomy.

Topics were clustered in three categories, namely: legislative framework, technological innovation and market creation. By means of these assessment levels, the report tackles a cognitive bias of Bioeconomy supply chain discussions, which currently focus on the challenges rather than the opportunities of transitioning primary economic sectors.

In contrast to fossil fuels sourced from concentrated points, followed by large-scale and centralized refining and distribution, biomass mobilization encompasses vast regional areas, a large array of inter- and transdisciplinary knowledge involved, and a multitude of stakeholders woven into the fabric of decentralized, adaptable, and intricate supply networks. The report explores a small selection of opportunities which will be central to future studies.

3.1.1 Introduction

Biomass supply in today's bioenergy sectors mainly consists of wood chips and wood pellets supplied to thermal conversion in heat and power, first generation biofuel resources and food wastes (mainly used cooking oil) supplied to biofuel production. Furthermore, commoditization of biomass and international trade have developed rapidly in the last decade with collection and preprocessing at depot/hub locations (e.g., pellet mills) before long distance transport to its end-users.

Local, low-value and heterogenous biomass feedstock types, including forestry and agricultural residues and biogenic wastes, are identified as the backbone of tomorrow's circular bioeconomy. Regional deployment strategies are being realized with different rates of success. For example, regional supply and price fluctuations, risks of impurities, etc., make it difficult to compete with existing international (wood pellet) markets that have developed over the last decade. Especially considering that commodity-type feedstock supply chains might be needed for producing advanced biofuels, chemicals and power with CCS at commercial scale (Lamers et al. 2016, Fritsche et al. 2019). Nevertheless, these current biomass provision structures are unfit to address the challenges of future environmentally, socially and economically sustainable feedstock supply chains. Activity 2 of the Regional Transitions project aimed to **develop strategies for the future feedstock provision of the circular bioeconomy.**

3.1.2 Method

Starting point of the analysis was the knowledge base of IEA Bioenergy Task 40 on international bioenergy trade, on the current provision of bioenergy, and mobilization strategies combined with scientific literature on this topic. This knowledge was transferred to local, low-value biomass sources under the consideration that these will become the feedstock base of the future circular bioeconomy. Topics were clustered in three categories, namely: legislative framework, technological innovation and market creation (Figure 4). A common denominator across these assessment levels was that supply from primary economic sectors of the bioeconomy should be strengthened to meeting the needs of the circular (bio)economy while other primary sectors, including fossil fuel extraction and refining, are declining.

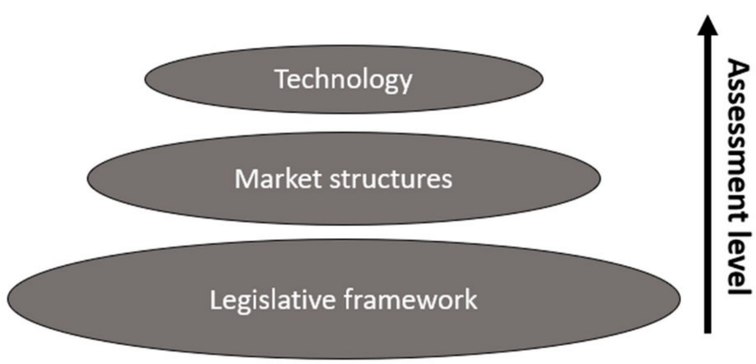

Figure 4 Biomass mobilization strategies selection and categorization. The arrow indicates the spatial and sectoral resolution of the assessment level, from low to high (Schipfer et al 2022).

3.1.3 Legislative framework for biomass mobilization

A preliminary list and description of EU polices that are important to consider for planning the mobilization of local, low-value and heterogenous biomass was made. A detailed description is provided in Schipfer et al. (2022).

The EU Green Deal provides a common strategy to reduce greenhouse gas emissions by 55% until 2030 and achieve climate neutrality by 2050 in the EU (EC 2019) and a common basis for polices and measures to achieve these targets. These include an amendment of the Renewable Energy Directive (Directive (EU) 2018/2001, REDII) with more strict sustainability criteria on bioenergy including updated GHG saving criteria, a phase out of dedicated/stand-alone power generation from biomass and enforced cascading principles for forest materials. On March 30, 2023, a provisional agreement on the amendment of the Renewable Energy Directive (RED III had been reached between the Council and the Parliament which has been endorsed by the member states' representatives in June. The EU Bioeconomy Strategy provides the primary action plan for biomass mobilization, including the deployment of local bioeconomies across Europe. Several other EU strategies and policies support the sustainable development of specific aspects of the bioeconomy, such as the Farm to Fork Strategy, the Forest Strategy for 2030, and the Biodiversity Strategy for 2030. Finally, financial support is provided as part of, amongst others, the EU Green Deal, or public-private partnerships for circular bioeconomy, including the industries joint undertaking—BBI JU (Biobased Industries Joint Undertaking) that could foster regional mobilization of biomass.

