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Opportunities and Challenges of the European Green Deal for the Chemical Industry: An Approach Measuring Innovations in Bioeconomy

Lisa Thormann, Ulf Neuling * and Martin Kaltschmitt

Institute of Environmental Technology and Energy Economics, Hamburg University of Technology, 21073 Hamburg, Germany; Thormann.lisa@gmail.com (L.T.); Kaltschmitt@tuhh.de (M.K.)
* Correspondence: ulf.neuling@tuhh.de

Abstract: The Circular Economy Action Plan, as part of the European Green Deal announced by the European Commission, is highly relevant to the chemical industry in relation to the production of sustainable products. Accordingly, the chemical industry faces the question of how far it can promote its own manufacture of sustainable products. Within this context, this article presents an approach on how to measure innovations in bioeconomy. The methodological framework developed provides the chemical industry with an approach to assess the effectiveness of innovative conversion technologies producing biogenic intermediate products (e.g., bulk chemicals). The innovations within the bioeconomy (TRL > 4; TRL—technology readiness level) are compared in terms of technical, economic, and environmental indicators for the current status, for the medium- and long-term as well as for different production sites. The methodological approach developed here is exemplarily applied, assessing the production of intermediate biogenic products via thermo-chemical conversion of lignocellulosic biomass. The results show the successful applicability of the developed assessment approach as well as significant differences in efficiency, costs, and environmental impact, both from the perspective of time and in spatial terms within the European Union. Thus, the methodological approach developed and presented enables the chemical industry to reduce challenges and to take advantage of the opportunities arising from the transition to a climate-neutral and circular economy.

Keywords: thermo-chemical conversion; pyrolysis; gasification; lignocellulosic biomass; biogenic intermediate chemical products; bioeconomy; spatial and temporal methodological approach; technology readiness level; European Green Deal

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1. Introduction

Europe is committed to become a world leader in a resource-efficient and sustainable economy by 2030 and beyond. In December 2019, the European Commission published a roadmap with measures to fulfil this concept, known as the European Green Deal. It outlines investments needed and financing tools available, and explains how to ensure an inclusive transition to boost the efficient use of (limited natural) resources by moving to a clean, circular economy as well as to restore biodiversity and cut pollution to reach the goal of a climate neutral European Union by 2050 [1]. To bring these overarching goals into force, the European Commission has developed a roadmap that gives an overview of the actions of the European Green Deal to be defined by 2021.

The Circular Economy Action Plan, relevant for the chemical industry, was already published in March 2020 as one of the actions of the roadmap. The aim of this Action Plan is to produce sustainable products, with particular focus on resource-intensive sectors such as textiles, construction, electronics, and plastics [2]. Accordingly, the chemical industry is faced with the questions of (i) how far it can promote its own manufacture of sustainable products and (ii) what effects circularity has on the respective product demand of the various types of customers (e.g., textile, construction, electronics, and plastics).

The chemical industry has an important role to play in the climate debate: (i) chemical products are essential for many low-carbon technologies, e.g., renewable energy, housing, and mobility; (ii) chemistry is needed to develop resilient materials, e.g., adapted to harsher weather conditions; and (iii) chemical production is energy and CO_2 intensive. For this reason, the chemical industry is classified as “difficult to reduce.” In this context, this article focuses on the development of an assessment methodology to answer the first question. Explicitly, three things need to happen for the chemical industry: (i) increasing production of sustainable products that are already being produced while decreasing the production of non-sustainable products; (ii) developing new types of sustainable products; and (iii) deploying these new types of sustainable products at a large scale.

Regarding the production of sustainable products, the focus is essentially on the supply of biogenic (bulk) chemicals as a raw material input for the provision of further processed products provided by the chemical industry. The European Chemical Industry Council’s (CEFIC) categorization differentiates between four categories of chemicals: (i) basic inorganics; (ii) consumer chemicals; (iii) polymers; and (iv) specialty chemicals. This leads to the main questions of this article: How can the provision of (bulk) chemicals retrieved from sustainable biogenic resources for the chemical industry as input material be assessed? The results for different plant locations in the EU are compared and evaluated regarding their current status as well as for the medium- and long-term.

Already in 2018, the European Commission developed the European Bioeconomy Strategy to establish a more innovative and low-emission economy that reconciles the sustainable use of renewable biological resources and materials for industrial purposes with the preservation of biological diversity and environmental protection [3]. In view of this European Bioeconomy Strategy and the European Green Deal, the possibilities of using and providing (bulk) chemicals of biogenic origin for the chemical industry need to be analyzed. Biomass-based chemicals can supplement or replace fossil fuel-based chemicals within the overall production chain. The use of biomass-derived chemicals in industry requires biogenic feedstock to be produced, supplied, pre-treated, and converted. To enable the chemical industry to use biomass as a raw material in a most efficient way, the organic matter is converted, e.g., into liquid intermediates, and further processed in refineries. The respective new technologies and processes aim to meet the following criteria: (i) renewability; (ii) saving resources of fossil fuel energy; (iii) decreasing the environmental impact; and (iv) improving productivity and sustainability. The respective innovations to be realized within the relevant bioeconomy industries are conceivable and should therefore be methodologically accessible [4]. The methodical approach of this work is based on a technical–economic–environmental assessment.

The demand for non-fossil alternatives for (bulk) chemicals, materials, and energy, as well as for selected services, is increasing rapidly to meet the European Green Deal mentioned above. Because of the growing demand for biomass-based (bulk) chemicals, the demand for the world’s limited agricultural land increases as new agricultural areas are needed. Additionally, several of the currently utilized crops for bioenergy provision can also be used to feed the global population, thus leading to a competing situation between food/feed production and biomass-based chemical production; one consequence is an effect on the prices for agricultural commodities. Lignocellulosic biomass offers an alternative to avoid competition with food and/or feed production. Usually, agricultural food crops gain (very) low yields on degraded or marginal land (e.g., land with an overall low productivity caused by climatic, edaphic, and/or anthropogenic conditions). Nevertheless, a variety of selected types of lignocellulosic biomass of woody and herbaceous origin have the ability to be grown on land that is poorly suitable for agricultural food crops [5,6], even though the hectare-specific yield is most likely quite low and thus the specific provision costs are relatively high. Nevertheless, the use of lignocellulosic biomass, i.e., (i) grown as energy crops on degraded or marginal land or (ii) collected from agricultural and forestry residues, is a viable option for the sustainable production of intermediate biogenic products within the European Union as well as on a global scale. This is true because the potentials of these resources are a priori limited.

In order to use lignocellulosic biomass on a commercial scale for biogenic (bulk) chemical production, a shift to advanced conversion technologies is needed [6]. Figure 1 displays the basic pathways of thermo-chemical and bio-chemical lignocellulosic biomass conversion into intermediate biogenic products for the chemical industry.

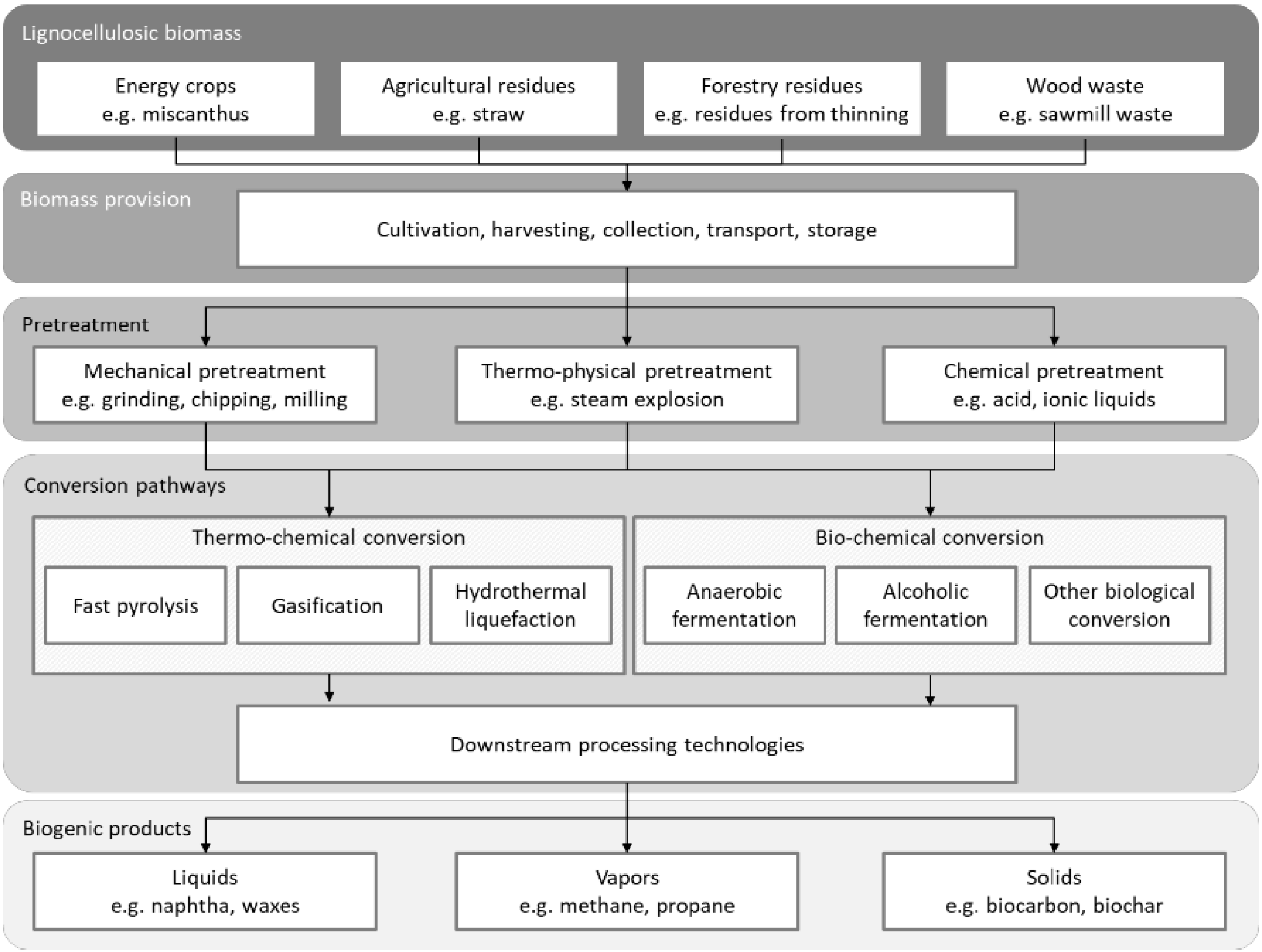


Figure 1. Selected pathways of thermo-chemical and bio-chemical lignocellulosic biomass conversion.

The developed methodology aims to provide a perspective for the future. The current status is compared with the medium-term (2030) and long-term (2045) developments within the EU-28. The thermo-chemical conversion pathways that have been exemplary evaluated are pyrolysis and gasification. The countries where the plants are located are in northern Europe, central Europe, and southern Europe, i.e., Sweden, Germany, and Spain.

2. Materials and Methods

Figure 2 provides a simplified illustration of the developed assessment methodology for innovations within the bioeconomy. In the first step, a baseline evaluation is carried out, covering biomass supply, logistics, and technical characterization of the selected conversion routes. In the subsequent second step, an economic and environmental assessment with regard to the production of intermediate biogenic materials for the chemical industry is conducted. These various steps are presented in detail below.