The EU has a diverse landscape of economic structures, cultures, economies and governmental structures. Furthermore, it has a diverse patchwork of legislative structures among and within member states, with subsidiarity as a core principle, to guarantee a degree of independence for lower authorities. The Multilevel Governance (MLG) analytical framework is proposed as it provides a more coherent policy mix across different spatial and organizational resolutions and sectors while acknowledging the underlying interactions. This could aid local and regional energy and climate initiatives. A case study for Austria on energy planning governance illustrates a "general willingness" to participate in local energy actions and cooperation at different governance levels (Dobravec et al. 2021). Shortcomings, such as data availability and spatial energy planning for renewables were identified and options to extend its scope to local levels and up to the EU. The valorization of socioeconomic benefits is also lacking still. The inclusion of the social dimension and possible benefits of regional mobilization strategies in policy making and energy system models, while recognizing the heterogenous context in which these systems are embedded, is therefore essential.

3.1.4 Market creation for biomass mobilization

Strategies that were identified to support the creation and establishment of markets for the mobilization of low-value and heterogeneous biomass sources are summarized below:

- **Physical and virtual bio-Hubs** are important options to address the incongruity of biomass supply scattered in both space and time, and large-scale conversion plants that require consistent, reliable and all-year round supply of biomass at large scale. These bio-hubs can also enable regional market creation. The IEA Bioenergy project Biohub collects best practices and disseminates different case studies from various world regions[1]. Virtual bio-hubs, such as the Biomass Commodity Exchange (BCEX) for cellulosic biomass trade in the US and the Electronic Reverse Auction (eRA) system for straw-based thermal power in Denmark could at least stabilize markets. So far, the establishment of new biomass markets by virtual bio-hubs is limited.
- **The commoditization of intermediary products or bioenergy carriers** is seen as an important step for their market uptake. It could improve price stability, market conditions, international trade. Furthermore, through internationally recognized sustainability standards and certification systems, sustainability along the supply chain could be safeguarded. Studies by IEA Bioenergy Task 40 (Lamers et al. 2016, Schipfer et al. 2020) and also IEA Bioenergy Tasks 39 and 45 (van Dam and Ugarte 2022, Majer et al. 2023) confirm these advantages, but also identify challenges. For example, smaller producers might be pushed out of the market. Furthermore, lack of transparency and high trade margins created inefficient wood pellet markets in central Europe. Other studies also argued that commoditization could hinder the development of regional energy projects and decentralized energy supply that foster from diverse stakeholder participation and local benefits including revenue generation, job creation and independence from multinational companies. Thus, balance should be found between larger, more efficient commodity markets and smaller, local or regional

[1] Case studies are available through this link: https://sunshinecoast.maps.arcgis.com/apps/dashboards/f56d358e82b041bd81bd589ec9fa1e45

specialized markets. To this extend, optimal supply chains should not solely focus on lowest cost, but should also include the number of stakeholders in a bioeconomy supply chain to avoid the relocation of supply chains to lowest cost regions, support the preservation of diverse, local supply chains and avoid that commoditization leads to an environmental race to the bottom. This property should ideally be translated into a key performance indicator.

- Finally, transparency is critical for the functioning and stability of international and regional markets. **Informative networks for knowledge exchange and market creation** are required to provide data on price information, production and consumption. Also, data on stocks and flows, including storage volumes are becoming increasingly important in the context of the increased flexibility service demand. IEA Bioenergy TCP and related TCPs are one of many examples[2] of these networks for knowledge exchange.

3.1.5 Mobilization through technological innovation

Technical innovations in biomass feedstock supply chains can foster the mobilization of biomass. Existing and future technologies are explored for pre-treatment, improvements in planning and harvesting and biomass production.