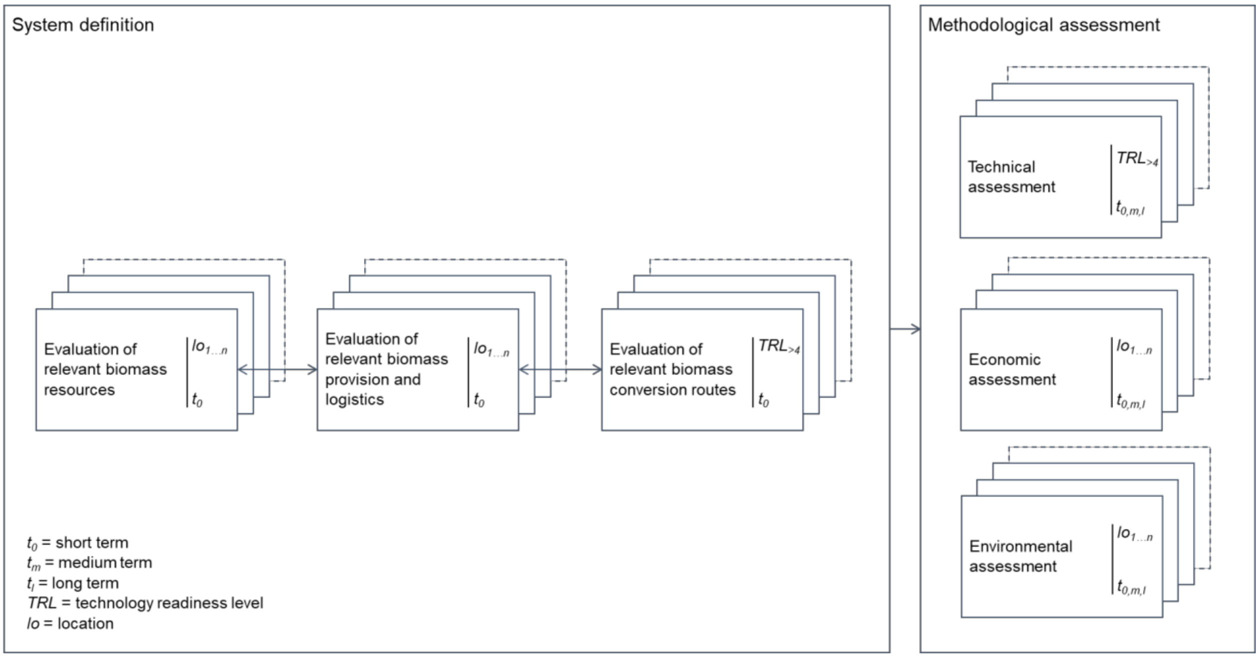


Figure 2. Simplified illustration of the methodological approach to the spatial and temporal evaluation and assessment of innovations in the bioeconomy.

2.1. *Framework for the Assessment*

The assessment of innovations in the bioeconomy depends, on the one hand, on a specified system definition including behavior at functional system boundaries and, on the other hand, on the treatment of scaling effects in the sense of deviations or necessary adjustments in the specification. The proposed innovation assessment considers these two aspects. A specification framework is introduced that allows for an explicit definition and derivation of possible functional system boundaries. This chapter describes the areas of biomass resources, provision, and logistics, as well as biomass conversion pathways.

For the presentation of the results, different plant locations within the European Union (EU) at different time horizons are considered. In the presentation of the system definition, a distinction is therefore made between constant and variable parameters in terms of spatial variance. Furthermore, a distinction is made as to whether the influencing variables are exogenous or endogenous. Figure 3 illustrates schematically some of the exogenous and endogenous variables. A detailed list of the variables can be found in the Supplementary Materials in Section S.1.1.

2.1.1. Evaluation of Relevant Biomass Resources

System Definition and Identification of System Boundaries

With regard to the sustainable use of resources, only residual lignocellulosic biomass or biomass grown on non-arable land is theoretically available as a raw material for the chemical industry. The main criterion considered for the selection of such lignocellulosic feedstock is the available technical potential for different types of lignocellulosic biomass resources in the selected regions: (i) forest residues; (ii) agricultural crop residues; and (iii) energy crops [7]. The technical potential assesses the available biomass feedstock under techno-structural framework conditions and under the state-of-the-art of technical possibilities [8].

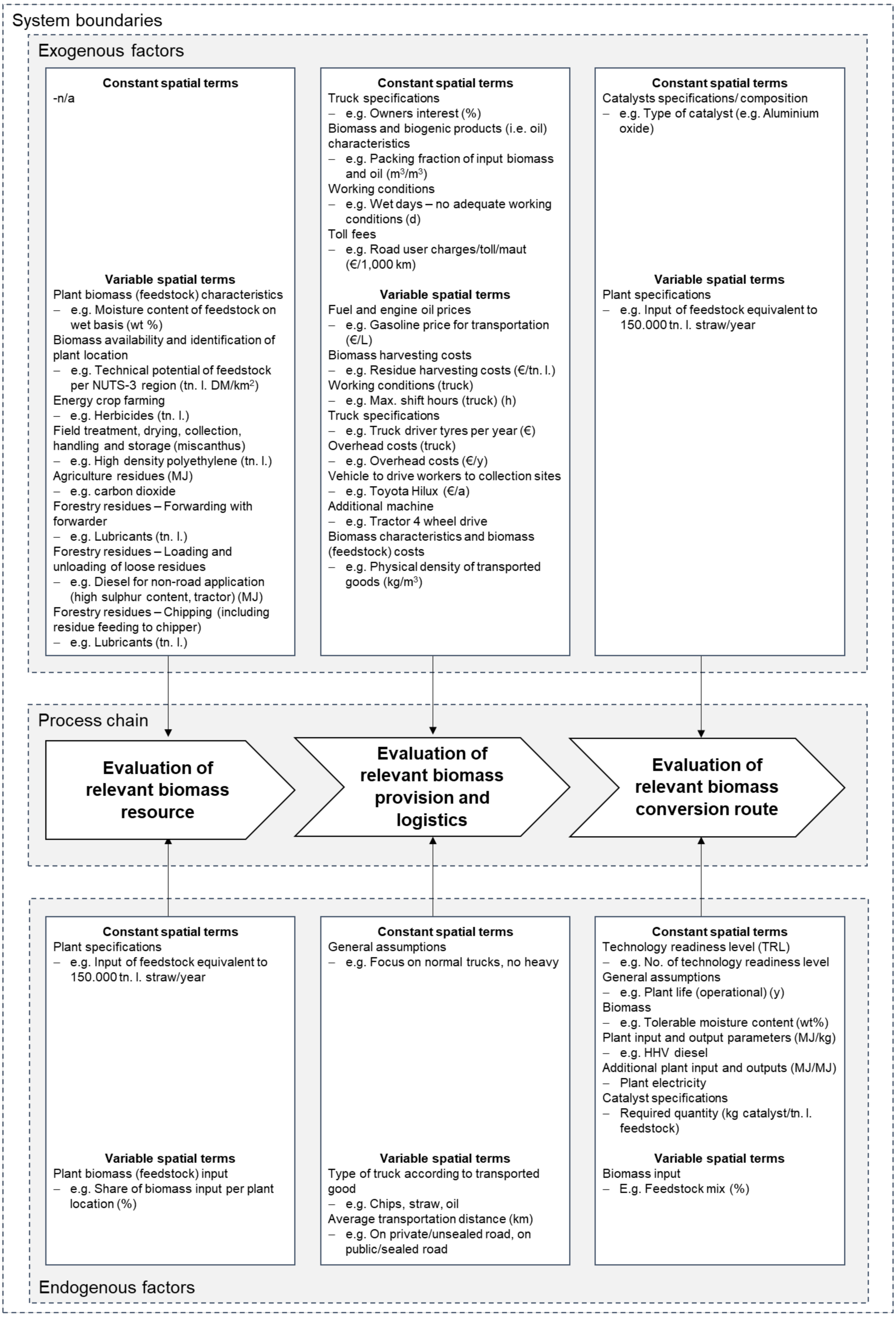


Figure 3. Simplified illustration of the exogenous and endogenous factors relevant for the processing chain.

Adequate characterization of the feedstock in order to determine the best possible conversion strategy (e.g., thermo-chemical conversion, biochemical conversion) becomes decisive. Thus, for an assessment of these biomass resources (technical potentials), the biomass composition is essential. This is true because the structural and chemical composition of the lignocellulosic feedstock notably influences the efficiency of the respective conversion process [9–11]. Thus, due to strong regional variation, the biomass resources need to be evaluated by the technical potential of the respective type of lignocellulosic feedstock per region. Moreover, the most suitable location for the respective conversion plant needs to be identified region-wise due to economic constraints related to long-distance transport. In addition, a further distinction can be made between the feedstock density (e.g., energy and physical density) and the moisture content; both characteristic values are equally relevant for biomass logistics and biomass conversion processes. Table S1 in the Supplementary Materials shows the applied variables according to their categorization.

Data Basis

The European Commission developed a categorization, where each European country is divided into so-called NUTS-3 regions; this is a nomenclature of territorial units for statistics. According to the technical biomass potential, a ranking can be made to identify suitable regions in the EU as possible locations for such biomass conversion plants. For suitable regions, the biomass resources to be included in such an assessment might be chosen as required (e.g., depending on the biomass actually produced or politically controlled availability).

The technical biomass potential to be used for the assessment carried out here is based on data provided by Dees et al. (2016) [12]. Equation (1) displays the basic principles of this approach. Subsequently, the area-specific amount of biomass input per type of biomass is assessed based on the share of each of the three types of lignocellulosic feedstock (*LF*) (i.e., forestry residues (*FR*), agricultural residues (*AR*), and energy crops (*EC*)). The result is available in energy per square kilometer.

$$LF_{NUTS\text{-}3} = \sum FR_{1,2,\ldots n} + \sum AR_{1,2,\ldots n;} + \sum EC_{1,2,\ldots n} \quad (1)$$

Once the NUTS-3 region with the highest technical potential of lignocellulosic feedstock is identified, it is assumed that the NUTS-3 regions are of circular shape and that the conversion plant is located in the center of the respective region.

2.1.2. Evaluation of Relevant Biomass Provision and Logistics

System Definition and Identification of System Boundaries

Independent from the biomass properties, different modes of transportation are available for feedstock transportation (i.e., tractor, truck, train, ship). Based on the size of the plant as well as on the transportation distance and the local conditions, the most suitable mode of transportation is chosen. The modal split of freight transportation on land within the EU is dominated by the mode of transportation. The share of road transportation varies between 70.6% and 94.1%, depending on the respective region [13]. For economic reasons, the most common mode of transportation for a distance between 0 to 100 km is transportation by truck (mainly due to loading and unloading costs) [14] (further details on biomass provision are described in the Supplementary Materials Section S.1.2).

Therefore, the methodology developed here calculates the transportation costs of the different types of biomass for truck transportation. The respective principles of biomass provision and logistics are presented in Figure 4. Thus, the biomass is collected at three collection sites and then transported to the conversion plant and, if needed, additionally to subsequent downstream processing plants. Three collection sites are assumed, as the amount of available biomass in relation to the area is considered sufficient by European standards. Relevant parameters for biomass provision and logistics are (i) mode of transportation; (ii) transportation distance; and (iii) transportation costs.

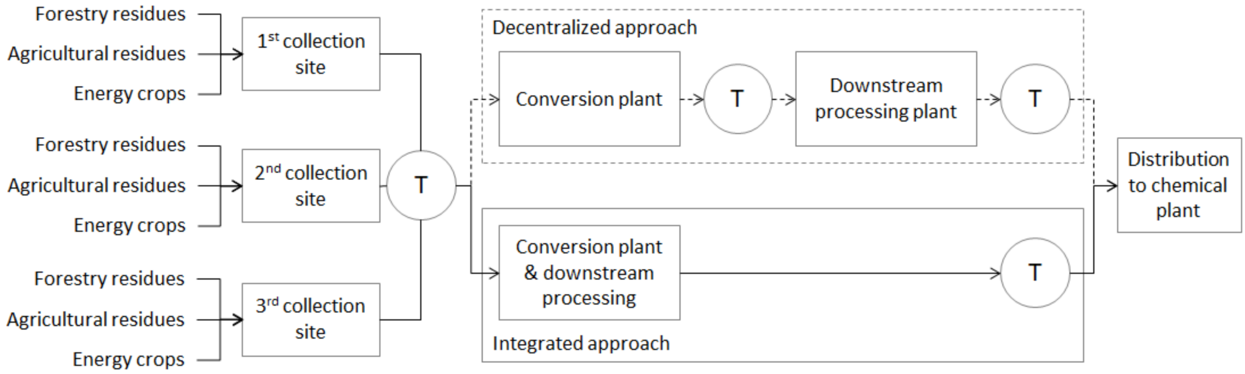


Figure 4. Model flowchart of the transportation of feedstock and intermediate products for fuel production from lignocellulose, T = transportation.