- **Decentralized pre-treatment** upstream in the supply chain improves downstream transportability and handling of biomass. Options that are already widely applied are mechanical pre-treatment options such as chipping, pelletization, briquetting and bailing. More advanced options that change the chemical structure of biomass to provide solid, liquid or gaseous intermediates, such as torrefaction, pyrolysis and biomethane from biomass gasification respectively, could potentially drive the future commoditization of biomass. Improved energy density, grindability, and hydrophobicity and the suitability to be transported and stored using existing (fossil fuel) infrastructure could reduce the supply chain cost. Additionally, it could provide further services including the provision of flexibility, a need that results from the increased deployment of intermittent renewables (mainly wind and PV).
- **Mobile/Portable pre-treatment** options are more expensive than the decentralized systems discussed above, but provide the flexibility to process feedstocks scattered in space and time. While these technologies could significantly mobilize local and heterogenous biomass resources, their present role in biomass mobilization is limited.
- **Geographic Information Systems (GIS)** are used in a longer-term (well over one year)[3], strategic context to identify the optimal location of biomass facilities or the supply and distribution network between facilities and end users. GIS is hardly used still for tactical and operational decision support[4] because GIS still lacks the short-term and medium-term temporal dimensions. Innovations, amongst others in remote sensing data and

---

[2] Other international and partly intergovernmental information networks include the International Renewable Energy Agency (IRENA), Sustainable Energy for All (SE4ALL), REN21, International Energy Forum (IEF), Global Bioenergy Partnership (GBEP), BioFuture Platform, EurObserv'ER, European Renewable Energy Council (EREC), and the Food and Agriculture Organisation's initiative on bioenergy and food security (FAO BEFS). On a European level, the European Energy Research Alliance (EERA) plays a significant role.

[3] Time horizons in supply chain operation modelling are substantially shorter from those in strategy and policy formulation.

[4] Tactical models focus on the medium-term (multiple periods, few months) and are used for inventory planning, fleet size estimations, stock levels, harvest quantities, etc. Operational models focus on the short term (few days) and deal with daily scheduling, vehicle routing, etc. (Biromo Holo et al. 2016).

data collection by drones and on the ground could change that.
- **Next-Generation primary sources**, such as the production of lignocellulosic energy crops including perennial grasses and short rotation coppice are still low, but the technical potential is substantial (see energy crops in Figure 2). It mainly requires innovations for agricultural management. These include, for example, crop rotation intercropping, multi-purpose cropping, cropping on marginal land and precision. Additionally, the production of micro and macro-algae should be mentioned, here particularly for food and specialty products. Algae production for energy or chemical purposes is considered challenging due to high water content.
- **Next-Generation primary sinks** could further enhance biomass mobilization. These include large scale, centralized systems with BECCU and BECCS (Olsson et al. 2022). Also, more decentralized options, such as halting deforestation, afforestation, reforestation, and forest restoration have significant carbon mitigation potential. Lastly, biochar addition to soil is also mentioned as a strategy to improve water holding capacity, nutrient use efficiency, and carbon sequestration.

3.1.6 Future outlook

Sustainable feedstock supply structures are a fundamental prerequisite for fostering the European bioeconomy. What distinguishes this approach is its profound integration within primary economic sectors, setting it apart from other sustainability agendas reliant on feedstock-independent photovoltaic and wind power.

Across the span of a century, our heavy reliance on fossil fuels sourced from concentrated points, followed by large-scale and centralized refining and distribution, has imprinted a cognitive bias regarding the optimal organization of a substantial portion of our primary sectors. Unfortunately, this bias tends to illuminate the challenges rather than the abundant opportunities that emerge from a strategic realignment of our carbon supply.

The present moment demands that we address and transcend this bias by directing our attention towards the opportunities inherent in the development of a multitude of supply chains and their links. This encompasses the exploration of various possible supply chain arrangements, the branching and cascading flows of biomass feedstocks and their constituents, and the comprehensive consideration of related ecological, social, and economic dimensions.

Embarking on this journey necessitates an initial step of embracing the diversity encapsulated within both fresh and residual feedstocks. This entails an understanding of their distinct physical properties, origins, and legal statuses, which are subject to variations based on sourcing practices, seasonal fluctuations, and weather conditions. Furthermore, this diversity extends to encompass the array of stakeholders involved, woven into the fabric of decentralized, adaptable, and intricate supply networks.