Biomass reception, storage, and handling is highly dependent on the type of feedstock employed. The biomass characteristics relevant to the type of use are:

(i) the chemical raw material properties (e.g., chemical composition, content of biogenic material, amount of trace elements, and water content, as well as chemical stability);
(ii) the physical raw material properties (e.g., quantity, density, ash content, particle size);
(iii) other raw material properties (e.g., origin, yield, seasonal availability, availability against competing uses, harvest time, transportation capacity, ease of transport, suitability for storage, storage stability, long term quality, technical suitability) [15].

Two transportation routes or distances have to be determined. First, the transportation from the feedstock source to the conversion plant needs to be identified and, second, the route from the conversion plant to the chemical plant has to be determined. Table S2 in the Supplementary Materials shows the applied variables according to their categorization.

Data Basis

A variety of aspects influence the analysis of the transportation distances, including (i) actual feedstock availability, e.g., on a monthly basis; (ii) local topography; and (iii) road infrastructure, as well as network. Thus, it is challenging to apply a generic approach for the assessment of the transportation distance. Accordingly, a general approach is applied in the methodology. Therefore, the following assumptions have been made [16,17]:

- Feedstock availability is evenly distributed over a circular feed supply area (e.g., NUTS-3 region);
- The conversion plant is located centrally within the respective region (i.e., to minimize the total direct distance from all of the feed sources to the conversion plant);
- Where multiple conversion plants are located in one catchment area (i.e., feed supply area), the location of each conversion plant will be the centroid of the sector that supplies it with the feedstock;
- The road infrastructure and network is ordinary to allow the use of a single winding factor to assess the actual distance from between feedstock source and conversion plant based on the direct distance between source and conversion plant (e.g., radius).

The catchment area, A, of the feedstock supply area is derived from Equation (2). This catchment area providing the feedstock sources is influenced by a land area limitation to take into account the fact that 5% of the total land area of the catchment area is, e.g., not accessible [18]. For the calculation, the necessary quantities of feedstock (quantity; i.e., input of feedstock required for all conversion plants in the catchment area) are taken into account. This is also true for the available yields of forestry residues (Y_{FR} yield of forestry residues), agricultural residues (Y_{AR} yield of agricultural residues), and energy crops (Y_{EC}

yield of energy crops). The availability of the respective biomass is taken into account using the availability factor (*a* availability factor).

$$A = \frac{Q_{in}}{Y_{FR}\ a + Y_{AR}\ a + Y_{EC}\ a} \quad (2)$$

To determine the mean direct transportation distance, *D*, from the conversion plant to the feedstock sources, the radius, *r*, is calculated based on the catchment area, *A*, using standard sector geometry. Equation (3) is based on a regression analysis from Bridgwater et al. (2002) [17], calculating the distances for systems with 1 to 10 conversion plants. However, the actual distance traveled between the feedstock source and the conversion plant is higher than the direct distance due to the existing road infrastructure and network. Thus, a so-called winding factor is applied. Here, a winding factor, *w*, of $\sqrt{2}$ is assumed to be suitable for European plant locations [17].

$$D = r\ w \quad (3)$$

Furthermore, the distance for trucks from the collection site to the highway (per one-way trip) (D_{US} indicates the transportation distance on an unsealed road (*US*)) is calculated based on Equation (4).

$$D_{us} = D\ US \quad (4)$$

The overall transportation costs, *T*, are defined based on the transportation distance, *D*, and the specific costs for transportation, *P*, and handling, *H* (Equation (5)) [19,20].

$$T = D\ P + H \quad (5)$$

The price per kilometer and gross ton includes (i) truck type, (ii) truck payload, (iii) fuel costs and usage, (iv) truck capital expenditures, (v) truck operating expenses, (vi) driver costs, (vii) road user charges, and (viii) load and unload times, as well as (ix) road type. The type of trucks that are chosen to transport the feedstock depend on the type of feedstock being transported. Forestry residues are transported from the central collection sites to the conversion plant by chip trucks, and agricultural residues and energy crops are transported by straw trucks. The use of a bin truck for forestry residues and herbaceous biomass can also be considered if the biomass is not packed ideally.

2.1.3. Evaluation of Relevant Biomass Conversion Routes

System Definition and Identification of System Boundaries

The technology readiness level (TRL) is used to select suitable technologies for the bioeconomy with the aim of enabling an evaluation of innovations for the processing from biomass as early as possible. Technology readiness levels (TRLs) are used to quantify the technical maturity of a specific technology. A mature technology corresponds to the highest level [21,22]. The nine TRA levels are characterized, as indicated in Table 1.

Table 1. Technology readiness level (TRL) definitions and qualifying criteria [23].

Level	Definition	Qualifying Criteria
1	Observation and reporting of fundamental principles	Peer-reviewed publication of research relevant to the proposed concept/application
2	Formulation of technology concept and application	Documented description of the application concept addressing feasibility and benefit
3	Analytical and experimental critical function and characteristic verification of concept	Documented analytical and experimental results validating predictions of key performance parameters

Table 1. *Cont.*

Level	Definition	Qualifying Criteria
4	Component and breadboard proof in a laboratory environment	Documented test performance demonstrating consensus with analytical predictions; documented definition of relevant environment
5	Component and breadboard proof in relevant environment	Documented test performance demonstrating consensus with analytical predictions; documented definition of scaling requirements
6	System/sub-system model or prototype demonstration in an operational environment	Documented test performance demonstrating consensus with analytical predictions
7	System prototype demonstration in an operational environment	Documented test performance demonstrating consensus with analytical predictions
8	Actual system completed and qualified through test and demonstration	Documented test performance verifying analytical predictions
9	Actual system proven through successful operations	Documented operational results

Technologies from TRL 4 (laboratory validated) and above can basically apply the methodology for assessing technologies in bioeconomies in the field of chemical production.

Data Basis

With regard to the data basis, a distinction is made between the process steps of the thermo-chemical conversion processes (i) pretreatment, (ii) thermo-chemical conversion, and (iii) downstream processing. The distinction between the three conversion steps is illustrated using the examples of fast pyrolysis and gasification (Figure 5).

In order for the conversion path to be evaluated using the presented methodology, the individual process steps and the process as an entirety have to comply with TRA 4. Table S3 in the Supplementary Materials shows the applied variables according to their categorization.

2.2. *Assessment Methods*

Below, the assessment procedure is discussed in detail. This includes technical, economic, and environmental aspects.

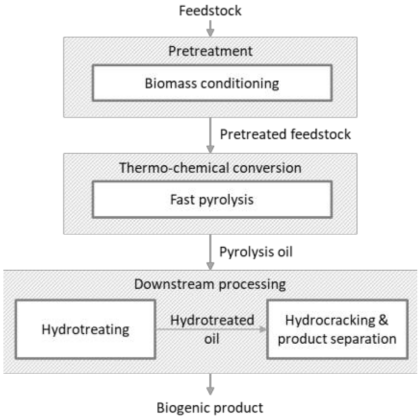
2.2.1. Technical Assessment

Key Performance Indicators

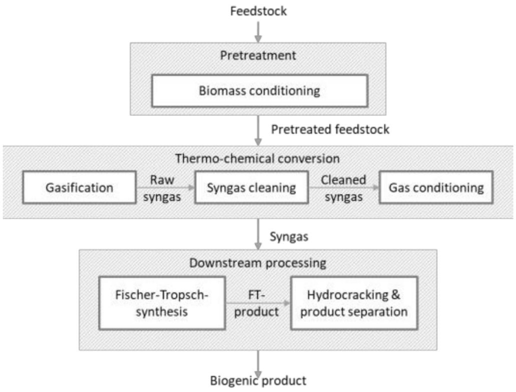
The reference values for the technical characterization of the processes are (i) utilization ratio ($\tilde{\eta}$) and (ii) mean energy efficiency ($\tilde{\omega}$).These two characteristic values are defined as shown in Equations (6) and (7) ($\tilde{\eta}$, utilization ratio; $\tilde{\omega}$, energy efficiency; E_{MP}, energy content of the main product *MP*; E_{CP}, energy content of the co-product *CP*; E_R, energy content of the resource *R*; E_{AM}, energy content of the auxiliary materials *AM*; E_{AE}, energy content of the auxiliary energy *AE*).

$$\tilde{\eta} = \frac{E_{MP}}{E_R + E_{AM} + E_{AE}} \quad (6)$$

$$\tilde{\omega} = \frac{E_{MP} + E_{CP}}{E_R + E_{AM} + E_{AE}} \quad (7)$$



(**a**)



(**b**)

Figure 5. Model flowchart of the thermo-chemical conversion processes for (**a**) fast pyrolysis and (**b**) gasification.

Based on these values, the mass balance (i.e., yield, conversion rate, and selectivity) as well as the energy balance (i.e., energy efficiency) can be assessed, as presented below.

Mass balancing aims to assess all mass flows within defined system boundaries or selected process steps. Such a general mass balance of a system is presented in Equation (8) (m_i mass crossing the balance boundaries during a standardized period of observation coming in I; m_o, mass crossing the balance boundaries during a standardized period of observation coming out o; m_l, mass losses l) [24].

$$\sum m_i = \sum m_o + \sum m_l \tag{8}$$

The yield of a product describes the correlation between the output of a conversion process and the maximum mass of product that can be gained from an educt (stoichiometry-based). This is shown in Equation (9) (Y_i, yield of a product i; n_i, mass of a product i after process; $n_{i,0}$, mass of a product i prior to process; $n_{i,j}$, maximum mass of a product I from educt j) [24].

$$Y_i = \frac{n_i - n_{i,0}}{n_{j,i}} \tag{9}$$

The conversion rate of a process can be defined by the ratio of the educt prior to and after the conversion process (Equation (10)) (X_i, conversion rate of a product i; n_i, mass of an educt i after process; $n_{i,0}$, mass of an educt i prior to process) [25].

$$X_i = \frac{n_{i,0} - n_i}{n_{i,0}} \tag{10}$$

The selectivity defines the ratio of the yield of a product limited by its maximum conversion rate (Equation (11)) ($S_{j,i}$, selectivity of a product i and the maximum conversion rate of educt j; Y_i, yield of a product i; X_j, conversion rate of an educt j) [26].

$$S_{j,i} = \frac{Y_i}{X_i} \tag{11}$$

The production of by-products, e.g., steam, electricity, are either used within the plant concepts or, e.g., fed into the local grid as electricity credit in case of surpluses.

Methods for Forecasting

The assessment of the development of future conversion processes for lignocellulosic biomass is based on the approach of technical trajectories. For most technologies/processes that are applicable, a maximum degree of maturity can (and will mostly) be reached. In spite of their individual variances, technologies tend to follow analogue technical trajectories. This implies, first, the rate and direction of change and improvement (i.e., from initial innovation to maturity), and second, the market development (i.e., from introduction to saturation) [27]. In Figure 6, a typical saturation curve of a technology is displayed.