The report (Schipfer et al. 2022) explores a small selection of opportunities which will be central to future studies. Taking cues from the rise of renewable energy communities, we're beginning to outline the advantages of, and challenges facing, circular Bioeconomy communities. Furthermore, the transformation of coal-mining regions will be a subject of scrutiny, exploring avenues for fossil fuel free revitalization and transition.

A core emphasis of subsequent endeavors will be the enhancement of systemic resilience of the economic metabolism, a crucial layer atop the bedrock of sustainability. This will be achieved through the development of flexible Bioeconomy networks, an area that commands special attention and will be the cornerstone of future projects.

4 Adoption of bioenergy by existing agriculture and forestry biomass feedstock suppliers in the United States

In Activity 3, Idaho National Lab (INL) evaluated the adoption of herbaceous and woody biomass supply by existing biomass feedstock suppliers including agriculture and forestry.

The study on herbaceous biomass is published elsewhere [Burli et al 2021]. The detailed study on forest biomass is published in a separate report [Hartley et al. 2023].

Highlights

The willingness of biomass feedstock producers to participate in bioenergy systems is key to the deployment of biobased value chains. Their decision-making process is, however, often influenced by numerous uncertainties and by randomness and probability due to imperfect information. An agent-based model (ABM) was used to analyze the adoption of innovative practices by forest and agriculture feedstock suppliers to deliver to the bioenergy sector. The study focused on:

- Farmer adoption of bioenergy feedstocks, considering a combination of factors such as farmer characteristics, spatial data, market structure, and social networks.
- The response of private forest landowners when faced with decisions about supplying woody material.

Herbaceous Producer Adoption
The results showed that the biggest influence on the adoption of crop residue harvest is the credibility of farmers, while media and farmer credibility significantly impact the adoption of energy crops due to their higher associated risks. Vertically integrated markets also had a positive impact on the adoption of crop residue harvesting, while media influence had the least impact. The research suggested that combining the interventions could boost the adoption rate substantially.

Woody Producer Adoption
Imperfect information available to forest landowners leads to decisions that are influenced by randomness and probability. Increased demand for solid wood products, better forest management, and consideration of urbanization and forest parcelization effects could improve the availability of woody materials for bioenergy. Results for the woody biomass case are found to be very different from the herbaceous case studies. The availability of forest residue is linked with primary forest products, and therefore highly dependent to the production of these. Alternative forest management approaches could increase forest residue availability, but the incentives to drive this behavior are yet unclear.

The adoption of innovative practices by forest and agriculture feedstock suppliers, an Agent-based model (ABM) approach

Agent based models (ABMs) are proposed as a suitable method for modeling this behavior, as they allow for the inclusion of economic and non-economic factors, heterogeneity among individuals, and an evaluation of broader system-level outcomes. The authors intend to use ABMs to examine farmer adoption of bioenergy feedstocks, considering a combination of factors such as farmer characteristics, spatial data, market structure, and social networks. They will also focus on low productive land for energy crop cultivation and high productive land for residue harvest.

An agent-based model was used to analyze the adoption of innovative practices in the bioenergy sector, focusing on farmers' participation in crop residue harvesting and energy crop cultivation. The study concluded that the biggest influence on the adoption of crop residue harvest is the credibility of farmers, while media and farmer credibility significantly impact the adoption of energy crops due to their higher associated risks. Vertically integrated markets also had a positive impact on grower adoption, while media influence had the least impact on crop residue harvesting. The research suggested potential synergies between scenarios that could boost adoption rates and promote faster growth in the bioenergy industry.

For woody biomass, its supply is tied to the production of primary products, suggesting that any increase in woody biomass for fuel will be dependent on increasing markets for primary products. The study also highlighted the potential to increase the availability of material through early management of forests, although incentives to drive this behavior remain unclear.

The study for herbaceous biomass involves a decision analysis at the farm level in a 50-county region across Nebraska (NE), Kansas (KS), and Colorado (CO) and focuses on bioenergy crop adoption using Agent-Based Modelling principles (Figure 5). The model simulates over 50 years with 2,000 farmer agents, who are stochastically generated and possess characteristics based on age, risk preferences, and innovation propensity.

The region utilized for this study was the state of Georgia (Figure 6). Georgia is part of the southeastern wood basket and approximately 64% forested, with about 24 million acres of forest land. Ownership of the forests of the state are divided among federal, state and private ownerships; with approximately 89% of the forest area held privately. The privately-owned forests are further broken down into non-industrial and industrial ownership, with 61.9% being owned by non-industrial private forest (NIPF) landowners and 38.1% held by corporate entities. Urbanization in the state is leading to an annual reduction of 55,697 acres or 0.2% of the forest acres.