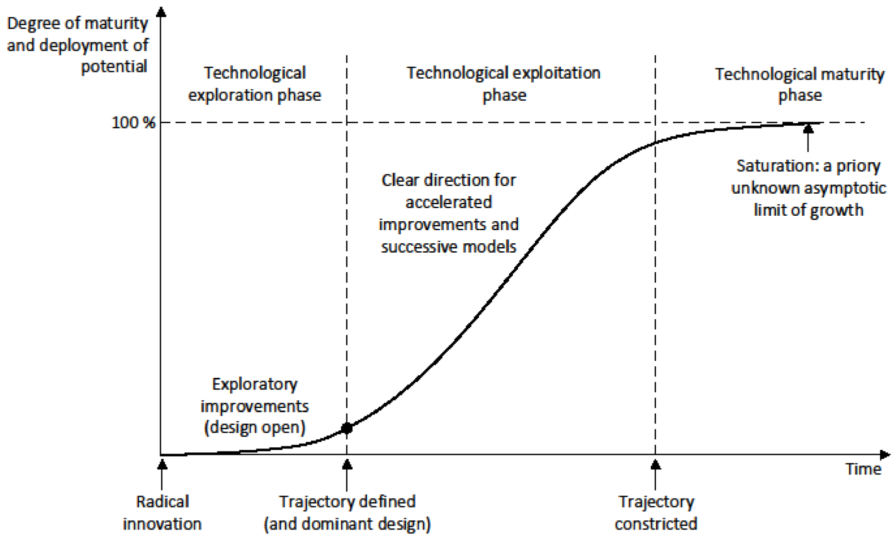


Figure 6. The trajectory of an individual technology, modified as per [27–29].

Apart from the indicators described previously, several other aspects need to be considered (e.g., competitive technologies, political framework, subsidies). For the development of a conceptual model for the technical forecasting, the approach of a technical trajectory supplemented by expert judgment is applied. To calculate the inflection or saturation point, Equation (12) is applied: $f(x)$, growing variable in question; a, b, parameters that need to be defined empirically; c, asymptotic limit of growth, i.e., maximum stock, saturation, carrying capacity; t, time).

$$f(x) = \frac{c}{1 + a\,e^{-b\,t}} \tag{12}$$

Equation (14) represents curves that are based on (i) regression analysis, (ii) non linearity, (iii) least square regression to gain a curve (equation) to follow the general trend of the data. Any forecasting with the S-curve tool is not a precise prediction of the future; it is rather a tool to understand how future technologies might develop. The logistic function displays the initial exponential growth until reaching the upper asymptote (i.e., maximum conversion rate) [30–32].

In addition, Figure 7 shows the basic methodology for determining future technical parameters such as, e.g., conversion efficiency. The key performance indicator identified for the conversion of lignocellulosic biomass is the utilization ratio of the plant. In this regard, the conversion efficiency is approximated to the theoretical maximum conversion efficiency with regard to future developments, and the results are accordingly given in a potential technical corridor in the medium- and long-term.

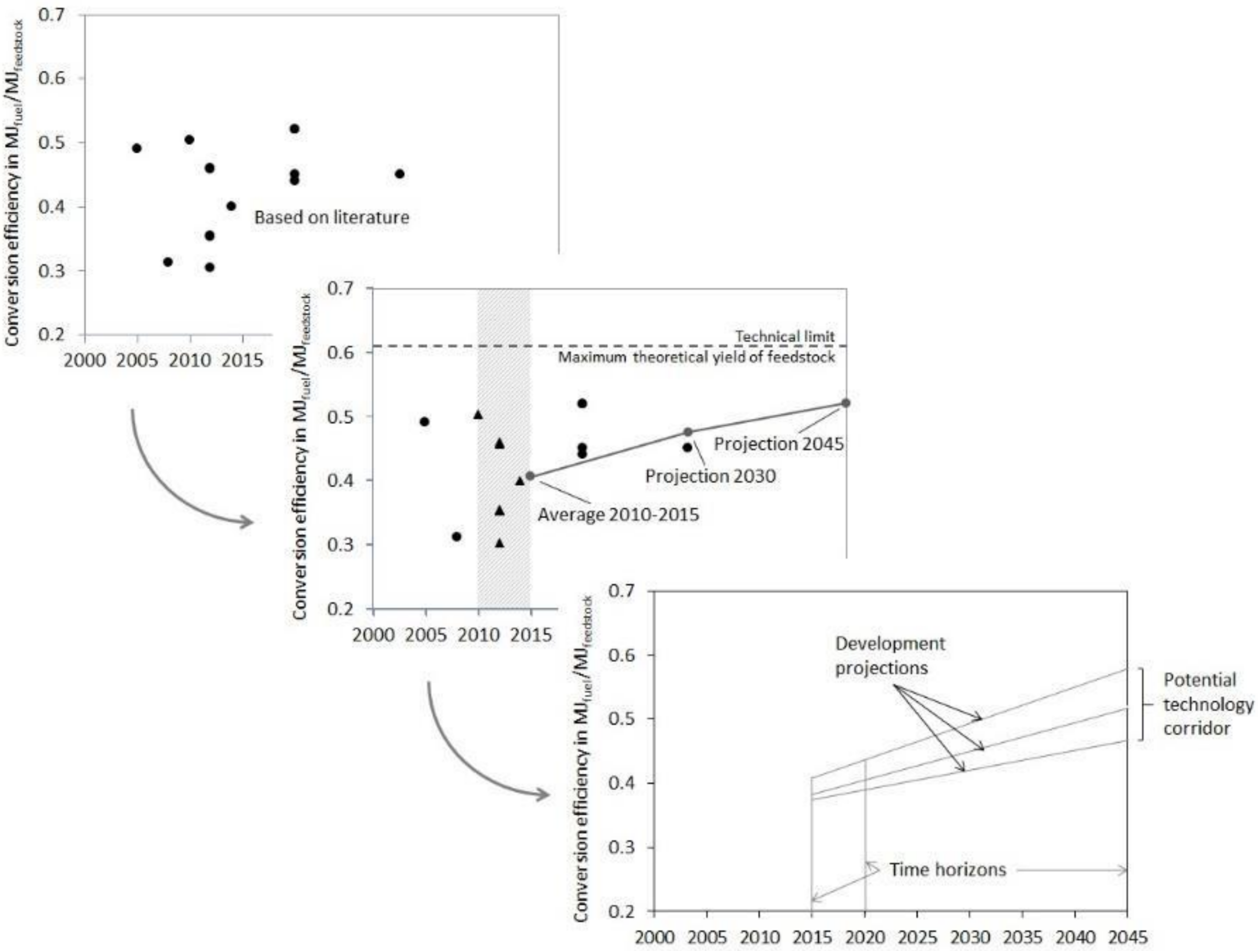


Figure 7. Schematic diagram of the procedure for the creation of development projections.

2.2.2. Economic Assessment

Key Performance Indicators

For the economic assessment and comparison of the concepts, specific costs (i.e., depending on the functional unit) are determined. The annuity methodology based on VDI 2067 is applied to calculate the process economics. The economic assessment takes four main cost groups into consideration [33]:

- Capital-related costs (e.g., technical and structural installation, noise protection, and thermal insulation measures and utility connection costs):
- Demand-related costs (e.g., energy costs, costs for operating materials);
- Operation-related costs (e.g., cleaning, servicing, inspection, maintenance);
- Miscellaneous costs (e.g., planning costs, insurance, taxes, administration costs).

For assessing the plant economics, the functional unit is defined as specific cost (i.e., fuel production costs). To carry out a comparison of the plant, a fixed reference value such as fuel production costs need to be defined (C_C, specific costs, e.g., fuel production costs per unit; A_C, annuity of capital-related costs; A_D, annuity of demand-related costs; A_O, annuity of operation-related costs; A_M, annuity of miscellaneous costs; v, reference value, e.g., annual production) (Equation (15)).

$$C_C = \frac{A_C + A_D + A_O + A_M}{v} \tag{13}$$

Capital-related costs are assessed based on the equipment costs (Equation (16)), the annuity factor (Equation (17)), and the installation factor (A_C, annuity of capital-related costs; I_0, equipment cost investment (base year, e.g., current status); f_a, annuity factor; f_i, installation factor as percentage of the equipment cost investment) (Equation (18)).

$$A_C = I_0\, f_a + I_0 \left(1 + \sum_{i=1}^{n} f_i\right) \tag{14}$$

Accordingly, the equipment costs are defined as shown in Equation (17) (I_0, equipment cost investment (base year, e.g., current status perspective); I_{IPS}, investment costs of the main installed plant sections $_{IPS}$; f_i, installation factor as a percentage of the equipment cost investment) [34].

$$I_0 = I_{IPS} \left(1 + \sum_{i=1}^{n} f_i\right) \tag{15}$$

If 100% of the costs are depreciated, no salvage value can be considered for the equipment costs. This is also a reasonable assumption because most of the equipment is designed for a specific application and thus cannot be used elsewhere without prior modification [35]. The annuity factor describes the even distribution of the capital costs over the operating life period of the plant (f_a, annuity factor; I, interest rate; n, plant life in years) (Equation (18)).

$$f_a = \frac{(1+i)^n\, i}{(1+i)^n - 1} \tag{16}$$

The original purchased equipment costs in the base year reflect the costs for a specific equipment size. The equipment sizes of the original equipment may vary depending on the equipment size of the developed processes and, thus, it needs adjustment. In addition, exponential scaling is applied to adapt the scale-up equipment costs (SEC). The original (base) cost for the equipment purchased reflects the base case for the equipment size and cost year. The equipment sizes required for the process may differ from the original base case, requiring an adjustment to the equipment cost. Instead of re-evaluating the equipment after minor changes in size, exponential scaling is applied to adjust the purchased equipment cost by using Equation (17) (BEC, base equipment cost; SC, scale-up capacity; BC, base capacity). The scaling exponent, n, is typically in the range of 0.6 to 0.7 [36].

$$SEC = BEC \left(\frac{SC}{BC}\right)^n \tag{17}$$

If the necessary cost data are not available, costs were calculated with the Chemical Engineering Plant Cost Index (CEPCI) ($I_{0,C,t}$, equipment costs investment of capacity C in year t; I_{0,C_0,t_0}, equipment costs investment of capacity, C_0, in base year t_0; d, scaling exponent; a_t, price index in year t_0 price; a_{t_0}, price index in base year t_0).The CEPCI is integrated within Equation (18) and aims to calculate a reference year into another year.

$$I_{0,C,t} = I_{0,C_0,t_0} \left(\frac{C}{C_0}\right)^d \frac{a_t}{a_{t_0}} \tag{18}$$

Subject to the availability of data, three different approaches can be considered [34,37–39]:

- Summary procedures; i.e., to assess the capital costs of a plant, a correlation between specific plant data (e.g., annual turnover) and the plant capacity is calculated by the use of a turnover ratio. This approach shows inaccuracies of about 50%;

- Factor-based methodologies; i.e., include module concepts and global and differentiated surcharge factors. Based on the technical specification of a plant, modules are aggregated and further assessed by factors to estimate the costs of new facilities. A typical multiplier for a new unit within a refinery to estimate the total installed costs of the plant is the Lang factor, describing a ratio of the total installation costs to the costs of the major technical components in a plant. This approach shows inaccuracies of about 30%. An increase in accuracy can be achieved by differentiating global factors according to the state of aggregation of input materials, intermediate products, and final products;
- Individual equipment assessment; i.e., for an individual assessment of all cost parameters, high costs for engineering services are necessary. This approach shows inaccuracies of about 5%.

Several of the process steps for the conversion of lignocellulosic biomass into biogenic chemicals/products are still on a laboratory scale or on a pilot plant scale. Thus, it is challenging to assess the equipment costs of such a plant on an individual basis. Hence, to overcome this challenge, a factor-based methodology is applied.