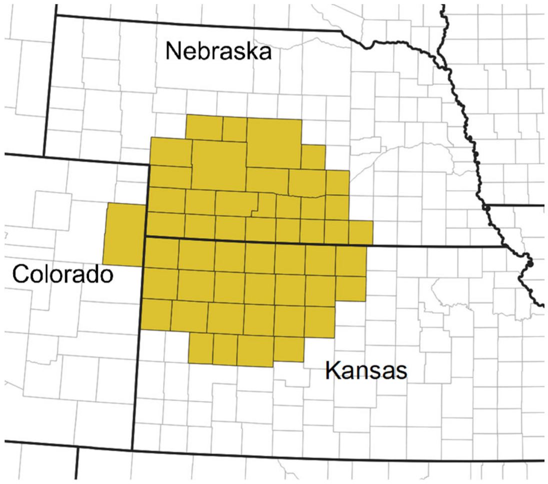

Figure 5 Study region for the analysis of herbaceous biomass encompassing 50 counties in eastern CO, southwestern NE, and northwestern KS. (Burli et al 2021).

Figure 6 Study region for the analysis of woody biomass encompassing the entire state of Georgia, USA

4.1.1 Herbaceous material from farmland, main insights

The ABM simulation for the adoption of bioenergy feedstocks by farmers, showed that several factors are important for their decision-making. Different influences were found for the adoption of crop residue harvest and the cultivation of energy crops that result from the higher risk of moving to new farming practices for energy crop cultivation and limited experience with these types of crops compared to crop residues.

Farmer's credibility had the largest impact on the adoption of crop residue harvest. Farmers mostly learn about bioenergy practices through their social networks that include multiple farmers and with the largest farms having the most impact. Also, the type of market structure was identified to influence the adoption rate. Vertically integrated structures with biorefineries directly receive feedstocks from farmers through individual purchasing contracts, provide assurance for demand and could reduce risks of these feedstock producers. In contrast, media and information dissemination did not have a significant influence, given that crop residue harvesting, and associated risks and hindrance are familiar to most farmers.

For energy crops, next to farmer's credibility, also media has a large impact on farmer adoption while market structure does not have a significant role in the adoption rate.

4.1.2 Woody biomass, main insights

Sawtimber demand is the largest determining factor of wood residue availability. When wood is harvested for sawtimber, the material that does not comply with the quality standards will become available as residues that can be used for bioenergy. This causal relationship with traditional wood products also means that the bioenergy sector hardly influences the availability of forest residues.

Another important source of wood supply could come available from small size classes within young forest stands. Entries into early stands are often considered a cost and therefore avoided by delaying harvest and precommercial thinning practices are so far only done for NIPF stands with management plans or corporate forestlands. Market demand that covers the cost of entry might be sufficient to expand precommercial thinning operations to other forests, thereby creating additional wood supply and growth benefits and added value in later stages of these forest stands.

Finally, urbanization and parcellation negatively impacts wood availability for bioenergy. Land transitions from forests to urban or suburban areas result in declining forest areas available for wood supply. Forest parcellation results in smaller forest parcels by subdivision of land. Although it does not affect total forest areas, it reduces harvest efficiency and harvest cycles because small parcel owners are less likely to harvest their forest land.

5 Conclusions

The global energy transition towards a climate neutral and circular carbon economy by 2050, creates a regional dynamic market context with new challenges and opportunities for bioenergy. Feedstock supply chains are a cornerstone for the deployment of sustainable and reliable biobased value chains. In the Regional Transitions project, experts from IEA Bioenergy Task 40 have explored possible strategies to develop these feedstock supply chains under the consideration of regional context conditions.

Scenario projections for the EU show that current bioenergy markets appear to be stagnated until 2030. However, bioenergy sectors are foreseen to grow substantially in the period beyond 2030 towards 2050 driven by emerging bioeconomy sectors including marine, aviation, chemicals, industrial heat and BECCCS. A period of latency, succeeded by a rapid growth will create multiple challenges, also for the development of national and international feedstock supply chains and related infrastructure. For example, global and EU models project a large increase in imported bioenergy commodities towards the EU, including Germany. The case study for Germany, however, provides more a picture of bioenergy being a part of the broader bioeconomy, where the focus of biomass is on the material use. National strategies confirm the shift towards high value end-use applications, but with a more nuanced role of net imports and exports of different bioeconomy products.