The main demand-related costs are for the feedstock and for energy. If co-products occur and can be sold on the market, the demand-related costs are reduced by the revenue of the co-products (A_D, annuity of demand-related costs; m_j, mass flow of input materials/co-products j per year; p_j, market price of input materials/co-products j; $\forall j$, for all j, e.g., feedstock costs, energy costs) (Equation (19)).

$$A_D = \sum_{\forall j} \dot{m}_j p_j \tag{19}$$

If a current market price is not available, a predicted market price is calculated based on the Producer Price Index (PPI) describing the average change over time in the selling prices received by domestic producers for their output (p_j, market price of input materials/co-products j; $b_{j,t}$, market price index of input materials/co-products j in year t; $b_{j,t0}$, market price index of input materials/co-products j in base year t_0) (Equation (20)) [40].

$$p_j = \frac{b_{j,t}}{b_{j,t_0}} \tag{20}$$

Annual operation-related costs occur without any correlation to the quantity of products produced and reflect the costs for maintenance and repairs as well as for labor (A_O, annuity of operation-related costs; I_0, equipment costs investment; f_m, percentage value of I_0 for maintenance and repairs per year; L, labor costs per year) (Equation (21)).

$$A_O = I_0\, f_r + L \tag{21}$$

Annual miscellaneous costs reflect the costs for insurance as a percentage value of the equipment costs as well as the costs for waste disposal (A_M, annuity of miscellaneous costs; I_0, equipment costs investment; f_r, percentage value of I_0 for insurance per year; W_a, annual waste disposal costs) (Equation (22)).

$$A_M = I_0 f_r + W_a \tag{22}$$

Methods for Forecasting

The estimation of the development of future specific costs is based on the learning/experience curve theory. The respective approach is based on learning as well as on scaling effects. It defines the reduction of the specific costs depending on the accumulated production. The learning/experience curve is defined by Equation (23) (I_t, investment in year t; I_0, investment in base year 0; $C_{cum,t}$, cumulated installed capacity in year t; $C_{cum,t0}$, cumulated installed capacity in base year t_0; r, learning rate) [41].

$$I_t = I_0 \left(\frac{C_{cum,\ t}}{C_{cum,t0}} \right)^{\frac{\log(1-r)}{log2}} \tag{23}$$

In addition, four additional key figures are calculated per plant concept: (i) net sales, *NS* and (ii) net income, *NI*.

The net sales are the gross sales, *GS*, generated by a business less any sales returns, *SR*, allowances, *AL*, and discounts, *D* (Equation (24)) [42].

$$NS = GS - SR - AL - D \tag{24}$$

The net income is calculated based on the total revenue, *TR*, and the total expense, *TE*, according to Equation (25) [43].

$$NI = TR - TE \tag{25}$$

2.2.3. Environmental Assessment

Key Performance Indicators

For the assessment of the environmental aspects of the various concepts, the methodology applied is lifecycle assessment (LCA). The characteristic features of life cycle assessment are that it (i) is a decision supporting tool, (ii) focuses on services typically represented by a product, (iii) provides comparative (relative) statements, (iv) has a holistic perspective, and (v) aggregates over time and space [44] (Figure 8).

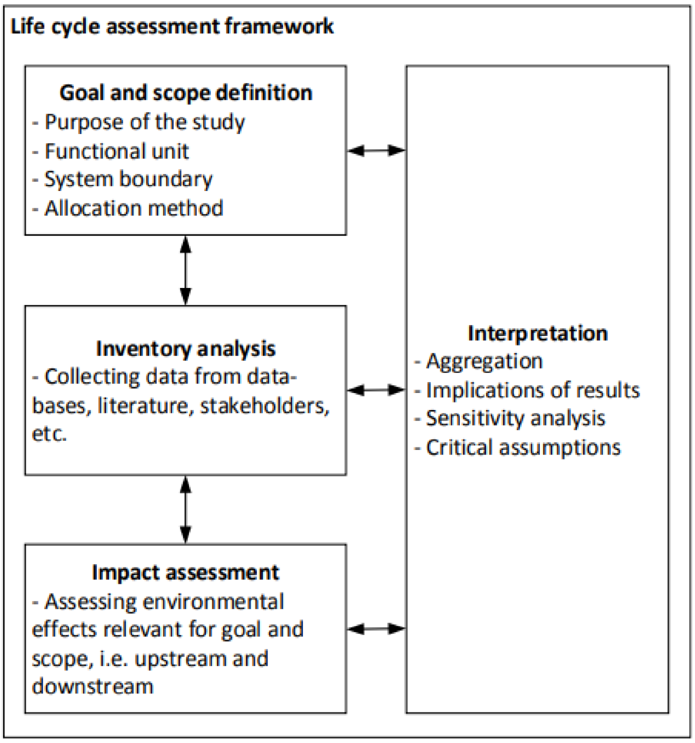


Figure 8. Life cycle assessment framework, modified as per [45,46].

In the first step, the goal and scope of the analysis are defined (i.e., temporal and spatial conditions, system boundaries). The investigated systems are defined related to the design as well as the boundaries, and the requirements of data quality are set. Both functional unit (i.e., a comparable quantity to which all environmental impacts are related, e.g., 1 kWh electrical energy, 1 MJ heat) and environmental impact categories are chosen prior to the assessment.

In the second step, inventory analysis, all necessary data required to describe the analyzed systems are collected. This includes all energy and material inputs and emission outputs during the overall life cycle throughout the production phase; depending on the scope, the use phase as well as the removal might also be included. Commercial available inventory databases are typically used to provide the necessary basic data [47,48]. All input and output flows are referred to the functional unit defined previously [28,49].

In the third step, the impact assessment (LCIA) determines the impacts of resource extractions and emissions or damages to the three areas of protection, i.e., human health, ecosystems, and resources. Relative impacts are entitled midpoint-indicators. An example for an impact category with a midpoint-indicator is the contribution to climate change. Here, emissions enforcing infrared radiation utilizes carbon dioxide as a reference substance by their relative kg CO_2-eq./GJ (e.g., 25 kg CO_2-eq. per kg methane) [50]. Classical impact assessment consists of the following mandatory elements: (i) classification; (ii) characterization; (iii) normalization; and (iv) valuation [51]. Normalization and valuation are optional steps of the impact assessment [50]:

- Classification. The classification assigns emissions to impact categories according to their potential effects;
- Characterization. The quantification of contributions to the different impact categories can be assessed by estimating impact potentials, *IP* (emitted amount per functional unit, *Q* characterization factor, *CF*) (Equation (26)) [44,52].

$$IP = Q\,CF \tag{26}$$

- Normalization. The expression of the impact potentials are considered in relation to a reference situation (e.g., person-equivalence, PE). The normalized impact potential, *nIP*, can be defined as displayed in Equation (27) (normalization reference, *NR*) [44].

$$nIP = \frac{IP}{NR} \tag{27}$$

- Valuation. The weights are ranked, grouped, or assigned depending on the different impact potentials (weighted impact potential, *wIP*, weighting factors, *WF*) (Equation (28)) [44].

$$wIP = nIP\,WF \tag{28}$$

In the last step, the interpretation, results are compared, sensitivity analyses are carried out, and conclusions are drawn [53].

Methods for Forecasting

For the updates of the environmental impacts, the following method is applied. Target emissions for specific technologies are defined by the European Commission; i.e., the target emissions for forecasting are partially legally predefined [54,55]. These target emissions are combined with an increase in conversion efficiency of the conversion processes. Accordingly, the approach for the development of future parameters is normative-exogenous.

3. Case Study

The developed methodologies aim to provide a perspective for the future. In the following, the methodology presented above will be applied to a case study.

3.1. System Definition

For the assessment of innovations in bioeconomy, the focus is put here on thermochemical conversion pathways, more precisely, on pyrolysis and gasification. Therefore, three plant locations within the EU-28 are compared. Below, a detailed overview of the basic assumptions and system boundaries is provided:

- Time horizon. The time horizon is the current status (i.e., 2017), the medium term (i.e., 2030), and the long term (i.e., 2045);
- Location. The application examples focus on the EU-28;
- Lignocellulosic biomass. The only biomass theoretically available as a raw material for the chemical industry is exclusively residual biomass, or biomass cultivated on non-arable or marginal/degraded land. The criterion considered for the selection of the feedstock is the technical potential for different types of lignocellulosic biomass resources in the selected regions: (i) forest residues; (ii) agricultural crop residues; and (iii) energy crops;
- Conversion pathways. The thermo-chemical conversion pathways exemplary evaluated are pyrolysis and gasification;
- Plant capacity. The plant capacity is set to a fixed amount of input biomass to the plant to ensure comparability;
- Plant locations. The countries where the plants are located are in northern Europe, Sweden, in central Europe, Germany, and in southern Europe, Spain.

The current status is compared with the medium and long-term developments in the EU-28. The next subsections display the baseline evaluation findings as a basis for the assessment of the results at the technical, economic, and environmental levels.

3.1.1. Determination of Relevant Biomass Resources

The criterion considered for the selection of the feedstock is the technical potential for different types of lignocellulosic biomass resources in the selected regions; this is true for (i) forest residues, (ii) agricultural crop residues, and (iii) energy crops [7].

The NUTS-3 regions with the highest technical potentials of forestry residues, agricultural residues, and energy crops for the current status are presented in Table 2. Thus, the regions with the highest technical biomass potential for the current status are Skåne län in Sweden, Mecklenburgische Seenplatte in Germany, and Ciudad Real in Spain. The amount of biomass utilized in the conversion plants (based on the results from Table S4 in the Supplementary Materials) is set to the equivalent of ~150,000 tn. l.t_{DM}/a of straw or ~2654 TJ/a or ~100 MW_{th}. The share of the different biomass sources (i.e., forestry residues, agricultural residues, and energy crops) is based on the share of the technical biomass potential (i.e., biomass availability) per region under consideration of the net calorific value of the respective source.

Table 2. Input biomass per thermo-chemical conversion plant per selected location.

Parameter	Unit	Northern Europe	Central Europe	Southern Europe
Country		Sweden	Germany	Spain
Location		Skåne Iän	Mecklenburgische Seenplatte	Ciudad Real
NUTS-3-region		SE224	DE80 J	ES422
NUTS-3 area	km^2	11,302	5468	19,813
Forestry residues [1]	tn. l.DM/a	35,071	24,881	6143
Agricultural residues	tn. l.DM/a	112,177	123,105	40,914
Energy crops	tn. l.DM/a	193	199	102,434
Sum	tn. l.DM/a	147,442	148,185	149,492

[1] The net calorific value for coniferous trees are considered for Sweden and Germany and for non-coniferous trees for Spain, depending on the most common wood species in the countries [8].

Section S.2.3 in the Supplementary Materials provides further information regarding the evaluation of relevant biomass resources.

3.1.2. Determination of Relevant Biomass Provision and Logistics

The availability of the feedstock per region (i.e., in tn. $l._{DM}$ per km^2) defines the composition of biomass feedstock to be converted in the conversion plants. The transportation distance with regard to the available amount of biomass per hectare is provided in Table 3. Accordingly, the transportation distance in Sweden is lower compared to Germany and Spain due to the higher availability of biomass per km^2.

Table 3. Transportation distance per NUTS-3 region.

Parameter	Unit	Northern Europe	Central Europe	Southern Europe
Annual available lignocellulosic biomass	MJ/km^2	5,109,743	4,964,876	3,387,719
Transportation on unsealed road [1]	km	27.3	28.4	39.5
Transportation distance on sealed road	km	4.8	5.0	7.0
Sum	km	32.2	33.4	46.5

[1] The distance on unsealed roads is assumed to be 15% of the total transportation distance.

Sections S.2.1 and S.2.3 in the Supplementary Materials provides further information regarding the system definition of relevant biomass provision and logistics.