Similarly, the assessment of mobilization strategies for local, low-value and heterogenous biomass feedstocks confirmed that there are trade-offs between larger, more efficient markets (commodification) and smaller, less efficient markets (specialization) creating a more diverse and nuanced picture of future biomass mobilization strategies. The added value of the supply side of the bioeconomy includes, amongst others, job creation and economic activities in vulnerable regions and strengthening the resource democratic significance of rural areas. The relocation of biobased supply chains to regions with lower production costs can be avoided if the broader added value of these supply chains is considered.

Finally, the willingness of biomass feedstock producers to participate in bioenergy systems is key to the deployment of biobased value chains. Results of the ABM analysis show that the adoption of innovative practices by agriculture feedstock suppliers to deliver to the bioenergy sector is largely influenced by credibility of farmers, while media significantly impacts the adoption of energy crops due to their higher associated risks. Combining different interventions could boost the adoption rate.

References

DELIVERABLES AND REFERENCES RELATED TO THE REGIONAL TRANSITIONS PROJECT

[Burli et al. 2021]
Farmer characteristics and decision-making: A model for bioenergy crop adoption. Energy 234: 121235 https://doi.org/10.1016/j.energy.2021.121235

[Hartley and Burli 2023]
The adoption of innovative production practices by forest feedstock suppliers in the southeast of the US – An Agent-based model (ABM) approach case study for the IEA Bioenergy Task 40 Regional Transitions project. IEA Bioenergy: Task 40, August 2023.

[Schipfer et al. 2022]
Strategies for the Mobilization and Deployment of Local Low-Value, Heterogeneous Biomass Resources for a Circular Bioeconomy. Energies, 2022, 15.2: 433.

[Schmid and Hennig 2023]
Regional Transitions of Biomass Utilisation - A Case Study for Germany. IEA Bioenergy: Task 40.

OTHER REFERENCES

[Birome Holo et al 2016]
Models for optimization and performance evaluation of biomass supply chains: An Operations Research perspective." Renewable Energy 87 (2016): 977-989

[Dobravec et al. 2021]
Multilevel governance energy planning and policy: a view on local energy initiatives. Energ Sustain Soc 11, 2 (2021). https://doi.org/10.1186/s13705-020-00277-y
[EC 2019]
The European Green Deal; European Commission: Brussels, Belgium, 2019.

[EC 2021]
Commission staff working document Impact Assessment report - Accompanying the Proposal for a Directive of the European Parliament and the Council. European Commission. Brussels, 14.7.2021 SWD(2021) 621 final PART 1/2. Available at: https://eur-lex.europa.eu/resource.html?uri=cellar:0f87c682-e576-11eb-a1a5-01aa75ed71a1.0001.02/DOC_1&format=PDF

[Fritsche et al 2019]
Margin potential for a long-term sustainable wood pellet supply chain. IEA Bioenergy Task 40. Available at: https://task40.ieabioenergy.com/wp-content/uploads/sites/29/2019/05/Fritsche-et-al-2019-IEA-Bio-T40-Margin-Pellet-Study.pdf

[Fritsche et al. 2020]
Future transitions for the Bioeconomy towards Sustainable Development and a Climate-Neutral Economy - Knowledge Synthesis Final Report. Report of the Network of Experts for the JRC in the framework of the European Commission's Knowledge Centre for Bioeconomy. Fritsche, Uwe R.; Brunori, Gianluca; Chiaramonti, David; Galanakis, Charis; Matthews,

Robert; Hellweg, Stefanie & Panoutsou, Calliope. EC Joint Research Centre. Luxembourg https://doi.org/10.2760/667966

[Fritsche et al. 2021]
Future transitions for the bioeconomy towards Sustainable Development and a Climate-Neutral Economy – Foresight Scenarios for the EU bioeconomy in 2050. Report of the Network of Experts for the JRC in the framework of the European Commission's Knowledge Centre for Bioeconomy. Fritsche, Uwe R. ; Brunori, Gianluca; Chiaramonti, David; Galanakis, Charis; Matthews, Robert & Panoutsou, Calliope. EC Joint Research Centre. Borzacchiello, M.; Stoermer, E. & Avraamides, M. (eds.). Luxembourg https://doi.org/10.2760/763277