3.1.3. Determination of Relevant Biomass Conversion Routes

Only a few holistic investigations dealing with technological, economic, and environmental impacts of the production of biogenic fuels have been published in recent years. Additionally, there is a substantial lack of publications based on experimental as well as on modeling data comparing different conversion and downstream processing technologies (of lignocellulosic biomass). Exemplary reference works for fast pyrolysis are the study by Peters [56] and publications by Jones [57,58]. These investigations address technological, economic, and environmental aspects of fast pyrolysis and downstream processing technologies, primarily based on their own experimental and modeling results. The data applied presents results of relevant parameters for the conversion processes to transportation fuels, but it neither provides an overview of the state of technology, including results based on laboratory scale, nor assesses the results in terms of technological, economic, and environmental aspects in relation to other fast pyrolysis and downstream processing technologies. Accordingly, the exemplary application focuses on a variety of thermo-chemical conversion pathways (i.e., Fischer–Tropsch (FT)-diesel and pyrolysis diesel).

Following this, the conversion routes selected are based on the latest research of thermo-chemical conversion pathways with a focus on fast pyrolysis. Four respective processing routes are assessed in comparison to one gasification and Fischer–Tropsch (FT) synthesis route:

- Plant I. In situ fast pyrolysis and catalytic vapor upgrading and hydrotreating [36];
- Plant II. Fast pyrolysis and slurry upgrading [59];
- Plant III. Fast pyrolysis and hydrotreating [60];
- Plant IV. Fast pyrolysis and liquid upgrading [56];
- Plant V. Gasification and Fischer–Tropsch (FT) synthesis [61].

Section S.2.1 in the Supplementary Materials provides further information regarding the system definition of relevant biomass conversion routes.

3.2. Data Basis

Based on the system definition for the case study according to Section 3.1, below, the most important basic data and assumptions are discussed in detail.

3.2.1. Technical Assessment

The technical specifications, being the basis of the technical evaluation, are shown in Table 4. A distinction is made between the five plant concepts. No distinction is made between the technical specifications with respect to the different sites, although different input biomass has been considered, because the technology will not differ within the European region and the input biomass will only influence the pretreatment, if at all.

Table 4. Overview of plant technical specifications.

	Unit	Plant I	Plant II	Plant III	Plant IV	Plant V
Yield of gasoline [1]	L/t_{DM}	191.6	89.6	137.0	208.1	63.0
Yield of diesel [2]	L/t_{DM}	63.5	85.1	150.1	158.2	130.7
Fuel produced	m^3/a	42,188	28,893	47,469	60,564	32,015
Diesel percentage	%	27	49	56	46	70
Yield of electricity	kWh/t_{DM}	795.8	2424.6	0	0	2148.5
Electricity required [3]	kWh/t_{DM}	0	0	122.45	422.10	0
Natural gas required	GJ/t_{DM}	0.01	0	2.08	3.28	0.09
Yield of co-product [4]	$€/t_{DM}$	2.5	0	0	9.6	9.4

[1] Gasoline and gasoline range products; [2] Diesel and diesel range products; [3] Electricity purchased; [4] Other than electricity.

3.2.2. Economic Assessment

In order to achieve a comprehensive economic assessment, several system boundaries were defined. Some of the factors are listed in Figure 3 and in the Supplementary Materials (Tables S1–S3):

- For the total (installed) equipment costs, no differentiation was considered between the three regions (i.e., Northern Europe, Central Europe and Southern Europe);
- The assessment neither considers any policy factors (e.g., carbon credits, subsidies, mandates, nor tax for the final transportation fuel product);
- The interest rate is set to 4% [62];
- The economic plant lifetime is 20 years according to the technical plant lifetime;
- The biomass input is set to 150,000 t_{DM}/a.

Market prices and equipment and material costs are taken from the literature or databases. If the year of the reference varies from the year of the assessment, it was adjusted according to the Chemical Engineering Plant Cost Index (CEPCI) or the Producer Price Index (PPI) into the present monetary value (Section 2.2.2).

Table 5 lists the plant specific aspects (i.e., labor specific factors). It becomes clear from this data that different numbers of employees are required for each plant concept, especially for the production labor and chargehand labor.

Table 5. Overview of plant economic specific assumptions.

	Unit	Plant I	Plant II	Plant III	Plant IV	Plant V
Shifts	per day	3	3	3	3	3
Production labor	per shift	11.0	10.8	15.5	13.0	14.0
Chargehand labor	per shift	4.1	3.8	2.1	4.0	3.1
Specialist labor	per shift	0.5	1.8	0.5	1.0	0.5
Office staff	per year	1	1	1	1	1
Management staff	per year	1	1	1	1	1

The applied economic learning rates have been determined according to the presented methodology, depending on the plant concept [63–68] (Table 6). The learning rate is the relative cost reduction occurring for each doubling of the cumulative installed capacity. For the sites in northern and central Europe, a learning rate of 0.0 has been assumed, as mainly forestry and agricultural residues are utilized. Compared to that, for the site in southern

Europe, a learning rate of 0.05 has been applied, as the cultivation and provision of energy crops is expected to improve efficiency.

Table 6. Overview of applied economic learning rate.

	Plant I	Plant II	Plant III	Plant IV	Plant V
Capital related costs	0.08				0.05–0.15
Demand related costs					
Feedstock	0.00 [1]–0.05 [2]				0.05
Catalyst	0.01				0.04–0.06
Energy	0				
Operating related costs					
Labor	0.075				
Maintenance	0.05				0.1
Miscellaneous costs	0.051				

[1] Relevant for forestry and agricultural residues; [2] Relevant for energy crops; spatial variances included.

Section S.2.2 in the Supplementary Materials provides further information, e.g., regarding the equipment costs and the demand related costs, as well as catalyst prices.

3.2.3. Environmental Assessment

The local environmental effects are already very largely regulated at the EU level, and the driver behind the bioeconomy is climate protection. Therefore, the focus of this investigation is concentrated on GHG emissions. Figure 9 illustrates the system boundaries assumed here.

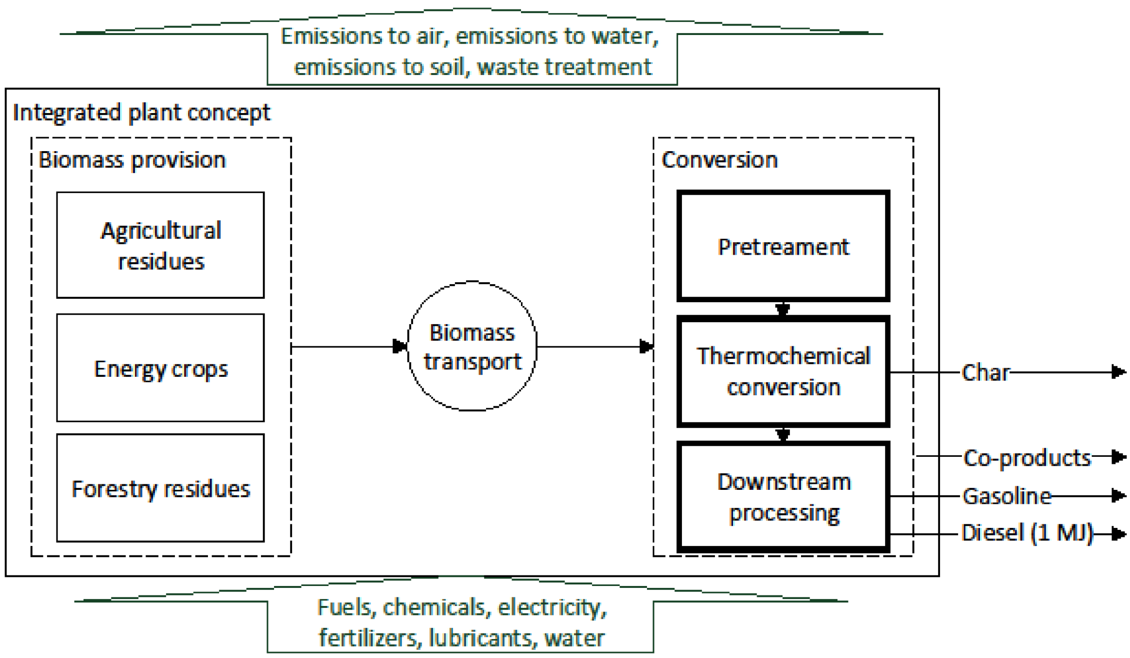


Figure 9. Block diagram of a biogenic system based on thermo-chemical conversion for the production of bulk chemicals as an exemplary representation of the input and output flows of an integrated plant concept.

The aim of the assessment is the comparison of the different conversion technologies in the selected regions. The functional unit for assessing bioenergy products is output oriented, e.g., 1 MJ of intermediate product (comparable to diesel) [56,69–71]. The assessment does not include the final use of the intermediate product and follows the principles of a cradle-to-gate approach.

The assessment follows an attributional approach. Typically, life cycle assessments of biogenic systems do not consider capital goods, because they do not determine the results of the assessment significantly [56,71]. Thus, this assessment does not take into account any capital goods to simplify the comparison to other studies in this field.

Section S.2.2 in the Supplementary Materials provides further information regarding the allocation methodology applied.

3.3. Results

3.3.1. Technical Assessment

Current Status

Figure 10 shows the evaluation of the technical results for the five plant concepts. The available intermediate products for the chemical industry are shown as diesel, gasoline, char, steam, and electricity. Therefore, the assessment of the technology focuses on the conversion efficiency of the thermo-chemical conversion and downstream processing technologies.

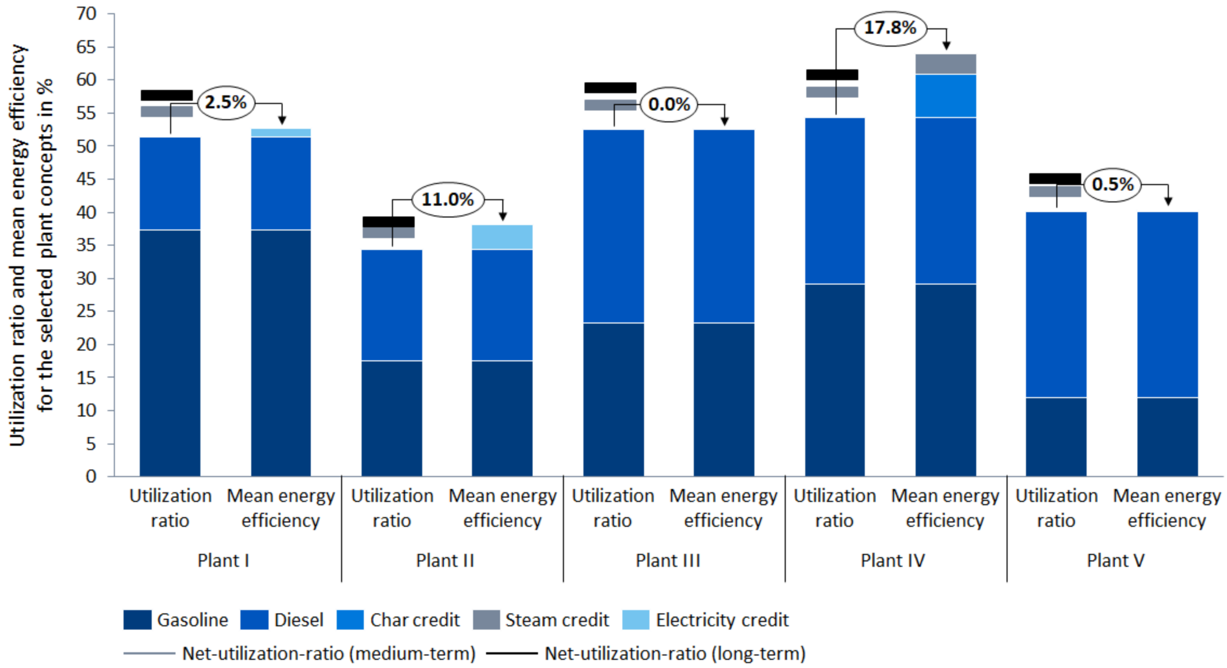


Figure 10. Utilization ratio of the plant concepts for the current status compared to the medium- and long-term perspective and mean energy efficiency for the current status.

Clear differences in the utilization ratio for the plant concepts become obvious. Plant concepts I, III, and IV achieve a utilization ratio of more than 50%, whereas plant concepts II and V have a significantly lower utilization ratio. Similar trends can be observed with regard to mean energy efficiency. Plant concept IV, achieving a significant increase in efficiency due to the co-products, is particularly notable.

- Plant I. Diesel and gasoline are produced via in situ fast pyrolysis and catalytic vapor upgrading and downstream processing including hydro-treating. As a result, the utilization ratio of the process is 51% for the current status. In comparison with the other plant concepts, this concept produces 27% diesel compared to gasoline. The mean energy efficiency is 53% and, thus, it is slightly higher compared to the average energy efficiency of the five plant concepts (50%). Plant I utilizes 0.01 MJ per kg of diesel as well as of natural gas. The electricity credit is around 0.22 MJ/kg.
- Plant II. This plant concept produces via fast pyrolysis and subsequent slurry upgrading, including Fischer–Tropsch (FT) synthesis ~49% diesel compared to gasoline.

The calculated utilization ratio of 34% is lower compared to the average value of the plant concepts (47%). The mean fuel efficiency is 38% and, thus, it is slightly lower compared to the average energy efficiency. The electricity credit is the highest of all plant concepts with around 0.67 MJ/kg.

- Plant III. The utilization ratio of the fast pyrolysis and liquid upgrading plant is 52%, as is the mean fuel efficiency. This plant concept produces 56% diesel. The electricity use is ~0.44 MJ/kg, and the natural gas use is the second highest with 2.08 MJ/kg.
- Plant IV. This plant concept of fast pyrolysis and liquid upgrading has the highest energy needs for electricity and natural gas with 1.52 MJ/kg and 3.28 MJ/kg, respectively. The plant produces 46% diesel. Credit can be given for 1.57 MJ/kg of char and 0.75 MJ/kg of steam.
- Plant V. Compared to the fast pyrolysis concepts, the gasification and Fischer–Tropsch (FT) synthesis concept gains yields of 40% utilization ratio and up to 43% mean energy efficiency. This plant concept produces 70% diesel. The electricity credit is 0.60 MJ/kg.

Medium- and Long-Term Perspective

For the assessment of medium- and long-term energy conversion efficiencies, the results are based on the saturation model and the use of technical limits defined by [64]. The utilization ratios of the medium and long-term concepts are also included in Figure 10.

- In plant I, diesel and gasoline are produced via in situ fast pyrolysis and catalytic vapor upgrading and downstream processing including hydro-treating. As a result, the utilization ratio of the process ranges between 55% and 58% for the medium- and long-term.
- Plant II produces via fast pyrolysis and subsequent slurry upgrading, including Fischer–Tropsch (FT) synthesis ~49% diesel compared to gasoline. The utilization ratio, 37% to 39%, is lower compared to the average value of the plant concepts.
- The utilization ratio of plant III of the fast pyrolysis and liquid upgrading plant is between 56% and 59%.
- Plant IV, with fast pyrolysis and liquid upgrading, has a utilization ratio for the medium- and long-term between 58% and 61%.
- Plant V, compared to the fast pyrolysis concepts, the gasification and Fischer–Tropsch synthesis concept has a utilization ratio for medium- and long-term perspectives between 43% and 45%.

3.3.2. Economic Assessment

This chapter introduces the findings from the economic assessment that was conducted to assess the plant concepts under economic criteria in terms of the biogenic intermediate production costs as well as the logistic costs. The following explanations show the economics according to the methodology described in Section 2.

Current Status

The economic assessment is based on estimated capital-related, demand-related, operation-related, and miscellaneous costs associated with constructing plants of this kind. Major variances can be seen in the fuel production costs for both the different plant concepts as well as the different regions. The results of the technical evaluation are accordingly reflected in the economic evaluation based on the costs per GJ generated. The most interesting concepts from an economic point of view are, accordingly, concepts I, III, and IV (Figure 11).

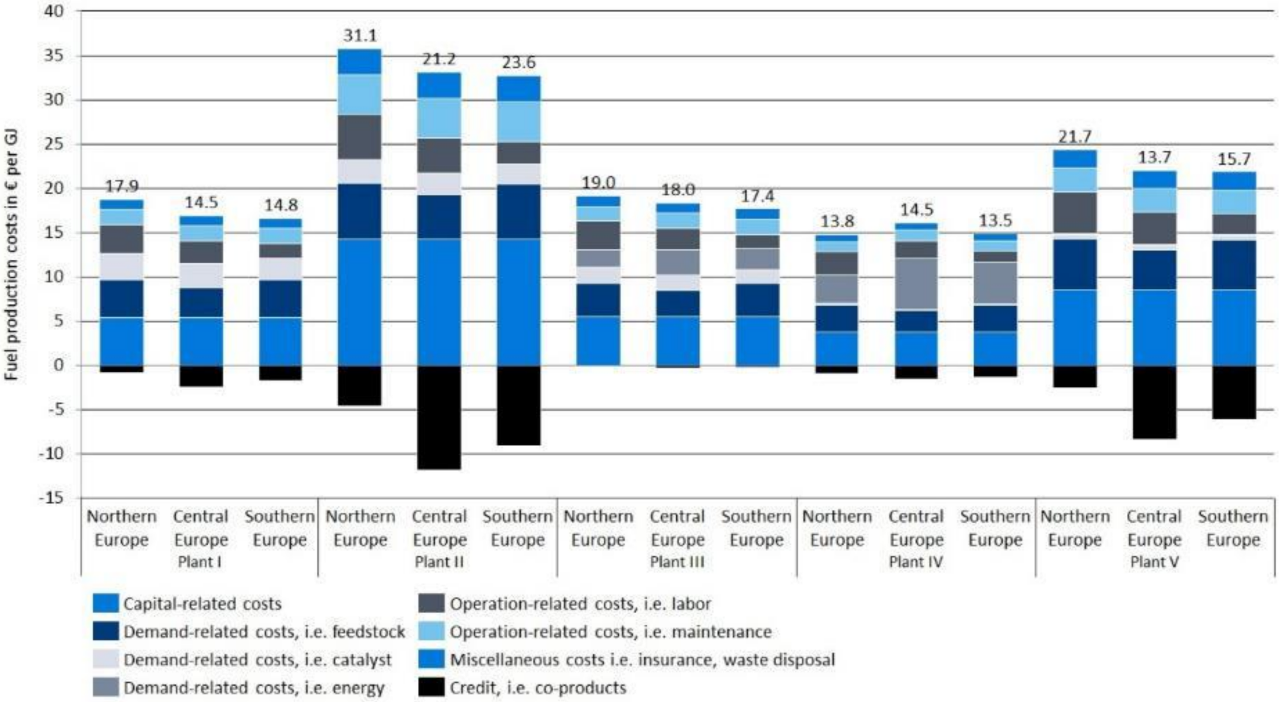


Figure 11. Fuel production costs for the current status.

Table 7 presents the (i) net sales and (ii) net income. While many conclusions can be drawn from each of the individual economic results presented previously, the economic effectiveness can only be truly understood when the findings from each of the five plant concepts are compared based on the net income. Four out of five plant concepts, no matter in which location, have a negative net income value, except for Plant IV, resulting in a positive value in northern Europe (344 k€/a) and in southern Europe (884 k€/a).

Table 7. Plant summary for the selected plant concepts and regions for the current status.

	Unit	Plant I	Plant II	Plant III	Plant IV	Plant V
			Northern Europe			
Net sales	k€/a	18,162	84,205	22,813	30,849	12,186
Net income	k€/a	−82,086	−23,901	−75,061	344	−12,911
			Central Europe			
Net sales	k€/a	14,227	−913	20,888	29,642	3190
Net income	k€/a	−9120	−30,276	−8027	−3706	−19,026
			Southern Europe			
Net sales	k€/a	17,136	3505	22,890	31,853	7426
Net income	k€/a	−5761	−25,448	−4771	884	−14,574

Medium- and Long-Term Perspective

The fuel production costs are presented in Figure 12 for the medium- and long-term perspectives. It is presumed that the five different plant types are built in locations with comparable characteristics (e.g., biomass availability) as well as infrastructure. The results are based on the installed plant capacities in MW output per plant concept. In the long-term, plant concepts I, III, and IV will also prevail here.

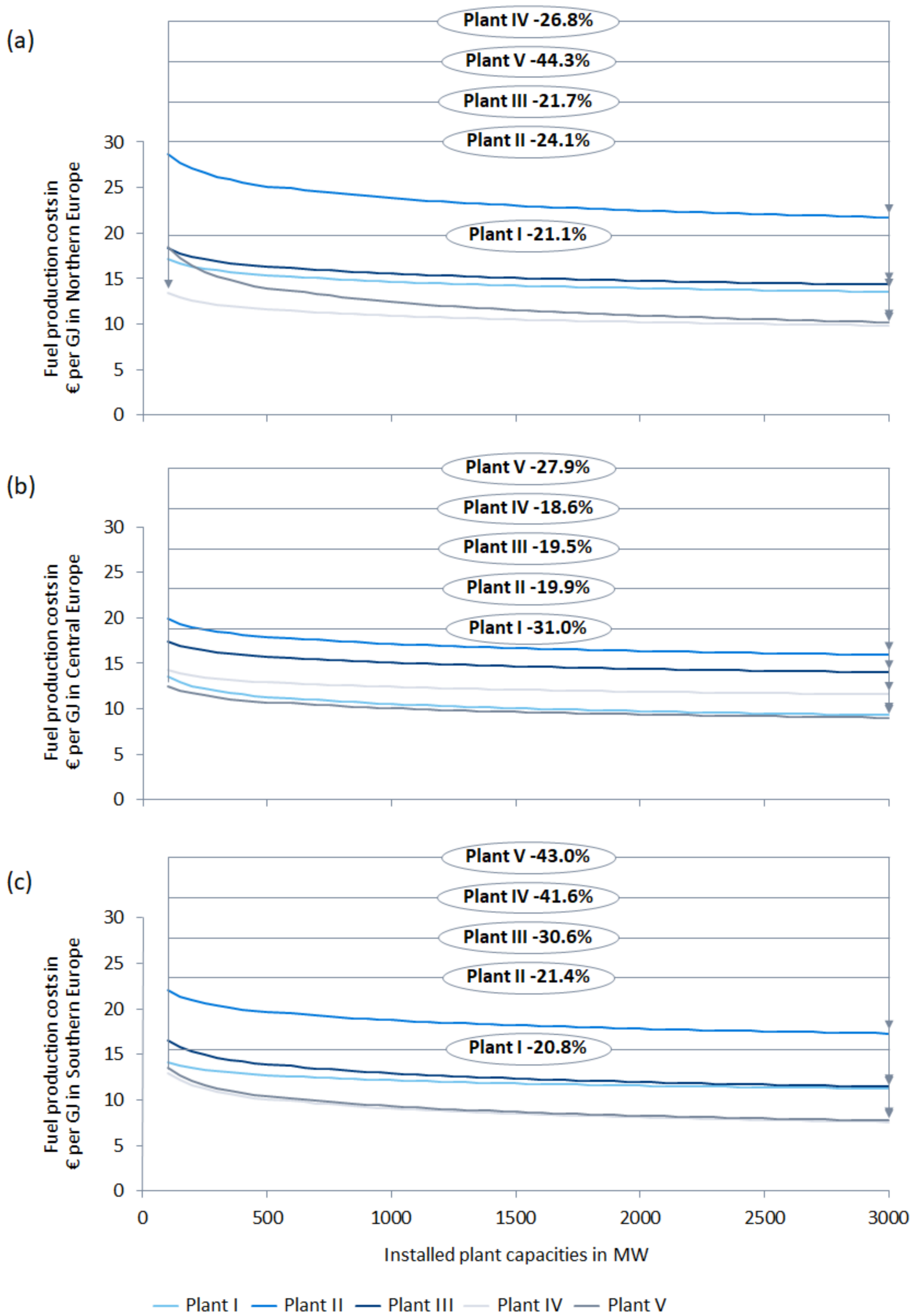


Figure 12. Specific fuel production costs for the medium- and long-term perspective: (**a**) Northern Europe, (**b**) Central Europe, and (**c**) Southern Europe.