[Hoefnagels and Germer 2018]
Supply potential, suitability and status of lignocellulosic feedstocks for advanced biofuels. D2.1 Report on lignocellulosic feedstock availability, market status and suitability for RESfuels, 2018. Available at: http://www.advancefuel.eu/contents/reports/d21-report-on-lignocellulosic-feedstock-availability.pdf

[IEA 2021]
Net Zero by 2050 - A Roadmap for the Global Energy Sector. International Energy Agency Special Report. Paris https://doi.org/10.1787/c8328405-en

[IPCC 2023]
CLIMATE CHANGE 2023 Synthesis Report - Summary for Policymakers. Intergovernmental Panel on Climate Change. Geneva
https://www.ipcc.ch/report/ar6/syr/downloads/report/IPCC_AR6_SYR_SPM.pdf

[IRENA 2022]
World Energy Transitions Outlook 2022: 1.5°C Pathway. International Renewable Energy Agency. Abu Dhabi https://www.irena.org/-/media/Files/IRENA/Agency/Publication/2022/Mar/IRENA_World_Energy_Transitions_Outlook_2022.pdf

[Junginger et al. 2019]
The future of biomass and bioenergy deployment and trade: a synthesis of 15 years IEA Bioenergy Task 40 on sustainable bioenergy trade. Biofuels, Bioproducts and Biorefining, 2019, 13.2: 247-266.

[Lamers, et al. (ed.) 2016]
Developing the global bioeconomy: technical, market, and environmental lessons from bioenergy. Academic Press, 2016.

[Majer et al. 2023]
Approaches to sustainability compliance and verification for forest biomass. IEA Bioenergy: Task 45. https://task45.ieabioenergy.com/wp-content/uploads/sites/13/2023/05/IEA-Bioenergy-T45-project-report-compliance-and-verification.pdf

[Mandley et al. 2020]
EU bioenergy development to 2050. Renewable and sustainable energy reviews, 2020, 127: 109858.

[Mandley et al. 2022]
EU bioenergy supply-chain projections to 2050 using a multi-model framework. Submitted (2022) to Biomass and Bioenergy. Preprint available via SSRN: http://dx.doi.org/10.2139/ssrn.4223426

[Matzenberger et al. 2015]
Future perspectives of international bioenergy trade. Renewable and Sustainable Energy Reviews, 2015, 43: 926-941.

[Olsson et al. 2021]
Decarbonizing industrial process heat: the role of biomass A report for the IEA Bioenergy Inter-task project on industrial process heat. IEA Bioenergy: Task 40. December 2021. Available at: https://www.ieabioenergy.com/wp-content/uploads/2022/02/Role-of-biomass-in-industrial-heat.pdf

[Olsson et al. 2022]
Deployment of BECCUS value chains: From concept to commercialization - Synthesis Report. IEA Bioenergy: Task 40, 36, 44 & 45 November 2022. Available at: https://www.ieabioenergy.com/wp-content/uploads/2023/03/Synthesis-BECCUS-1.0-report_final_update.pdf

[Schipfer et al. 2020]
The European Wood Pellets for Heating Market - Price Developments, Trade and Market Efficiency. Energy 2020, 212, 118636.

[SER 2020]
Biomass in the balance - A sustainability framework for high-value use of bio-based raw materials. Social and Economic Council of the Netherlands (SER), July 2020. Available at: https://www.ser.nl/-/media/ser/downloads/engels/2020/biomass-in-the-balance.pdf

[Thrän et al. 2020]
Roles of bioenergy in energy system pathways towards a "well-below-2-degrees-Celsius (WB2)" world: Workshop report and synthesis of presented studies. A strategic inter-task study carried out with cooperation between. IEA bioenergy tasks, 2020, 40: 44-45. Available at: https://www.ieabioenergy.com/wp-content/uploads/2020/07/Roles-of-bioenergy-in-energy-system-pathways-towards-a-WB2-world-Workshop-Report.pdf[van Dam and Ugarte 2022]
Improvement opportunities for policies and certification schemes promoting sustainable biofuels with low GHG emissions Part 1: A review of policy frameworks. SQ Consult for IEA Bioenergy: Task 39 https://task39.ieabioenergy.com/wp-content/uploads/sites/37/2023/01/Improvement-opportunities-for-policies-and-certification-schemes-promoting-sustainable-biofuels-with-low-GHG-emissions-1.pdf

IEA Bioenergy

Technology Collaboration Programme