However, clear differences can be seen in the plant concepts depending on the location. In northern and southern Europe, plant concept IV is to be preferred, whereas in central Europe, plant concept V would be preferable. In the medium- and long-term, however, with a strong increase in installed plant capacities, it can be assumed that the production of intermediate biogenic products can definitely make a cost-effective contribution to the chemical industry.

Section S.2.3 in the Supplementary Materials provides further information regarding a parameter variation of the economic assessment.

3.3.3. Environmental Assessment

Current Status

The specific GHG-emissions are dominated by the influence of the biomass provision (Figure 13). Biomass cultivation and harvesting depends on the use (i.e., burning) of fossil sources. Thus, the GHG-emissions of the biomass provision are comparably high. Depending on the combination of feedstock utilized in the plants per region, the specific GHG-emissions of the biomass provision varies. The use of the fossil fuel energy needed for the production of agricultural residues is higher compared to the production of energy crops and forestry residues. However, the differences between the various sites assessed here are negligible in terms of the specific GHG-emissions from biomass provision.

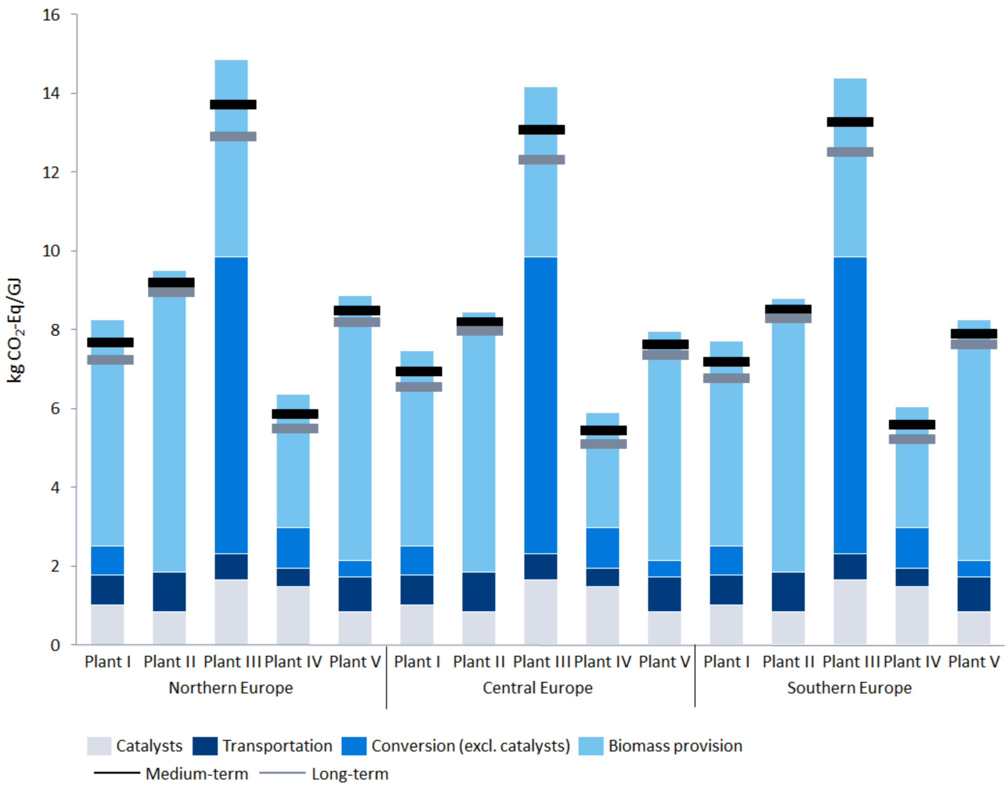


Figure 13. Kg CO_2-eqivalent/GJ of the production of intermediate products per plant concept and region for the current status, medium-, and long-term perspectives. The modeling is based on [28,47,48,56,72–79].

With regard to the specific GHG-emissions for the transport of the biomass, there are barely any differences between the locations.

The impact of the specific GHG-emissions of the conversion processes are primarily caused by the impact of the fossil fuel energy needed for the conversion processes. Because, in plant concept II, the process energy is obtained from the biomass and no additional fossil fuel energy are required or consumed, the specific GHG-emissions during the conversion are 0. Plant III and plant IV need natural gas for the conversion processes. The specific GHG-emissions due to the use of catalysts have a significant effect on the overall result. Among other things, plant concepts I and V thus show lower values than plant concepts III and IV, as the catalysts have a significantly lower replacement rate per year. The use of the support material has only a subordinate role. In contrast, the type of catalyst is important. In particular, the use of ruthenium and molybdenum in plant concept III and the use of cobalt-molybdenum in plant IV are decisive here.

Medium- and Long-Term Perspectives

In the medium- and long-term, all plant concepts are expected to have a lower environmental impact because, as described in the methodology, the utilization rate is used to update the specific GHG-emissions. Accordingly, the changes in the results are also the same between the locations.

4. Discussion and Conclusions

The aim of the Circular Economy Action Plan, relevant for the chemical industry, is to produce sustainable products, with a particular focus on resource-intensive sectors such as textiles, electronics, and plastics. Accordingly, the chemical industry is faced with the question of how far it can promote its own manufacture of sustainable products. Thus, within this article, the effectiveness of a developed methodological approach to assess innovations in bioeconomy in the chemical industry were examined. The methodological framework provided allows the chemical industry to assess the effectiveness of innovative conversion technologies producing biogenic intermediate products (e.g., bulk chemicals). The innovations within the bioeconomy (TRL > 4; TRL—technology readiness level) are compared in terms of technical, economic, and environmental indicators for the current status and the medium- and long-term as well as for different production sites. The methodological approach developed is exemplarily applied, assessing the production of intermediate biogenic products via thermo-chemical conversion of lignocellulose. The results show significant differences in time perspective and in spatial terms within the European Union (EU).

- Utilization ratio and energy efficiency. Clear differences in the utilization ratio for the plant concepts become obvious. Plant concepts I, III, and IV achieve a utilization ratio of more than 50%, whereas plant concepts II and V have a significantly lower utilization ratio. Similar trends can be observed with regard to mean energy efficiency. Plant concept IV, achieving a significant increase in efficiency due to the co-products, is particularly notable.
- Costs. Four out of five plant concepts, no matter in which location, have a negative net income value, except for Plant IV, resulting in a positive value in northern Europe (344 k€/a) and in southern Europe (884 k€/a). Therefore, according to current data, it can be assumed that no profitable production of intermediate biogenic products for the chemical industry is currently possible. In the medium- and long-term, however, with a strong increase in installed plant capacities, it can be assumed that the production of intermediate biogenic products can definitely make a cost-effective contribution to the chemical industry, assuming there is a strong increase in CO_2-taxes and thus a clear price increase for fossil fuel energy.
- Environmental impact. Among other things, plant concepts I and V show lower values than plant concepts III and IV, as the catalysts have a significantly lower replacement rates per year.

The article from S. Spatari et al., 2020 shows similar results for a comparison of different plant concepts for the production of catalytic and fast pyrolysis-to-renewable diesel. Additionally, S. Gupta et al., 2021 and Y. Sorunmu et al., 2019 also show comparable results for the current status in terms of technical, economic, and environmental assessment, But these studies but do not distinguish between different locations and also largely refrain from forwarding the results [80–82].

The methodological approach developed enables the European chemical industry to reduce challenges and to take advantage of the opportunities arising from the transition to a climate-neutral and circular economy due to the complexity of value chains and their interdependencies. The assessment methodology used to analyze the technical parameters provides a solid basis for comparing different plant concepts and also taking into account any co-products that may arise.

The learning rate assessment method used to analyze the economic parameters provides a solid basis for comparing different plant concepts. It is more common in the evaluation of conversion pathways to use the alternative evaluation method of two-factor or multi-factor curves, which incorporate other factors such as (i) improvements in the manufacturing process (i.e., learning by doing) and (ii) improvements in technology characteristics (i.e., learning by researching) [83,84]. As also concluded by A. Elia et al., 2021, most of the published multi-factor learning curve analyses focus on the effects of drivers that relate to each other. This means that the other learning drivers such as market dynamics and learning through interaction across different stakeholders and geographies are still poorly quantified, even though their impact on cost reduction is recognized in the innovation literature. Therefore, the results using the learning curve provide clearly defined results whose misinterpretation cannot occur as easily as when a multi-factor analysis is carried out, in which the multiple driving forces are included, but the ratios to each other are still not clarified.

The evaluation of the environmental results showed that, in particular, the specific GHG-emissions are strongly influenced by the catalysts used in the processes. The evaluation of the catalysts was quite complex, as very few software solutions for the environmental assessment of process chains (can) evaluate catalysts and their respective raw materials. In the future, it will be very important to create a good database in order to be able to evaluate the use of catalysts in particular.

To achieve its transition, the EU's industrial policy package should lay the foundations for the use of radical industrial policy measures to accelerate the transformation of the European chemical industry through the European Green Deal. Moreover, European policies should not maintain or even intensify the competition for scarce biomass resources within Europe, but should adopt methodological approaches that ensure optimal use of biomass.

Supplementary Materials: The following are available online at https://www.mdpi.com/article/10.3390/resources10090091/s1, Figure S1: Simplified process scheme of the raw material supply chain from lignocellulosic biomass, Figure S2: Share of contribution to the product price from cradle to plant gate, excluding potential co-products, Figure S3: Allocation factors for the selected plant concepts per product (i.e., diesel) and co-product (i.e., gasoline, electricity, char, and steam), Figure S4: Transportation costs for (a) chip, (b) straw, and (c) oil trucks on sealed and unsealed roads, Figure S5: Variation of the parameters (i) feedstock costs, (ii) labor costs, (iii) fuel sale price, (iv) energy costs, (v) capital costs, (vi) yield, and (vii) catalyst costs for the five plant concepts in northern Europe, Figure S6: Variation of the parameters (i) feedstock costs, (ii) labor costs, (iii) fuel sale price, (iv) energy costs, (v) capital costs, (vi) yield, and (vii) catalyst costs for the five plant concepts in central Europe, Figure S7: Variation of the parameters (i) feedstock costs, (ii) labor costs, (iii) fuel sale price, (iv) energy costs, (v) capital costs, (vi) yield, and (vii) catalyst costs for the five plant concepts in southern Europe, Table S1: Overview of constant and variable input parameters for the evaluation of relevant biomass resources, Table S2: Overview of constant and variable input parameters for the evaluation of relevant biomass provisions and logistics, Table S3: Overview of constant and variable input parameters for the evaluation of relevant biomass conversion route, Table S4: General input variables for biomass provision and logistics, Table S5: Costs components of transportation, Table S6: Selected technical parameters for the five plant concepts, Table S7: Equipment costs summary and specifications for the current status, calculations based on [8–16] (References [8–16] are cited in the supplementary materials), Table S8: Energy prices for industrial consumers and sellers [17] (Reference [17] are cited in the supplementary materials), Table S9: Catalyst prices [8–12,19] (References [8–12,19] are cited in the supplementary materials) and expert knowledge, Table S10: Selected allocation methods for grain and straw [20] (Reference [20] are cited in the supplementary materials), Table S11: Technical potential of forestry residues, agricultural residues, and energy crops in selected NUTS-3 regions for the current status, calcu-lated based on [21] (Reference [21] are cited in the supplementary materials).

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